NEW YORK ACADEMY OF SCIENCES

# SCIENTIFIC SURVEY

OF

# Porto Rico and the Virgin Islands

VOLUME II—Part 3

## The Geology of the Fajardo District, Porto Rico—

*Howard A. Meyerhoff*

Introduction, Tertiary and Quarternary Geology and Physiography —*H. A. Meyerhoff*

Cretaceous Geology—*H. A. Meyerhoff and I. F. Smith*


NEW YORK:
PUBLISHED BY THE ACADEMY
1931

NEW YORK ACADEMY OF SCIENCES

# SCIENTIFIC SURVEY

OF

# Porto Rico and the Virgin Islands

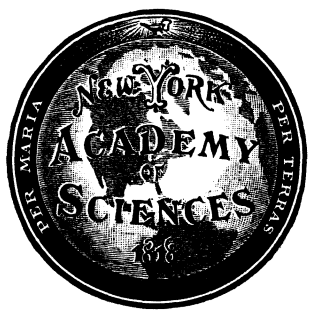
VOLUME II—Part 3

## The Geology of the Fajardo District, Porto Rico—

*Howard A. Meyerhoff*

Introduction, Tertiary and Quarternary Geology and Physiography —*H. A. Meyerhoff*

Cretaceous Geology—*H. A. Meyerhoff and I. F. Smith*




NEW YORK:
PUBLISHED BY THE ACADEMY
1931

# THE GEOLOGY OF THE FAJARDO DISTRICT PORTO RICO

By Howard A. Meyerhoff

INCLUDING A SECTION ON CRETACEOUS GEOLOGY
PREPARED WITH THE COLLABORATION OF
ISABEL F. SMITH

CONTENTS

## INTRODUCTION

### Geological Field Work in the Fajardo District

The Fajardo district, named from the town of Fajardo, embraces approximately 450 square miles of northeastern Porto Rico. It constitutes one of the seven districts into which the island was divided for the purpose of detailed geologic study, to follow the reconnaissant survey by C. P. Berkey and C. N. Fenner in 1914.[1]

Prior to the survey inaugurated by the New York Academy of Sciences, no systematic geological work had been done in the northeastern portion of Porto Rico, although some general information, applicable directly or indirectly to the region, was available in the works of R. T. Hill[2], P. T. Cleve[3], and other authors. In the course of the Academy's

[1] Berkey, C. P.: Geologic reconnoissance of Porto Rico. Annals, New York Academy of Sciences, Vol. XXVI, 1915, pp. 1-70; Introduction to the geology of Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, 1919, Vol. I, pp. 11-29.

[2] See bibliography.

[3] Cleve, P. T.: On the geology of the northeastern West India Islands. Kongl. Svenska Vetenskaps Akademicus, Handlingar, 1871, Bandet IX, No. 12, Stockholm, pp. 1-48.

comprehensive survey, however, the district has received attention from several investigators. In 1914 it was examined by Berkey and Fenner in their preliminary work; in 1916 its landforms were studied by A. K. Lobeck;[4] in 1921 a survey of its areal geology was begun, but unforeseen circumstances prevented the completion of this survey; and in 1923 the late Professor James F. Kemp made a brief examination of the mineral deposits reported or prospected in the Fajardo region in the course of his study of the economic geology of Porto Rico.[5] In 1924, through the kindness of Professor Kemp and Dr. N. L. Britton, the writer was asked to supplement his geological studies in the Virgin Islands with an areal survey of the contiguous and closely related Fajardo district. This report is the outcome.

The field survey on which the present work is based was made by the writer with the assistance of Mrs. Meyerhoff during June, July, and August, 1925. A superficial acquaintance with the district had been previously obtained in May, 1924, when a hasty examination of its main geological features was undertaken for the purpose of establishing the general geologic relationships between Porto Rico and the islands to the east. Additional studies were made in the district in August and September, 1926, to augment the meager paleontological collection from the coastal plain strata, to determine the limits of the dioritic intrusion in the vicinity of Rio Blanco, and to fill in other gaps in the collections and observations accumulated during the summer of 1925.

The data gathered in the course of field work cannot be regarded as altogether satisfactory, and the present report on the areal geology of the district reflects the limitations of the material from which it has been prepared. Many problems which arose in the progress of the work were not solved, because their solution would have entailed several additional weeks of close field examination, and in most cases there was no assurance of successful results even with further study. The inaccessibility of parts of the district constituted one important source of difficulty. Only four trails thread the Luquillo National Forest and the Luquillo Mountains belt, and two of these, closed by uncut vegetation, proved impassable. In consequence, traverse lines through and around the mountains were spaced somewhat irregularly; and to add to this handicap the heavy covering of vegetation and the complete absence of rocks *in situ* even on the steep mountain slopes thwarted every effort

[4] Lobeck, A. K.: The physiography of Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, 1922, Vol. I, Pt. 4, pp. 301-379.

[5] The untimely death of Professor Kemp interrupted the preparation of a report on the mineral resources of the island, for inclusion in Part 4 of this volume. Tentative plans have been made for the completion of this work.

to obtain reliable structural and stratigraphic information in this part of the district. Traverses across the upland section immediately east of the mountains were of such length that in several cases there was little time for careful study of local problems and details. Too often attention had to be confined to the outcrops and other features in the immediate vicinity of the caminos.[6] Notwithstanding the difficulty of travel through the central part of the district, a net-work of traverse lines was made across it, at no point more than five miles apart, and at an average spacing of three miles. The entire district was examined on foot, for no feasible method of using horses on one-way trips over poor and uncertain trails could be devised. Motor transportation was utilized but one day for reconnaissance and was employed otherwise only for transportation to and from the immediate area in which the day's work was done. For most purposes the bus or "guagua" service proved adequate.

In the conduct of the field survey Rio Piedras was selected as central headquarters. Transportation facilities from this town to Canovanas on the east and to Caguas and Juncos on the south (see geologic map) proved so excellent that approximately two-fifths of the district could be covered without change of base. The Luquillo Mountains were studied from the government forestry cabin at the northern edge of the Luquillo National Forest, about three and one-half miles south of Mameyes, where temporary headquarters were maintained for a week. Fajardo served as a base for the work done in the northeastern and eastern parts of the district, and a few days were spent at Naguabo during the study of the southeastern portion of the Luquillo Mountains. Temporary lodging was obtained in Barrio [7] Guzman Arriba at the western edge of the National Forest, and at Florida estate in the valley of Rio Blanco in Barrio Rio Blanco Abajo.

## Acknowledgments

Invaluable assistance was received from many sources in the prosecution of the field work. Inasmuch as accurate areal geology is conditioned by the adequacy of the maps which guide it, the author's first acknowledgment may appropriately be made to the Military Intelligence Division of the War Department, which generously supplied copies of

[6] The word "camino" is employed for a country road or trail; "carretera" is used to designate a "hard" or paved road. Less than twenty per cent. of the Fajardo district is immediately accessible to the carreteras.

[7] The word "barrio," which will recur on subsequent pages of the report, is roughly equivalent to "township."

the reconnaissance contour maps of Porto Rico, made by Major Armstrong in 1908. These maps were of exceptional service in planning the work of the summer and in geologic mapping. The writer feels especial indebtedness to Mr. W. P. Kramer and to other members of the Forest Service at Rio Piedras for innumerable kindnesses, among them the use of the cabin south of Mameyes as a base of operations during the field examination of the Luquillo Mountains; the assignment of a forest guard as guide and helper during the Luquillo Mountains work; and the care of mail, supplies, and specimens during the writer's extended absences from Rio Piedras. To Señor Jorge Bird Leon of Fajardo the writer owes a debt of thanks for the use of his launch, *Bluebird,* in the survey of the islands off the east coast of the Fajardo district. Indebtedness is also acknowledged to Commissioner of Agriculture, Carlos E. Chardon, and to Mr. O. W. Barrett, formerly of the Department of Agriculture, for their kind attention to the expedition's affairs in San Juan and for helpful suggestions with regard to the field work; to Señor Edmundo Martinez of Rio Piedras, whose help solved many of the practical difficulties encountered in the early stages of the work; and to the forest guard, Bartolo Peraza, whose guidance and thoughtful service made possible what work was done in the Luquillo Mountains. A tribute is also due the inhabitants of the district for their unfailing courtesy, spontaneous interest, and friendly hospitality.

The writer feels a debt of gratitude that can never be repaid to the late Professor James F. Kemp for helpful notes and suggestions which guided both the field and laboratory study. And finally, in the field and the laboratory, Dr. N. L. Britton has proved an unfailing source of inspiration and help, and to him is largely due whatever merit the present report may have.

In the laboratory studies and in the preparation of the report, figures, and maps, the writer owes much to the help and criticism given by his former colleague, Professor Isabel F. Smith, who has collaborated in the preparation of the section dealing with the Cretaceous geology; to the suggestions and criticisms given in the petrographic studies by Professor R. J. Colony of Columbia University; to Miss Anne E. Burgess, who has given substantial aid in the preparation of the manuscript; and to Mrs. Meyerhoff, whose assistance has been utilized in every phase of the work. The writer wishes to take this opportunity to express his personal appreciation and that of the New York Academy of Sciences for the aid given toward the prosecution of the laboratory work by Smith College through its president, William Allan Neilson.

## GEOGRAPHY

### Location and Boundaries

The Fajardo district includes the 450 square miles of northeastern Porto Rico which lie between longitudes 65°34′ and 66°6′ west, and latitudes 18°15′ and 18°28′ north. In the prosecution of the field work it was found expedient to extend detailed investigations as far south as 18°13′ into the Humacao district, and as far west as 66°8′ into the San Juan district. The geologic map accompanying the report covers the entire area studied.

The Atlantic coast forms a natural boundary on the north, and Fajardo Roads and Vieques Passage limit the district on the east. On the south a natural boundary is supplied by a lowland which extends from Caguas to the east coast at Playa de Naguabo, a distance of twenty-four miles. The northern wall of the lowland is a steep, youthfully dissected escarpment that trends slightly south of east and crosses the southern boundary of the district as originally defined; but all of the scarp is included within the somewhat larger area described in this report. On the west there is no strong topographic feature delimiting the district, but the military road from Rio Piedras to Caguas, following a succession of low passes, crosses the boundary at La Muda, and at all points lies within a relatively short distance of it.

### Settlement and Communication

Except for the area included within the Luquillo National Forest, the Fajardo district is one of the most populous in Porto Rico. Towns and villages are numerous, the more important of which include Santurce, a community incorporated in the city of San Juan, with a population estimated at 40,000; Caguas[8], with 12,200 inhabitants; Fajardo, 6,600; Rio Piedras, 5,900; Juncos,[8] 4,300; Naguabo,[8] 3,700; Carolina, 3,150; Gurabo, 2,550; Rio Grande, 2,000; Aguas Buenas,[8] 2,000; Luquillo, 1,250; Canovanas, 1,100; Ceiba, 850. Trujillo Alto, Loiza (viejo), Mameyes, Rio Blanco, and El Rio are moderate-sized villages within, or at the edge of, the district, and smaller ones, including the "colonias" or settlements on the larger sugar estates, are common. The rural population, which is widely disseminated throughout most parts of the district except in the mountains, approximates 150,000, making a total population of nearly 250,000, or roughly 500 inhabitants per square mile.

[8] These towns lie outside the original boundaries of the district but were included in the broader limits of the survey. All figures are from the 1920 census.

The distribution of towns and of the rural population is uneven, however, and responds rather directly to the agricultural pursuits followed in the various portions of the district. Agriculture in turn is directly related to soils, topography, and rainfall. The suitability of much of the country of low relief for large-scale sugar production and the suitability of the lowland extending from Caguas to Naguabo for tobacco and sugar are responsible for the concentration of towns and villages in these lower sections around the borders of the district. The density of population here has naturally led to the construction of excellent carreteras connecting all the principal settlements with one another and with San Juan (see geologic map). The old Spanish military road thus extends from San Juan through Rio Piedras across the low pass to Caguas, connecting at La Muda with another road from the capital by way of Guaynabo. The Porto Rico Railway, Light, and Power Company maintains a freight railroad to Caguas via Trujillo Alto and the entrenched gorge of Rio Grande de Loiza. Automobile highways radiate outward from Caguas to Aguas Buenas, Cayey, San Lorenzo, and eastward to Gurabo and Juncos. Juncos is connected with Torres, Rio Blanco, and Naguabo on the east, and with Humacao on the southeast by excellent roads. The coastal section on the north and east sides of the district is served by a carretera from Rio Piedras to Humacao via Carolina, Canovanas, Rio Grande, Luquillo, Fajardo, Ceiba, and Naguabo. Cane railroads parallel many of the carreteras in the lowlands and all but girdle the district.

The interior of the Fajardo district presents a strong contrast to the marginal sections. In the west it is a maturely dissected region, the relief and ruggedness of which increase southward and eastward. There is little flat land; and the moderate rainfall, thin vegetation, heavy lateritic soils, and steep slopes make large farms unprofitable. It is thus a country of small farms, in which centers of population are lacking. There is but one village, Trujillo Alto, with 539 inhabitants. It is connected with Rio Piedras by a carretera, which was being extended southward at the time the field survey was made. In the balance of the western interior there are only two carreteras, one under construction from Canovanas to Juncos along Rio Canovanas at the western edge of the Luquillo Mountains; the other, a short blind road from Rio Piedras to Barrio Cupey. Caminos serve the rest of the area, most of them threading the country from north to south, and linking the towns on the northern carretera with those in the Caguas-Naguabo lowland. The greater part of the eastern interior is a region of very high relief, em-

bracing the Luquillo Mountains and their deeply dissected foothills. The population is thin, and settlers are excluded from the twenty square miles of the mountain slopes and summits which are included in the national forest. Travel routes are therefore few and are so infrequently utilized that one of them was found impossible to follow, even with the expert guidance of a forest guard, and others were reported as impassable.

FIG. 1.—*El Yunque*

A view from the Canovanas-Juncos carretera, showing the peak's detachment from the central range, which forms the southern skyline.

## PHYSICAL GEOGRAPHY

Consideration will be given to the genesis of the physiographic features of the Fajardo district in later sections of the report; but an introductory description of the topographic subdivisions and their characteristics is germane to the discussion of the areal geology that follows.

In elevation the area studied ranges from sea-level to 3500 feet. In the Luquillo Mountains about seven eminences rise well above 3000 feet, including East Peak, West Peak, El Yunque (Fig. 1), El Toro, and others which have no names. El Yunque (3496 feet) is popularly assumed to be the highest, but the more remote El Toro, lying in the western part of the mountain area, is about 40 feet higher. The mountains dwarf all the other topographic elements (Fig. 2) and are the more conspicuous because they are located within short distances of the coastline. The backbone of the range lies but three to five miles north of the

Caguas-Naguabo lowland. East Peak is situated eight miles west of Vieques Sound, and El Yunque lies but six miles south of the Atlantic coast. In consequence, the Luquillo Mountains constitute one of the strongest relief features in Porto Rico, surpassed only by the steep ascent of the Cordillera Central from the south coast in the south central part of the island near Ponce.

FIG. 2.—*The Luquillo Mountains*

The range rises to its full height of 3500 feet within eight miles of the Atlantic coast, and the low playas and lagoonal flats of the coastal section, like this one near Loiza, extend inland almost to its base.

The Fajardo district as a whole may be divided into four major sections:

(1) A coastal section, which includes a coastal plain and playas forming an irregular border around the northern and eastern sides of the district. This is a belt of flat or rolling country (Fig. 2), fringed along sections of the coast by lagoons and marshes that are separated from the ocean by low bars. The latter generally support large groves of coconut palms, which form the basis of a flourishing industry in this part of the island. The belt varies in width from little more than a strip of beach along parts of the eastern and northeastern coast, to a zone seven or eight miles wide. Alluvial or lagoonal deposits veneer the playas and coastal plain throughout much of the section, making it a region of considerable fertility that serves as the setting for a vigorous

sugar industry. It is here, too, that most of the coastal towns are located.

(2) An interior lowland, extending from a point four miles west of Caguas, the town from which it is named, eastward to Naguabo. This section includes the rest of the towns within, and marginal to, the district. The lowland is flanked on the north by a strong, youthfully dis-

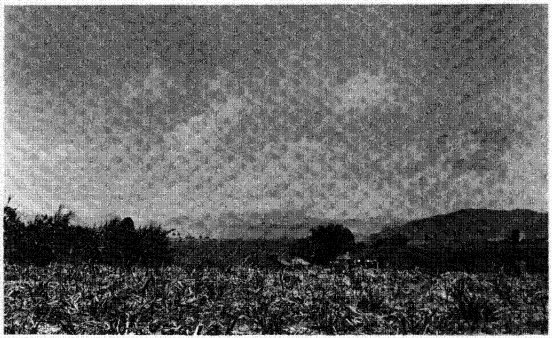


FIG. 3.—*The Caguas lowland*

The slightly dissected alluvial floor may be seen extending southward into the valley of Rio Turabo. The summits of the Sierra de Cayey merge with the clouds to form the background; the high bench which flanks the mountains on the north is a remnant of the "upper," or Saint John, peneplane; the hills on the right rise to the elevation of the Caguana peneplane.

sected escarpment, 1000 to 2000 feet high. Although breached at the water-gap of Rio Grande de Loiza northeast of Caguas, and low and broken for a short distance west of that point, the linear escarpment is the most persistent and impressive topographic feature in the district. On the south the Caguas lowland is hemmed in by deeply dissected hills, which have been opened out broadly along the courses of the larger streams (Fig. 3). The depression begins on the west not far from Aguas Buenas in two slender prongs. Eastward they unite to form a basinal depression approximately five miles in width, expanding locally where broad valleys join it from the south. Some of these tributary valleys, like that of Rio Valencianos, extend as flat-floored alluvial plains for distances of three to four miles into the mounting elevations of the

Sierra de Cayey. The rock floor of most of the lowland is deeply buried beneath alluvium, through which, however, a few low, rounded rock hills and ridges protrude. The elevation of the alluvial surface varies within narrow limits, the maximum being approximately 400 feet and the average 250 feet above sea-level.[9] As the prevalent direction of the trade winds is slightly north of east, the lowland, lying on the lee side

FIG. 4.—*The western hill section*

The fine texture of the topography and the maturity of the dissection which characterize this area near Trujillo Alto are typical of most of the hill section. At either end of the Luquillo Mountains, which form the background, the horizontal benches are remnants of the Saint John peneplane.

of the Luquillo Mountains, is comparatively dry and hot. The rainfall is sufficient, however, to favor the growth of sugar cane throughout its length; and in the vicinity of Caguas, Gurabo, and Juncos tobacco is raised in considerable quantity.

(3) A western hill section, which extends from the western border of the district to its center, increasing in height and relief from north to

[9] The above description differs from Lobeck's (op. cit., pp. 318-319) in regarding what he calls the flood plains of Rio Grande de Loiza and its tributaries as the essential element in the lowland, and the rock hills and ridges as the subordinate and incidental features. The rock hills on the southern side of the lowland are spurs from the Sierra de Cayey and rise to levels that can be traced in all directions as widespread erosional surfaces. They do not constitute part of the more deeply excavated section under consideration. The latter has an average elevation of 250 feet and an area exceeding 40 square miles, more than seventy-five per cent. of which is covered with alluvium. As later discussion will show, only a moderate proportion of the alluvium may be regarded as normal floodplain material deposited by the Rio Grande de Loiza and its tributaries.

south and from west to east (Fig. 4). On the east the linear north-south valley of Rio Canovanas may be taken as a convenient boundary, and on the south the section terminates in the strong ridge which forms the northern wall of the Caguas lowland, and which constitutes the extremely asymmetrical drainage divide between the short streams flowing south into the lowland, and the much longer streams flowing north to the Atlantic. The hill section averages about 1000 to 1500 feet in elevation; but a portion of its surface on the north and west ranges from 200 to 500 feet, whereas the marginal ridge on the south attains a height in excess of 2000 feet. The depth of dissection varies with the elevation and is generally well under 1000 feet. Despite the moderate relief, the topography as a whole is subdued; cliffs and rock-walled valleys are few, and most of the rounded hills have a thick covering of residual soil which, because of excessive cultivation and inadequate protection, is fast being depleted by rainwash. A few of the valleys have been aggraded, and what alluvium has accumulated is now undergoing dissection. The diversified agricultural possibilities of this region have led to the development of small holdings, and an evenly distributed rural population occupies almost every portion of it.

(4) The Luquillo Mountains section, which occupies the eastern half of the interior, and which may be sub-divided into a narrow foothill belt and the mountain area. High, rugged foothills flank the mountains on the east, north, and west, forming elongated spurs that protrude outward from the mountain mass, separated one from the other by profound gorges. On the east and north they rise sharply above the coastal section (Fig. 2), and on the west their height is accentuated by the deep valley of Rio Canovanas. At 1600 feet many of the spurs flatten, but farther inland they rise again in steep slopes to the highest summits, which exceed 3000 feet in elevation. The mountains have been so deeply scoured by stream erosion that descents of 2000 feet or more in a single mile are not uncommon. Their flanks are precipitous, yet cliffs and crags are few in number, and what few there are prove practically inaccessible. In the foot-hill belt the slopes are mantled by a thin covering of residual soil that offers scant attraction to the farmer. In consequence, the settlement of this section is thin, and the agricultural pursuits of the inhabitants are limited to the raising of coffee and bananas and to charcoal-burning. Settlement and private agricultural development are not permitted in the Luquillo National Forest, and as a result of this regulation and the lack of such restrictions in other sections, it is the only large tract of upland tropical wilderness left in Porto Rico.

## Rainfall and Run-off

The distribution of rainfall in the Fajardo district depends upon the elevation and relative positions of the various topographic elements with respect to the trade winds and mountain barriers. The height of the Luquillo Mountains and their location at the northeastern corner of the island are factors which give them heavy precipitation. Their summits are often blanketed in clouds, and in every season rainfall is abundant. The highest points receive over 125 inches of rain annually, and even the flanks of the range get 90 to 125 inches. The driest parts of the district, on the other hand, are the lower sections along the east coast and the western part of the Caguas lowland, which receive from 60 to 80 inches. The precipitation in the balance of the district ranges from 70 to 90 inches annually.

The rainfall is distributed somewhat unevenly through the year, except in the Luquillo Mountains. Precipitation is comparatively heavy from May until November, and is relatively low from December until April. The distribution of rainfall thus follows the usual law for countries situated near the northern limits of the trade wind belt, where there is a rainy season when the sun is directly overhead and a comparatively dry season when the sun lies farthest to the south. Like most mountain masses, the Luquillo Mountains are not subject to the strict operation of the law, and in general the laws of precipitation are found to undergo greater irregularity in a small oceanic island like Porto Rico than on continental masses in the tropics. Rain may fall during any month of the year, and local droughts have been known to occur during the normal rainy season.

The abundant rainfall in the Fajardo district is productive of a heavy, rapid run-off and of numerous streams. Stream-flow fluctuates not only with the seasons but between storms, and in parts of the district the fluctuation in water volume not infrequently amounts to several hundred per cent. within literally a matter of minutes. During a heavy shower which lasted ninety minutes the writer has watched a stream with an estimated flow of 1250 second-feet rise until it was discharging at a rate of not less than 20,000 second-feet. Most of the increase in volume was effected during the first half-hour of the storm, and thereafter the balance between surface run-off and stream flow was established and maintained. Two hours after precipitation ceased the volume had decreased to 10,000 second-feet, and within twenty-four hours, approximately to

2000. The storm in question was not unusual nor were there any local peculiarities which made the behaviour of this stream abnormal.

Run-off is exceedingly rapid primarily because of the scarcity of permanent vegetation and the prevalence of impervious clay soils. Except for the forest growth in the Luquillo National Forest and on some of the mountain flanks where coffee and bananas are raised, the woody vegetation has been removed to clear the land for cultivation or to furnish charcoal, the only available fuel. There is, in consequence, no restraining factor to retard the precipitous passage of rain-water over the surface, and with it a heavy burden of sediment, derived from the clay soils, which are torn away notwithstanding a natural tenacity that holds them to the steepest slopes.[10] In the forested Luquillo Mountains, on the other hand, the streams undergo much smaller volumetric changes, even during abnormal rains or prolonged dry weather, because of the slower drainage. Little soil is removed, and the mountain streams, though they become cloudy, carry a relatively small amount of sediment, even with peak loads of water.

Vegetation is undoubtedly the principal factor in controlling the rate of run-off, but the kinds of soils have an important influence. Impervious clay soils, which shed water rapidly, predominate in the district and, where they are present, run-off is rapid and variable in the extreme. Ground-water is scarce or non-existent, and the majority of the small tributary streams are intermittent. In the more restricted areas which are covered by soils of disintegration or alluvium, water-absorption is great, ground-water is abundant, and more of the local streams are perennial. In all parts of the district the drainage reflects the elements of control exerted by the types of vegetation and soil.

Most of the drainage of the Fajardo district is indigenous. The only drainage system of importance that extends far beyond the district's limits is the Rio Grande de Loiza system, which heads in the Sierra de Cayey, only seven miles from the Caribbean and six miles from Vieques Passage. It drains an area nearly 500 square miles in extent, about half of which lies in the west central and southwestern parts of the Fajardo

[10] Berkey has attributed the tenacity of the soils in part to the absence of quartz grains in them (Berkey, C. P., Geological reconnoissance of Porto Rico, op. cit., pp. 34-35). His statement may be further generalized. Those rocks which contain no quartz yield tenacious residual soils provided the minerals in them have been thoroughly decomposed to a clay-sized residue. Those rocks, such as diorite, which disintegrate before they undergo decomposition, exhibit no tenacity, whether they contain quartz or not. Such soils are readily removed by rain-wash, and the rocks from which they develop are rapidly reduced to lowlands. The principle appears to be one of disintegration versus decomposition: the presence or absence of quartz is incidental. Further consideration will be given to the problems of rock weathering in a later section of the report.

district. Its tributaries drain the northern flanks of the Sierra de Cayey, the western four-fifths of the Caguas lowland, practically all of the hill section, the western edge of the Luquillo Mountains, and a small part of the northern coastal section. Its more important tributaries within the Fajardo district are Rio Gurabo, which drains the central part of the Caguas lowland, rising within six miles of the Caribbean and Vieques Passage;

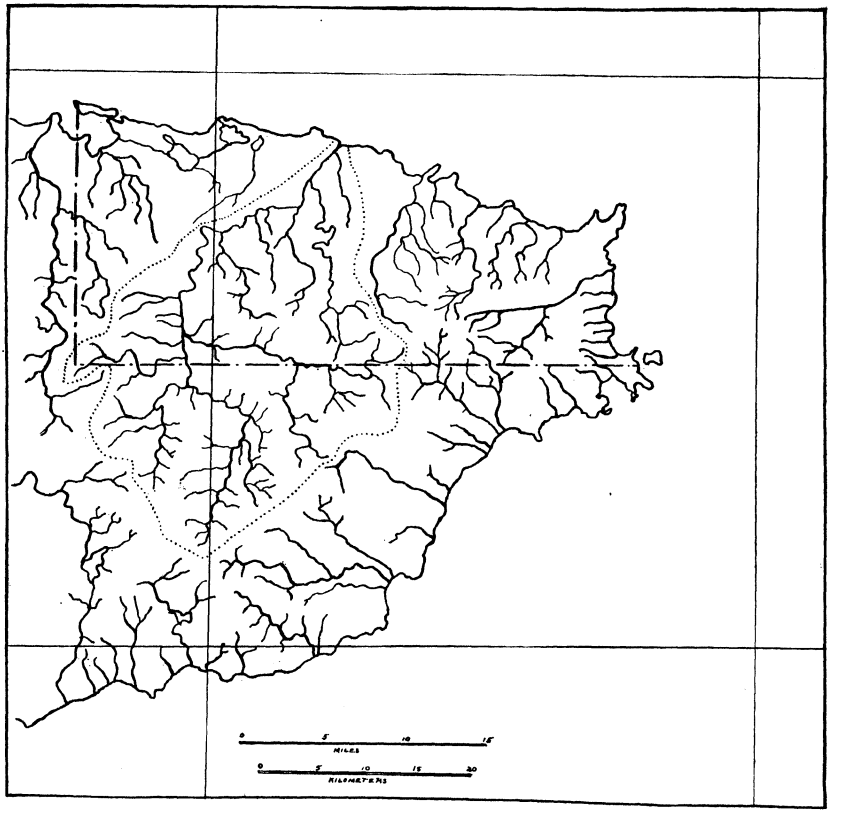


FIG. 5.—*The drainage of eastern Porto Rico*

The limits of the Fajardo district and of the Rio Grande de Loiza drainage system are shown. The position of the Caguas lowland is indicated by the large west-flowing tributary (Rio Gurabo) near the southern district boundary.

and Rio Canovanas, which heads in the ridge bounding the Caguas lowland on the north, flows north along the arbitrary boundary between the hill section and the Luquillo Mountains, and joins the Rio Grande de Loiza at the southern margin of the coastal section. In the eastern half

of the district there is no dominant system, but the streams are disposed more or less radially around the Luquillo Mountains, which act as a water-shed. Here the streams are relatively short, and except for Rio Fajardo they flow in direct courses to the coast. The principal ones include rios Herrera, Grande, Mameyes, and Sabana, which flow northward into the Atlantic; Rio Fajardo, which enters Vieques Sound on the east; and Rio Blanco, which empties into the Caribbean on the southeast. The disposition of the drainage can be best visualized by reference to the accompanying map (Fig. 5). The genesis of the drainage pattern will be discussed later as a phase of the geologic development of the district.

## GEOLOGY

The salient facts of Porto Rico's geological development have been so often stressed in the reports of the Scientific Survey that repetition here seems unnecessary. The history of the district is revealed by three distinct rock groups and by the erosional forms into which they have been carved.

Approximately four-fifths of the Fajardo district is underlaid by rocks of the "Older Series." They are largely igneous in derivation and may for the moment be subdivided into three types: modified and unmodified pyroclastics, with which a few normal sedimentary rocks of organic origin are associated; contemporaneous extrusive and shallow intrusive volcanics; and somewhat younger plutonic intrusives, ranging from irregular apophyses to the large batholith of the Humacao district, which outcrops along parts of the southern border of the region described in this report. The evidence thus far adduced indicates that most, and probably all, of the "Older Series" is referable to the Upper Cretaceous. The youngest plutonic intrusives invaded the older rocks during the intense orogenic disturbances which closed the period, and which imparted to the group as a whole its present structural complexity. Since the epoch of folding, these materials have constituted a nuclear mountainous core, which deep erosion and marginal sedimentation have profoundly modified.

In northeastern Porto Rico early Tertiary erosion appears to have persisted somewhat longer than it did in the more westerly portion of the northern coast, for only the youngest member of the mid-Tertiary series of limestones, the Quebradillas formation, is represented. It extends from Cataño, south of the city of San Juan at the western border of the district, eastward to Loiza. There is good reason to believe that

it continues still farther east in the broadening submarine platform which lies offshore; but on the mainland the Tertiary outcrops completely disappear, and from Luquillo to Cape San Juan Cretaceous rocks commonly crowd to the water's edge. Even where best developed, the Quebradillas limestone has been reduced to a minor topographic rôle in the course of post-Tertiary erosion. Riddled and nearly baseleveled by subterranean solution, it finds expression in a few scattered erosional pillars and clusters, which stand like mute monuments testifying to its ancient extent and importance. The bases of many of these residuals lie buried in alluvium and lagoonal deposits, which have accumulated in consequence of recent fluctuations in baselevel, all but obliterating the Tertiary deposits.

Opinion varies, but it is probable that the Quebradillas limestone was deposited in early Miocene time. Pronounced uplift and some warping followed closely in the wake of mid-Tertiary sedimentation, and a long erosional history, renewed and prolonged twice by Pliocene and Pleistocene uplifts of considerable magnitude, followed. While erosional surfaces were being formed and pushed inland during the first two of the three late Cenozoic cycles which have left their impress on Porto Rico's landforms, there was no chance for regional sedimentation to take place, and scant opportunity for the preservation of the local deposits that undoubtedly were formed. Since the start of the third, or Quaternary, cycle in early Pleistocene time, on the other hand, the island has exhibited relative tectonic stability. Glacial and postglacial variations in the strandline have displayed no definite tendencies. Sediments formed in the normal course of the erosion cycle have been spared from destruction and in themselves offer the investigator some puzzling problems.

Along the northern coast of the island lies the oldest of these Quaternary deposits, a calcarenyte of eolian origin, named from its spectacular outcrops in the city of San Juan. Its occurrences are restricted to a few prominent points along shore in the western half of the Fajardo district; but like the Tertiary coastal plain above which it rises, it seems to continue eastward in a narrow, drowned ridge on the submarine platform, to reappear in the islands of Cordilleras Reefs at the northwestern corner of Vieques Sound. The submerged linear ridge, with which the outcrops on the mainland are aligned, suggests that the dunes of the San Juan formation were raised by the trade winds as they swept the calcareous sands of an off-shore bar, or barrier beach. Partial submergence of the dune ridge, increasing in magnitude eastward, aided materially

in its consolidation and consequent preservation but is snatching with its left hand what it gave with its right. Partial submergence has brought the formation within the sphere of action of the waves, which have battered it until but few stranded and doomed remnants are left exposed upon the present shoreline.

Another chain of consequences has resulted from partial submergence. Lagoonal and estuarine deposits have accumulated along large sections of the north coast and in the small estuaries in all parts of the coastal margins. Fluvial aggradation has proceeded rapidly, and the alluvium has mingled with the brackish water deposits, usually replacing them completely by overlap in the neighborhood of the larger streams. Fluvial aggradation has also taken place far inland, where its relation to recent changes in level is problematical, and where other causal factors must be sought to unravel the complicated interplay of erosional and depositional processes.

This record has been summarized from the facts revealed in the Fajardo district. Save for a few minor omissions it is the record of all Porto Rico and the Virgin Islands. It presents nothing that is new, yet, considered in detail, it provides much that is different. It is hoped that the details that follow will help solve some of the problems which have arisen in the labors of the Scientific Survey and will cast new light on others. Chronologic presentation, which seems the best method of dealing with the data collected, requires their arrangement under the following topics:

1. Cretaceous geology
2. The Tertiary coastal plain
3. Quaternary sedimentation
4. Erosional landforms

## Cretaceous Geology

by

H. A. Meyerhoff and I. F. Smith

The "Older Series" of rocks in Porto Rico and in the Virgin Islands has left every investigator associated with the Scientific Survey a heritage of problems. Many contributions have been made toward their solution, but few, if any, of the larger issues have been definitely settled. In fact, the claim that each investigation has raised more questions than it has answered is hardly an extravagant one. The age of the

"Older Series," the character and significance of the structures of the formations, and the stratigraphic succession are still open questions. The petrography of the rock types has been presented in considerable detail, but the broader field of petrogenesis has not been fully dealt with. These four subjects constitute the major problems of the Cretaceous geology of Porto Rico, and in the presentation of the results of the Fajardo survey they will serve as logical headings under which the numerous minor questions may be grouped. An historical résumé of the status of each of the subjects will furnish a desirable background and perspective in the ensuing consideration of the Cretaceous geology of the district.

## THE AGE OF THE "OLDER SERIES"

The Cretaceous age of the rocks which form the cores of the Virgin Islands and of Porto Rico was established by P. T. Cleve as early as 1871.[11] Cleve's conclusion was based upon the evidence of a small fauna, most of which seems to have come from the Virgin Islands; and so far as it involved Porto Rico, his opinion appears to have been inferential. He expressed grave doubt concerning the identification of two Paleozoic corals of the genus *Favosites* reported from the Virgin Islands, and which probably were specimens of rudistids; and although he leaves open the possibility of an earlier age for some of the associated volcanic rocks, he is positive that the oldest fossiliferous formations are Cretaceous. Practically all European geologists have concurred in Cleve's opinion that they are to be correlated with the Upper Cretaceous strata of the Alps. With the authenticity of the correlation well established, it is puzzling to find the mountainous oldland of Porto Rico mapped as "undivided Paleozoic" by American geologists as recently as 1912,[12] notwithstanding the statement of R. T. Hill, which is cited in explanation, that the oldest rocks on the island are Cretaceous and early Tertiary.

The conviction that the history of the Antillean region dates far back into geologic time is deep-rooted, and attempts are constantly being made to decipher the earliest events. Schuchert has sketched phases of late Paleozoic history in the Caribbean area and has hazarded an opinion

[11] Cleve, P. T.: On the geology of the northeastern West India Islands, op. cit., pp. 1-48.

[12] Willis, Bailey: Index to the stratigraphy of North America. U. S. Geological Survey, Prof. Paper 71, 1912, p. 348.

concerning a few pre-Cambrian developments.[13] More recently Matley has differentiated Jamaican rocks which he believes were formed long before the Mesozoic and early Tertiary strata with which they occur.[14] Convinced that similar rocks should be found in the older mountain axes of all the Greater Antilles, he has reviewed the evidence in favor of the presence of pre-Mesozoic rocks in the other islands and, concerning Porto Rico and the Virgin Islands, states: ". . . the inability of the American geologists to find pre-Cretaceous rocks in Porto Rico and the (American) Virgin Islands may be due to the inadequacy of the field work . . . fuller surveys of Porto Rico may result in showing that its 'Older Series' possibly contains pre-Cretaceous rocks of the same general age as the similar rocks of the other Antilles." [15] In support of this thesis K. W. Earle's opinion regarding the rocks of the British Virgin Islands is cited, and K. W. Earle himself contributes a discussion of Matley's paper,[16] in which he postulates that too much importance has been attached to the presence of Cretaceous fossils in the limestone at Coki Point, Saint Thomas, as a basis for dating all the associated rocks; and that, judging from comparative studies of Cretaceous and Eocene rocks from the Lesser Antilles, the unfossiliferous sediments and volcanics of the British Virgin Islands are probably older,—perhaps as old as the Archaean.

The senior author has examined the "Older Series" in many parts of Porto Rico and in all the larger islands and cays of the American and British Virgin Islands. He has failed to find a single item of evidence in support of Matley's and Earle's views and has collected data which seem to disprove them. A preliminary summary of these data is submitted herewith, but elaboration must be postponed until the Virgin Islands and other Porto Rican studies are completed:

(1) The resolution of the complex rocks of northeastern Porto Rico into a conformable series of formations, into which all the igneous rocks are clearly intrusive, precludes the possibility of a basal complex. If the rock section be traced westward, it is found that the volcanic and sedimentary formations of central and western Porto Rico are parts of the same rock series; that Cretaceous fossils occur in the sedimentary

[13] Schuchert, Charles: Geological history of the Antillean region. Bulletin, Geological Society of America, 1929, Vol. XL, pp. 337-360.

[14] Matley, C. A.: The basal complex of Jamaica, with special reference to the Kingston district. With petrographical notes by Frank Higham. Quarterly Journal of the Geological Society, 1929, Vol. LXXXV, pp. 440-492.

[15] Ibid., pp. 472-473.

[16] Ibid., pp. 490-491.

members in every part of the series, and that the intrusives maintain the same relationships throughout the island.

(2) The stratified rocks of Saint Thomas are lithologically similar to those of the Fajardo district and are perhaps stratigraphically identical. The Cretaceous fossils at Coki Point may, therefore, be regarded as a reliable index of the age of the whole rock section.

(3) The Saint Thomas succession can be traced eastward in the islands of Pillsbury Sound and The Narrows to Saint John and western Tortola. On both the latter the same lithologic succession appears to be repeated in inverse order as the result of simple folding.

(4) Metamorphic characteristics are present in all the stratified rocks from Saint Thomas to Saint John and Tortola, but they increase in intensity eastward in the direction of the batholithic intrusion (or intrusions) of eastern Tortola, Beef Island, and Virgin Gorda.

(5) The most intense metamorphism is found in the schists and gneisses on the islands south of Sir Francis Drake Channel. On Cooper Island the intrusive contact between sediments and diorite is exposed, and the conversion of the former to gneiss is clearly the direct outcome of the intrusion. In the islands to the east and west the metamorphic effects diminish, and the rocks involved again possess lithologic characteristics that are typical of the members of the Upper Cretaceous section. There is no basis for ascribing to them a greater age.

Recent investigations have thus done little to advance the question of the geologic age of the "Older Series" beyond the conclusion which Cleve reached in 1871. Early in the history of the present survey Berkey wrote: "There is no good reason . . . why the whole of the 'Older Series' could not have been accumulated in a single geological period. The fossil content of the upper members of this series indicates that this period was the Cretaceous. . . . Whether or not the older members date back to an immediately preceding time cannot yet be definitely stated, but whatever there is, is clearly so closely associated with the Cretaceous beds that they can all be treated as a single historical unit." [17]

D. R. Semmes [18] endeavored to fix the age of the "Older Series" more precisely on the basis of foraminiferal faunules which he discovered in four of the formations of the San Juan district. Two of the collections

[17] Berkey, C. P.: Geological reconnoissance of Porto Rico, op. cit., p. 58.

[18] Semmes, D. R.: The geology of the San Juan district, Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, 1919, Vol. I, Pt. 1, pp. 72-75.

came from shaly strata, and of the species identified he has listed several long-ranged forms, which in assemblage have an Upper Cretaceous aspect. The other two collections, which were found in beds of limestone, contain species that are identical or closely related, but both these faunules differ strikingly from the shaly facies. Although only one form could be specifically identified, Semmes believed the faunal assemblage from the limestones to be Eocene in age. In suggesting that the older formations in the series are referable to the Lower Cretaceous, or Comanchean, Semmes was undoubtedly influenced by Hodge's studies in the Coamo-Guayama district immediately to the south.

Semmes's claim that the foraminiferal limestones in the San Juan district are Eocene must be rejected on structural and stratigraphic grounds. One of them, the La Muda limestone in the eastern part of the district, passes stratigraphically beneath the foraminiferal shales which outcrop southwest of Bayamon, and which Semmes on more satisfactory micropaleontologic evidence placed in the Upper Cretaceous. The shales occupy the center of a northwestward pitching syncline, which extends from Toa Alta to Aguas Buenas, and the La Muda limestone is exposed upon its northeastern limb. The Corozal limestone, the second of the supposed Eocene formations, outcrops on the southwestern limb of the same fold. If this interpretation of the structure is correct, the Corozal limestone occupies the same stratigraphic position with respect to the shales as the La Muda limestone, and the two calcareous members may be equivalent. The exact structural and stratigraphic position of the fossiliferous Unibon shales, which Semmes places in the Upper Cretaceous, has not been determined, but they appear to be somewhat older than the other three fossil-bearing horizons. The limestones thus lie between beds that have been referred to the Upper Cretaceous, and the faunal distinctions which Semmes recognized are ecologic and are without stratigraphic significance.

Further complications develop when the foraminiferal strata of the San Juan district are traced into the Coamo-Guayama district. All of them pass directly or indirectly by way of the Fajardo district, into the two stratigraphic divisions which Hodge has called the Rio de la Plata and the Barranquitas-Cayey series, and both of which he has referred to the Lower Cretaceous, or Comanchean.[19] The same formations have thus been placed in the Lower Cretaceous, the Upper Cretaceous, and the

[19] Hodge, E. T.: Geology of the Coamo-Guayama district. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, 1920, Vol. I, Pt. 2, pp. 130-137, 192-193.

Eocene. Hodge's claim for the Lower Cretaceous age of the Rio de la Plata and the Barranquitas-Cayey series rests primarily upon the identification of two corals, which he refers to the species *Cladophyllia furcifera.* This form is an index fossil of the Edwards limestone, one of the formations in the Fredericksburg series of the Texas Comanchean, and to the writer's knowledge it has not been reported outside the Gulf Comanchean area by any other author. The genus *Cladophyllia,* on the other hand, ranges from the Lower Cretaceous to the Holocene and has a wide geographic distribution. It seems unwise, therefore, to accept without some reservation an identification based on two imperfectly preserved specimens, or, granting that they belong to the species *Cladophyllia furcifera,* to assume that the form has the same stratigraphic value that it possesses in Texas. The other evidence which Hodge advances in support of the Comanchean age of the Rio de la Plata and Barranquitas-Cayey series is equally inconclusive and cannot be claimed to provide cumulative proof of his contention. The microfauna listed from the formations is unquestionably Cretaceous, but not a species in it is restricted to the Lower Cretaceous. The small, poorly preserved flora found in one of the members of the Barranquitas-Cayey series was examined by E. W. Berry and F. H. Knowlton, who pronounced it Mesozoic; but they were unable to state that it indicates the Comanchean age of the associated rocks. The unconformity which Hodge postulates at the top of the Barranquitas-Cayey series, separating it from the overlying Sierra de Cayey conglomerates, is indicated primarily by the abrupt change in lithology; but changes of this kind, which occur in several parts of the rock section, can be more satisfactorily explained as the result of renewed outbursts of explosive volcanic activity. Certainly they do not indicate any fundamental change in local conditions, or a profound erosional break; and no special one of the several that occur can be assigned the degree of importance which the stratigraphic hiatus between the Comanchean and the Upper Cretaceous normally exhibits.

The Rio de la Plata and Barranquitas-Cayey series have not been reported in the Ponce and Lares districts, and they have not yet been differentiated in the Arecibo district. In fact, none of the workers in the western half of the island has found any reason to suspect the existence of these or other rocks of possible Lower Cretaceous age. According to Hodge's interpretation of the structure, the monoclinal dip of the strata exposes progressively younger formations to the south and

west, whereas the oldest formations extend northwestward into the San Juan district, where they end near its western boundary against the dioritic and porphyritic intrusives in the vicinity of Morovis. If this interpretation be correct, the failure of the surveys in western Porto Rico to reveal evidence of Comanchean rocks is explained. On the other hand, Mitchell's structural studies near the eastern limits of the Ponce district show that all the formations are repeated by folding, and that the dip is not monoclinal. The results of his work imply that strata of the supposed Comanchean series should be present in the region west of the San Juan and Coamo-Guayama districts, yet the facts collected indicate that all the rocks are Upper Cretaceous. To the north in the San Juan district, where the strata of the Rio de la Plata and Barranquitas-Cayey series cover a large area, Semmes has pronounced them Upper Cretaceous and Eocene. The concensus of opinion is thus against the existence of rocks older than Upper Cretaceous in any part of Porto Rico; but, as this review has endeavored to show, the evidence used to support both sides of the question is indecisive or circumstantial. New data must be sought if a final conclusion is to be reached.

Interest in the possibility that Mesozoic formations antedating the Upper Cretaceous may be present in the island has lately received added impetus as a result of the discovery of two ammonite molds in the ashy shales exposed at kilometer 86.5 on the San Juan-Ponce carretera between Aibonito and Coamo. The fact that ammonites are characteristically associated with the Jurassic has naturally led to a query concerning the age of the fossils found, and as ammonites are exceptionally good stratigraphic guides, considerable importance must be attached to their identification. Every physical factor is against the Jurassic age of the specimens. They were found near the top of the Barranquitas-Cayey series, which Hodge considers to be the highest member of the Comanchean series. The pyroclastic character of the sediments in which they were embedded invites a contrast with the only known Jurassic strata in the West Indies; namely, the Jurassic limestones of western Cuba. The latter lie unconformably beneath Cretaceous strata and, in the limited section exposed, indicate an origin completely dissociated from contemporaneous volcanic activity. Physical characteristics are of limited value, however, for both structural and lithologic relationships may be expected to undergo radical changes in the thousand miles that separate Porto Rico and Pinar del Rio province in western Cuba. The specific identity of the fossils will, therefore, constitute the only acceptable testimony concerning the age of the beds in which they are found.

Dr. N. L. Britton has placed the specimens in the hands of the senior author, but unfortunately attempts to identify them have not yet been successful. One consists of a flattened and unornamented external mold; the other is a cast of the exterior of a shell, in which some features of surface ornamentation were preserved, while the diagnostic sutures were completely destroyed (Fig. 6). It is expected that a definite statement regarding their biologic affiliations and stratigraphic significance can be made in a later report on the Arecibo district, into which the ammonite-

FIG. 6.—*Ammonites from the "Older Series"*

These two unidentified specimens, found in the ashy shales at kilometer 86.5 on the San Juan-Ponce carretera, are the only ammonites which have thus far been found in Porto Rico. Reproduced from drawings by Miss Helen Z. Hunt.

bearing strata extend. For the present they must remain another of the potential but unevaluated clues to the age of the more ancient rocks in Porto Rico.

The age of the youngest rocks in the "Older Series" is as much an unsolved riddle as the age of the oldest. In 1899 [20] R. T. Hill suggested that early Eocene strata occur, but his suggestion was based more upon the stratigraphic possibility of their existence than upon tangible evidence. Cleve, too, made a similar suggestion. Of the investigators associated with the Scientific Survey, only Semmes and Hodge have advanced testimony purporting to prove the presence of Eocene rocks in Porto Rico. As stated above, Semmes opinion was based upon an inconclusive microfauna and upon insufficient structural data. His Eocene formations lie stratigraphically below shales which he placed in the Upper Cretaceous, and both his Upper Cretaceous and Eocene are in part equivalent to the Rio de la Plata and Barranquitas-Cayey series, which Hodge refers to the Lower Cretaceous. No support can, therefore, be given to Semmes's claim.

Hodge, on the other hand, furnishes the only substantial evidence available for the presence of early Tertiary rocks in the "Older Series." In

[20] Hill, R. T.: Mineral resources of Porto Rico. U. S. Geological Survey, Annual Report, 1899, Vol. XX. Pt. 6, p. 771.

his "Rio Jueyes Series" he reports the occurrence of one specimen of *Venericardia alticosta,*[21] a typical Eocene form in the Gulf Coast. He stresses the familiar fact that the stratigraphic position of guide fossils may change in widely separated geographic localities, but he believes that the presence of the radiolarian form *Porodiscus concentricus,* as well as an undetermined species of the genus *Amphistegina,* conclusively establishes the early Tertiary age of the Rio Jueyes Series and the younger formations in the Coamo-Guayama district. But Hodge questions the identification of *Porodiscus concentricus* and has assigned an incorrect index value to the genus *Amphistegina,* which ranges from the late Paleozoic to the present. In the last analysis, therefore, the Eocene age of the upper half of the "Older Series" represented in the Coamo-Guayama district, approximately 9000 feet of material according to Hodge's estimates, depends upon the specific determination of one specimen of *Venericardia alticosta,* and upon its position in the geologic column. The rocks assigned to the Eocene pass westward into the Ponce district, where G. J. Mitchell found specimens of the conclusively Upper Cretaceous form, *Radiolites,* in limestone high in the series.[22] The age of this aberrant pelecypod is so firmly fixed that its presence in the fauna is unquestionably of greater significance than that of any or all of the species listed by Hodge; but again a final conclusion must be withheld because, if Mitchell's interpretation of the geologic structure of southern Porto Rico, rather than Hodge's, should prove correct, it is still possible that basal Tertiary strata are infolded into the Upper Cretaceous sediments. In the stratigraphic sequence proposed by Maury[23] the assignment of several members of the "Older Series" to the Middle and Upper Eocene appears to be based solely on the conclusions reached by Hodge and Semmes, for no new evidence requiring consideration has been advanced to support the sequence suggested.[24]

Theoretical considerations also militate to some extent against the acceptance of Hodge's conclusions concerning the occurrence of rocks younger than the Cretaceous. His estimates give the "Older Series" of the Coamo-Guayama district a total thickness of not less than 20,000 feet. Of this amount he places approximately 9000 feet in the Eocene,

[21] Hodge, E. T.: op. cit., pp. 193-197.

[22] Mitchell, G. J.: The geology of the Ponce district, Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, 1922, Vol. I, Pt. 3, pp. 256-257, 288.

[23] Maury, C. J.: Porto Rican and Dominican stratigraphy. Science, N. S., 1929, Vol. LXX, p. 609.

[24] See Meyerhoff, H. A.: The pre-Oligocene stratigraphy of Porto Rico. Science, N. S., 1930, Vol. LXXI, pp. 322-323.

and probably more, for the top of the section is not exposed within the limits of his district; 5000 feet or more he assigns to the Comanchean, and the remaining 6000 feet go, apparently by default, into the Upper Cretaceous. It is difficult to believe that less than one-third of the section belongs in the system which has proved to be the most important of the older systems in the Greater Antilles. The assignment of 9000 feet of material to the Eocene likewise creates a problem difficult of solution; for it must be assumed that folding, injection, and local metamorphism, as well as the erosion of several thousand feet of rock, took place in the relatively short interval between late Eocene time and the Middle Oligocene, when coastal-plain deposition began. The scattered early Tertiary rocks in other parts of the Caribbean region, although deformed, have not undergone the complicated history which this view requires, whereas the Cretaceous rocks invariably have.

Although it is clear that the contradictory data available do not warrant a categorical dismissal of the case for the Eocene, the bulk of the evidence is against its existence in Porto Rico. The possibility that Lower Cretaceous, and even Jurassic rocks, may be represented is, on the other hand, entitled to more serious consideration. Comanchean sediments attain importance around the entire Caribbean border, and Jurassic strata have been differentiated in Cuba. Comanchean rocks have been described in Haiti, but it is admittedly on stratigraphic and structural grounds that their differentiation is based; paleontologic evidence confirming their age has not been found.[25] Until Mesozoic diastrophism in the Antillean region is better understood, and some reason for the absence of the Lower Cretaceous is known, the presence of materials belonging to this epoch may always be suspected and proof of their existence sought.

It was confidently expected that the calcareous deposits of the Fajardo district would furnish paleontological data that might aid in a partial solution of the age problem. Two limestone members, repeated by folding, outcrop prominently in the western quarter of the district and along its southern margin. Calcareous tuffs and shales are conspicuous elsewhere, especially surrounding the massive pyroclastic and igneous rocks which underlie the hills of the interior. C. A. Reeds mentions the two limestones near La Muda and Trujillo Alto among the fossiliferous formations of the "Older Series," and, although the senior author's

[25] Woodring, Brown, and Burbank: Geology of the Republic of Haiti. Republic of Haiti, Department of Public Works, Port au Prince, 1924, pp. 85-93.

search for megascopic forms in all of their outcrops was unsuccessful, Dr. N. L. Britton has recently sent two sets of specimens taken from the quarry at the type locality of the La Muda limestone, and these have been added to the Fajardo collection. The material is recrystallized and is too fragmentary for specific identification, but its affiliations are unmistakable. All of it belongs to a single rudistid species, probably of the genus *Radiolites*. Its timely discovery has settled the Cretaceous age of the La Muda limestone more satisfactorily than the indirect proofs provided by the formation's structural and stratigraphic relations. The presence of rudistids disposes of the possibility that Eocene rocks are present in the Fajardo and the San Juan districts, and, as the La Muda limestone forms one of the members of Hodge's Rio de la Plata series, there is little likelihood that the ammonites in the overlying Barranquitas-Cayey series are Jurassic specimens.

No other megascopic fossils have been found, but both the La Muda and Trujillo Alto limestones and some of the other stratified rocks contain a microfauna. The La Muda limestone is invariably the most fossiliferous horizon and contains the greatest variety of forms. Specimens from the quarries near La Muda and Guaynabo and along the railroad between Rio Piedras and Trujillo Alto are full of minute fossils, but most of them are poorly preserved. Many are broken or show strong signs of mechanical wear. Study of the forms was perforce based upon the cross-sections exposed in slides, and as a result little satisfaction is felt with the attempts made to identify the specimens specifically. Of the few forms concerning the identity of which the writers are certain, all are long-lived species which possess no diagnostic value. A few species of Foraminifera have been provisionally identified, but either they are the same as those reported by Semmes, Hodge, and other investigators, or they are equally worthless in determining the precise age of the sediments in which they were buried. Radiolaria proved to be numerous in some localities, the only common species being that recorded by Hodge as *Porodiscus concentricus* Ehrenberg (?). Diatoms are sparingly present, and fragments of algæ and other unclassified organisms were noted. The character of the assemblage is such that no general conclusions concerning its stratigraphic significance are valuable enough to be given serious consideration.

It is important that searches for megascopic fossils be continued in the Fajardo district. Unless the structure of central and eastern Porto Rico has been seriously misinterpreted, the oldest rocks of the "Older

Series" are exposed in the northeastern part of the island. If Lower Cretaceous rocks are to be found, the Fajardo district is, therefore, the most promising area for study. How much more can be done with the microfauna as a means of determining the age of the rocks is problematical. The specimens dissolve long before the somewhat silicified rocks in which they are embedded disintegrate or decompose, and it is common to find only the space they occupied left in a rock which to the eye shows few of the marks of weathering. It is possible that Radiolaria and diatoms may be washed from the deeply weathered calcareous tuffs, but it is doubtful whether Foraminifera can be obtained by this method. Their identification in thin-section is difficult; yet, in view of the vast progress made in the field of micropaleontology within the past decade, it seems reasonable to believe that exact classification and correlation of the Porto Rican Mesozoic deposits can ultimately be made on the basis of the microscopic organic remains, if megascopic fossils fail. With the latter much more can be done than has been done; but the sedimentary formations must be combed for better specimens and for more representative faunal groups. Thus far fossil collecting has been unsystematic; identification and interpretation of the specimens have been undertaken without adequate information about the stratigraphic succession, on the general assumption that the structure is too complex and the lithologic units too variable for the determination of a definite order of superposition. If the present report can make but a small contribution that will aid in fixing the age of the "Older Series," perhaps it can make a start toward the solution of the structural and stratigraphic problems in the central and eastern parts of the island. The results offered in the following pages are incomplete and imperfect; but sufficient data are at hand to correct some of the assumptions that have hampered part of the work done in this half of Porto Rico; to indicate the general character of the structure as well as some of the details of its expression; and to sketch in a portion of the stratigraphic succession. The structure will be examined first.

## THE STRUCTURE OF THE CRETACEOUS

The problem of interpreting the geologic structure of the "Older Series" is inherently difficult of solution because of the initial irregularities in the accumulation of the materials, and because of the intrusion and orogenic deformation they have suffered since. From the nature and distribution of the rocks it must be inferred that accumula-

tion took place with reference to a series of volcanic vents, a few of which lay within the limits of the present island. Berkey described one vent at the site of the Jacaguas, or Guayabal, reservoir in the south central part of the island, and he noted a few others;[26] but in the several district surveys little significance seems to have been attached to this feature, either as a factor modifying the present structure, or as an influence in the initial distribution of the associated fragmental and sedimentary rocks. The pyroclastic character of nearly all the Cretaceous system in Porto Rico reveals the dominant rôle played by explosive volcanic activity during the entire period of its formation. The alternation of massive and stratified rocks adds a picture of intermittent subsidence, affecting a low platform above which the scattered volcanoes or volcanic clusters rose. Violent eruption built its surface above sea-level; in the intervening cycles of quiescence gradual depression carried it slightly below. Now and then new vents were opened through the older rocks; and cones, both large and small, were heaped up on a surface of simple sediments. Aggradation was rapid, and so little opportunity was given for subaërial erosion of the forms produced that normal hydroclastic sediments are extremely scarce.

The reconstruction of an orderly sequence from complex elements of this nature is difficult enough in a region where the rocks have remained undisturbed, but in Porto Rico eruptive activity was succeeded by intense folding and plutonic intrusion. To the diverse primary structures of the surface-materials were added involved secondary structures, and the irregular distribution which characterized the rocks at the time they were formed was further obscured by the dioritic magmas which invaded the section. As a result it is quite impossible to ascribe proportionate values to the processes which created the irregular primary structures, the igneous activity which later modified them, and the diastrophic movements that folded, faulted, and warped them. The task is made still more hopeless by the massive character of many of the explosive products, in which structural trends cannot be deciphered; by the deep weathering which has locally obliterated the structure, reduced the number of outcrops, and given diverse types of rocks much the same appearance; and by the inaccessibility of many critical areas. Yet some understanding of the diastrophic structures must be acquired before any of the earlier history can be restored.

[26] Berkey, C. P.: Geological reconnoissance of Porto Rico, op. cit., p. 37; Introduction to the geology of Porto Rico, op. cit., p. 20.

Practically every criterion upon which the geologist ordinarily expects to rely in unraveling the structure of a region has failed when applied to the Cretaceous system of Porto Rico. In most sedimentary areas a carefully plotted structure section normal to the strike of the strata will reveal the major features of deformation; and several sections, if not too widely spaced, will furnish a basis for sound generalization. Yet, it may be questioned whether the painstaking cross-sections which Berkey, Semmes, Mitchell, and Hubbard have published can be pieced together to form a clear and adequate conception of the island's geologic structure. The sections which they have drawn contain no common stratigraphic units which can be used in interdistrict correlation; in fact, correlation of folds and rocks within the separate districts has seldom proved possible. Persistent and characteristic key horizons by which the structures may be traced have not been isolated. Prominent limestones peter out rapidly along the strike or undergo radical lateral changes; the innumerable stratified and massive pyroclastic types are so nearly alike and individually exhibit such lithologic inconstancy, that their use in correlation is precluded. It is not, therefore, the mere scarcity or inadequacy of structural information which makes interpretation difficult, but the dearth of firmly established stratigraphic data as well. To some extent these two interdependent problems must be considered together in the present section.

A definitive treatment of the structure of the Cretaceous strata in Porto Rico is obviously out of the question at this time, but a general statement of its outstanding characteristics may be formulated. The "Older Series" has been folded along an axis which has a prevailing northwesterly trend. Whether the folding is to be referred to one orogeny or to two is not yet known, for some of its features may be attributed either to torsional compression in a single period of deformation, or to compression from different directions during two distinct periods. Hubbard calls attention to the presence of broad north-south flexures, which seem to be superimposed upon the dominant system of folds in the northwestern part of the island.[27] The feature he describes is equally pronounced in the neighboring Arecibo district and is also expressed in the crenate character of the folds along the northern margin of Cretaceous outcrops in the Fajardo district (see geologic map). Hubbard is inclined to regard these secondary flexures as evidence of a separate disturbance of moderate intensity, and the fact that post-Creta-

[27] Hubbard, Bela: The geology of the Lares district, Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, 1923, Vol. II, p. 32.

ceous and post-Eocene epochs of folding have been differentiated in other islands of the West Indies entitles his opinion to careful study. Until the age and subdivisions of the "Older Series" are established, and the details of the structural features are known, there is little chance that a problem as broad as this can be satisfactorily solved. Attention may more appropriately be focused on the effects of deformation, rather than on its causes.

A first impression of the structure, if obtained in one of the areas of thinly stratified rocks, may give the observer an exaggerated idea of intricacy; for in many such localities the folds are small, compressed, and sometimes distorted. Many of them plunge rapidly; some are overturned; a few pass into minor thrust faults. A more deliberate analysis, however, reveals that these small structures are merely subordinate parts of much larger folds, which, though less obvious because of their great size, constitute the controlling structural elements. Semmes [28] and Hubbard [29] have both described the anticlinorial and synclinorial character of the dominant folds and have shown that the smaller but more arresting features of deformation are ordinarily restricted to the comparatively incompetent shaly sediments. In the unstratified pyroclastic rocks the structures are practically undeterminable. These materials appear to have been relatively competent under pressure, and fracturing is a more common feature than folding. Dikes fill many of the fractures, and their abundance in the massive rocks of the Fajardo district contrasts noticeably with their scarcity in the areas of thinly stratified sediments.

Faults are more often indicated than seen. Crush zones and slickensides, abrupt changes of strike, off-sets in topographic forms have been noted in nearly every part of the island. Although the amount of differential movement along some of the fractures has been thought to be large, the faults which can be studied invariably show small displacements. This fact suggests that displacement in the aggregate was perhaps moderate, or even great, but that the movements associated with individual fractures were small. Both thrust and normal faults have been identified, and all appear to have developed during the diastrophic and plutonic disturbances which preceded Oligocene time. In general, the thrust faults are simply related to asymmetric and overturned folds; the normal faults, on the other hand, exhibit no systematic relation to

[28] Semmes, D. R.: op. cit., p. 98.
[29] Hubbard, Bela: op. cit., p. 31.

the orogenic structures, and thus far have not been resolved into coherent systems. It is likely that many of the normal faults can be classified among the displacements that ordinarily accompany and follow the intrusion and solidification of subjacent magmatic bodies.

The geologic structure of the Fajardo district illustrates all of the features which characterize the Cretaceous rocks in the rest of Porto Rico. It has been studied in some detail because of its importance in determining the stratigraphic sequence, and the results are presented in full in the hope that they may serve as a basis for a definitive treatment of the structure of the entire island. A number of the conclusions reached are provisional. The scarcity of good outcrops and the inaccessibility of critical areas, especially in the Luquillo Mountains, have left a few alternative hypotheses for local problems on the authors' hands; but in most cases where doubt exists concerning the true character of the structure, it has proved possible to limit the alternatives quite narrowly. In extending outcrops across some sections of the geologic map, however, it has been necessary to make definite assumptions with regard to the underlying structure and to ignore other possibilities. Later field studies may make some revision of the map necessary, therefore, and, as far as possible, the areas and problems which need more thorough investigation will be designated.

*The structure of the western border*

According to Semmes and Hodge, a cross-section through Porto Rico from San Juan to Santa Isabel would reveal a huge single arch, or anticlinorium, on the flanks of which the stratified formations have undergone folding on a smaller and more complicated scale. The axis of the arch and the eroded edges of the sediments upon its sides would be found to strike east-southeast, passing diagonally into the Fajardo and Humacao districts. If their interpretation be correct, the Fajardo district should lie upon the northern limb of the arch, and, except for local reversals, northerly dips should prevail. Semmes believed that the structure is further complicated by an unconformity, which is indicated by the abnormal strike of the Aguas Buenas limestones and the associated beds, at right angles to the predominant northwesterly structural trend in the San Juan district.[30] His interpretation received further support from the work of Hodge, who included these strata in the Rio de la Plata series, which he believed lies unconformably be-

[30] Semmes, D. R.: op. cit., pp. 64-65, 95-96; cf. Berkey, C. P.: Introduction to the geology of Porto Rico, op. cit., p. 17.

neath the Upper Cretaceous sediments of the Coamo-Guayama district. Semmes suggested that the unconformable contact between the older and younger strata might be exposed in the valley of Rio Grande de Loiza, whither the Aguas Buenas formations appeared to extend by projection. These opinions and suggestions were utilized as a starting point in the present study, and in an effort to verify them four full-length north-south sections and one partial section were plotted across the district between the western border and the Carolina-Gurabo camino.

Reliable stratigraphic markers, or key horizons, were needed to follow the changes in dip and strike; and for this purpose the several limestones reported by Berkey and Semmes promised the greatest help, in spite of the fact that the different formational names given to each of the limestone exposures implied that none of the beds is repeated by folding. The massive pyroclastics could not be differentiated; and the ashy shales prominent in the vicinity of Rio Piedras proved too much like those near Bayamon and the Guaynabo filtering station to be used as a dependable stratigraphic guide. In this region the following limestones had been differentiated and named: (1) the Trujillo Alto limestone, a dense, bluish, microfossiliferous formation, which outcrops along the carretera about one and one-half miles north of Trujillo Alto; (2) the La Muda limestone, concerning the identity of which there is some doubt and confusion;[31] (3) the Aguas Buenas limestones, comprising two calcareous beds that form conspicuous exposures southwest of Aguas Buenas, and which Semmes thought rest unconformably below the other two formations.

[31] In the vicinity of La Muda there are two limestone formations; a grayish white, cavernous limestone outcropping about one mile north of the village, and the bluish, tuffaceous Trujillo Alto formation, which outcrops on the carretera one mile southeast of the settlement. Berkey's statements regarding the character and location of the La Muda are not sufficiently precise to make its identity certain. The adjective "cavernous," which he uses in describing it, can only apply to the formation north of the village; but in this event his statement that it lies above a conglomerate bed is in error. The conglomerate rests upon it. The Trujillo Alto limestone, on the other hand, lies above the conglomerate, but 2000-2500 feet of stratified calcareous tuffs separate the two. It is safer to assume that the descriptive adjective which he used is more decisive than an interpretation concerning its stratigraphic relation to an adjacent formation, for Berkey clearly had in mind a sedimentary rock which differs in physical characteristics from the Trujillo Alto. The limestone at the southern edge of Guaynabo, which Semmes called the "La Muda," is the same as that north of La Muda, but in projecting it southeastward Semmes extended it into the Trujillo Alto limestone south of the village, and, like Berkey, seems to have been unaware of the presence of two distinct beds. The confusion which exists may be settled by fixing the formational name upon the white or light gray, cavernous strata one mile north of La Muda and at the southern outskirts of Guaynabo. This usage of the name will be employed throughout the present report.

The field analysis of the structure in the western part of the Fajardo district and in the eastern part of the San Juan district established the persistence of the La Muda and Trujillo Alto limestones, as well as their repetition in the section in consequence of folding, by developing the following facts:

(1) In the Trujillo Alto region there are two distinct limestones. The slate-blue, tuffaceous beds to which Berkey gave the name are exposed

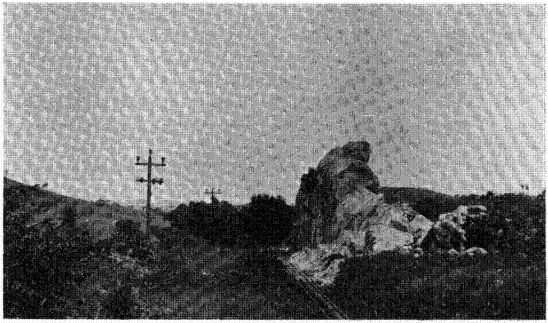


FIG. 7.—*The La Muda limestone*

A quarried outcrop along the railroad between Rio Piedras and Trujillo Alto. In spite of the development of large caverns within it, it forms a relatively strong structural ridge for several miles.

along the carretera one and one-half miles north of the settlement. The second is buried beneath the alluvium deposited by Rio Grande de Loiza at the northern edge of Trujillo Alto; but, less than a mile west-northwest of the town, its outcrops rise above the valley floor and continue westward for three miles, acquiring spectacular prominence along the tracks of the Porto Rico Railway, Light, and Power Company (Fig. 7). The formation is white or light gray in color, and its massive beds are exceedingly cavernous. It measures approximately 300 feet in thickness. The two limestones are parallel and strike almost due east-west, but westward, near the Rio Piedras-Caguas carretera, the strike swings to the northwest. The dip of both formations is 30 degrees north and clearly establishes their relative stratigraphical positions: the bluish limestone occupies a position above the gray formation, from which it

is separated by 2000-2500 feet of calcareous tuffs and by a bed of agglomerate, or tuffaceous conglomerate, which rests directly upon the gray limestone.

(2) In the neighborhood of La Muda two limestones are also present. The more northerly is a massive, white or light gray, cavernous formation, which can be traced northwestward into the San Juan district for more than three miles, until it is lost in the deep lateritic soils southeast of Bayamon. The more southerly is a dense, bluish limestone, which is thinner and somewhat tuffaceous. Both beds strike almost due northwest and dip about 50 degrees southwest. The strata separating them consist essentially of calcareous tuffs, but immediately above the lower formation is a ridge-making layer of agglomerate or tuffaceous conglomerate. The outcrops of this entire rock series are somewhat discontinuous, for they are cut by small, irregular porphyritic intrusions and closely associated breccias.

(3) The Aguas Buenas limestones consist likewise of an older formation of white to light gray limestone, in which some of the most spectacular caves of the interior have been dissolved, and of a younger slate-blue horizon, from which the former is separated by calcareous tuffs and a basal agglomerate, or tuffaceous conglomerate. The strike of all these beds south of Aguas Buenas is northeast, and the dip is 20 degrees or more northwest.

Unsafe as correlation on the basis of physical characteristics may be, the repetition of four distinctive formations in the same order of superposition leaves little question concerning the exact equivalence of the white limestone, the conglomerate, the stratified calcareous tuffs, and the blue tuffaceous limestones near Trujillo Alto, La Muda, and Aguas Buenas. And the opposing dips of the beds in these three localities indicate with equal clarity the simple anticlinal and synclinal nature of the structure (Fig. 8). In the sections at La Muda and Aguas Buenas, moreover, the sequence can be extended upward by including an unusual member of strongly banded material which lies above the blue limestone. Semmes describes this rock as a chert, in which crumpling has been caused by solifluction and has been accentuated by the subsequent infiltration of hematite.[32] A microscopic section of the rock was referred by the writers to R. J. Colony, who has identified the chert- or quartz-like mineral as laumontite, and who suggests that the formation was derived from a calcareous tuff by alteration. The rock occupies an analogous position on both limbs of the

[32] Semmes, D. R.: op. cit., pp. 65-66.

pitching syncline which lies between La Muda and Aguas Buenas, but if it is present in the Trujillo Alto section, it was overlooked. No effort was made to locate it, however, for its significance as a stratigraphic guide was not appreciated when the field work was in progress. Even if it prove to be missing, the white cavernous limestone, the agglomerate, the calcareous tuffs, and the bluish limestone constitute a sufficiently distinctive lithologic succession to force some revision of the prevailing idea that the stratified materials are lithologically too inconstant to be employed as horizon markers, and to establish the simply folded character of the structure across the district.

The behavior of the folds is interesting. From north to south along the western edge of the Fajardo district the structures comprise an anticline, a syncline, and an anticline. The crest of the last lies near the boundary between the San Juan and Coamo-Guayama districts, and its axis strikes slightly north of east, whereas that of the northern anticline strikes southeast. The two meet a short distance east of the valley of Rio Grande de Loiza, about three miles south of Trujillo Alto, where they merge into a single dome-like structure that can be traced eastward for more than twenty miles to Cape San Juan. Between the two converging arches lies a sharply plunging syncline. If traced westward into the San Juan district, the trough is found to flatten, and its axis swings from a westerly to a northwesterly direction, carrying the fold diagonally across the district toward Toa Alta. On the southern limb the calcareous strata strike southwestward from the caves near Aguas Buenas and appear to bend sharply to the northwest a mile or two west of Cidra. The two limestone members have not been traced beyond Cidra, but one of them is reported to continue at least as far as

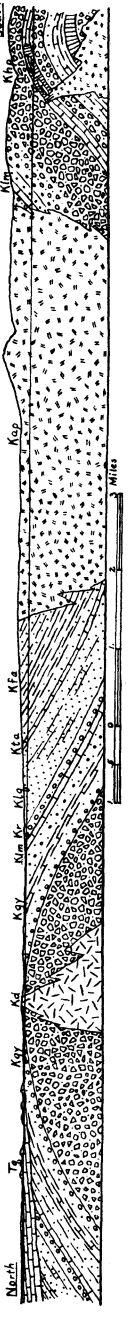



FIG. 8.—*Structure section from Cataño through Aguas Buenas*

The section follows the western border of the Fajardo district. It is somewhat generalized and does not show the definite plunge of the several folds. Horizontal and vertical scales are alike.

Tq=Quebradillas limestone; Kgy=Guaynabo formation; Kd=diorite intrusion; Klm=La Muda limestone; Kr=Rio conglomerate; Klq=Luquillo formation; Kta=Trujillo Alto limestone; Kfa=Fajardo shales; Kop=andesite porphyry; Khp=Hato Puerco tuffs.

Comerio. The syncline thus exhibits a rectangular ground plan, which is sufficiently unique to indicate the need of more careful field study in the elbow extending from the Aguas Buenas caves to Cidra and thence to Comerio. The area lies outside the limits of the Fajardo district, and the senior author was able to spend but two inconclusive days deciphering the structure. It appeared to be more complex in its details than the general statements made by Semmes, Hodge, and the present writers indicate, but the conclusions which have just been stated were fully supported by the data obtained.

Efforts to trace the lithologic succession of the western border eastward from Trujillo Alto were attended by difficulties. The domed structure in the hill section has caused the removal of the younger stratified series from all parts of the interior, and although the sediments continue along the northern flank of the anticline, the members undergo a decided change toward the east. Within a short distance of Trujillo Alto the white cavernous limestone ends by overlap against the underlying massive pyroclastic rocks. The bluish limestone outcrops on the carretera about one mile south of Canovanas, but it is more thinly stratified and shaly. Somewhat similar beds are found in the valley of Rio Sabana about one and one-third miles southeast of Luquillo (Fig. 9), but their correlation with the bluish limestone can only be made tentatively, because deep weathering and a large intrusive in the intervening area made it impossible to prove the continuity of the horizon in the field. It has not been found east or south of the Rio Sabana locality. The calcareous tuffs, on the other hand, persist along the entire length of the structure, but with a noticeable reduction in the calcium carbonate content. The nature of these changes suggests the existence of a volcanic center near the central and eastern parts of the district, and this hypothesis is strengthened by the profusion of porphyritic intrusions and andesitic flows in many sections of the interior, culminating in the almost continuous outcrops of igneous rocks north of Juncos and eastward along the borders of the Caguas-Naguabo lowland.

Near the south-central boundary of the Fajardo district both limestone members reappear, but their structure almost defies interpretation because of the complicated series of andesitic and dioritic intrusions associated with them. Fettke has described them under the name "Collores limestone",[33] but he appears to have misinterpreted their relationship and

[33] Fettke, C. R.: The geology of the Humacao district, Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, 1924, Vol. II, pp. 149-151. Magnetite deposits of eastern Porto Rico. Amer. Insti. Min. and Met. Eng., Trans., 1924, Vol. LXX, pp. 1024-1042.

FIG. 9.—*The Trujillo Alto limestone*

This thin formation of tuffaceous limestone and calcareous tuff, exposed on Rio Sabana, is thought to be the easternmost occurrence of the Trujillo Alto limestone.

has in consequence failed to differentiate between them. The two calcareous formations outcrop in association with the magnetite deposits east of Juncos. Notwithstanding the intense contact metamorphism which the beds have suffered locally, both have retained their identity. The lower bed is an unfossiliferous grayish white limestone composed of me-

dium to coarse, interlocking calcite crystals. Fettke has traced it along its southeasterly strike for a distance of six miles, throughout which it maintains an estimated thickness of 250 feet and a persistent dip of 30 to 40 degrees to the northeast. The second bed is exposed a little less than a mile northeast of the first, approximately one mile south of the village of Torres. Circumscribed by the alluvium of the Caguas lowland on the northwest and of the Rio Anton Ruiz valley on the southeast, and obscured by the porphyritic intrusives on the southwest and northeast, it has been traced but a short distance. Its strike parallels the grayish white limestone, but its dip has not been satisfactorily determined. Fettke has given it as 52 degrees southeast, but he measured the angle, not on the limestone, but on an associated ledge of andesite, the relation of which to the calcareous bed is not clear. On the basis of this uncertain determination Fettke postulated a synclinal structure between the two limestones and concluded that they are one and the same formation.

This conclusion disregards the fact that the two beds are lithologically different. The formation near Torres is dark gray in color and is much finer and less even in texture than the light gray limestone. The latter is comparatively pure; the former is tuffaceous, and the microscope reveals fragments of plagioclase, quartz, and ferromagnesian minerals within it. Recrystalization and the destruction of micropaleontologic remains render direct comparison of the dark gray limestone with the Trujillo Alto in other parts of the district of little value; but both the megascopic and microscopic features differentiate it at once from the light gray limestone. If both beds are assumed to possess the northeasterly dip observed in the light gray bed, their relative stratigraphic positions are exactly the same as those of the La Muda and Trujillo Alto limestones in all other localities where the two are present in the section. In view of the facts that the two formations are lithologically different, and that it is possible Fettke's dip measurement was made on the contact plane of an intrusive body, the authors believe that the two formations are distinct, and that they must be correlated with the La Muda and Trujillo Alto limestones. More careful study of these two beds in the Juncos-Torres section is necessary, however, before a final conclusion is justified. And, should the correlation postulated prove correct, field evidence should be sought to verify the synclinal structure which must exist between these outcrops and the upland to the north.

Whether the La Muda and Trujillo Alto limestones extend into the central and western parts of Porto Rico, it is impossible to say until a

careful restudy is undertaken. They appear to be important horizon markers, but an effort to correlate them with the limestones described in the districts to the west must be based on many more field observations than are available at the present time. It is hoped that some contributions may be made to this question when the Cretaceous of the Arecibo district is differentiated.

*Structural problems of the Caguas Lowland and Luquillo Mountains*

In the central and southern parts of the Fajardo district the geological structure is not easily deciphered. In the interior the rocks consist of porphyries and andesites, and of massive tuffs and agglomerates, in which the only observable structures are joints and intrusive contacts. These features have not been resolved into systems that can be used to interpret the broader structural relations; but the northward dip of the calcareous tuffs and limestones near the northern limits of the Cretaceous outcrops, the apparent repetition of these strata in the magnetite belt east of Juncos, and the low southerly dip of the rocks near Guzman Abajo suggest that the dominant structure is anticlinal. The convergence of the two lower anticlines from the west appears to have given the arch great height and breadth near the point of junction, east of which the structure forks and declines in elevation; one broad, pitching anticline stretches toward Cape San Juan, and the other, a much narrower fold, extends eastward between the central range and southern foothills of the Luquillo Mountains to the east coast. The evidence of bifurcation in the structure is not entirely conclusive, and the field data on which the interpretation is based require further exposition. Rather closely linked with the problem is the structural character of the Luquillo Mountains and of the Caguas-Naguabo lowland; and the discussion that follows will center largely on the origin of these two arresting topographic forms.

The Luquillo Mountains, in spite of the clustered and unsystematic arrangement of the prominent peaks, may be resolved into three elements, two of which exhibit definite east-west elongation: (1) a central range, with El Toro marking its western end, and East Peak its eastern extremity; (2) the southern foothills, which are rather irregularly distributed yet roughly parallel the eastern portion of the main range; and (3) the El Yunque outlier, an isolated eminence which stands out appreciably beyond the northern flank of the central ridge, but is tied to it by a narrow divide that sags nearly 1000 feet below the adjacent

mountain summits (Fig. 1). The trend of the central range and the southern foothills, as well as that of some of the ravines and valleys associated with them, coincides closely with the strikes of the underlying rocks, so far as could be determined from scarce and widely scattered structural observations.

The *raison d'être* of the mountains, which tower 1500 feet and more above the fringing upland remnants, and 3000 feet above the nearby lowlands and coastal areas, is not immediately apparent. They are located near the northeastern corner of the island where rainfall is abundant, and where, in the course of late Cenozoic erosional history, reduction with respect to the Atlantic base-level should ordinarily have proceeded rapidly. During the Tertiary they were situated between the two major river systems of the region, which comprised Rio Grande de Loiza and its tributaries, and the stream system draining the lowland that now forms Vieques Sound and Fajardo Roads (Fig. 5); but their seeming remoteness from these main drainage lines was more than offset by their proximity to the Atlantic. There is, moreover, much more reason to believe that the Luquillo Mountains served as a partial cause of the location of the Tertiary drainage, than that they constitute a result. The fact that the headwaters of both the Rio Grande de Loiza and the Vieques Sound systems surround and isolate the mountain area is a convincing indication that the latter has persisted in spite of the growth of extensive river systems on every side, and in spite of its nearness to the sea. Some special cause must be sought, therefore, to explain its prominence.

Lobeck dismissed the hypothesis that comparatively recent warping may account for the abnormal elevation and position of the mountain mass, on convincing physiographic evidence;[34] but it is not clear that he gave due consideration to the possibility of recent faulting and tilting. Although his arguments against warping apply equally well to such a theory, so strong a case in its favor can be constructed on the basis of the topographic features that it is at least entitled to discussion. Superficially the upland comprising the western hill section and the Luquillo Mountains possesses many of the characteristics of a tilted fault block. Except for local conformance to the underlying structure, the streams that drain it flow northward as if consequent upon the back-slope of a tilted block; and the upland increases in elevation from north to south ending at the high, linear east-west escarpment which

[34] Lobeck, A. K.: op. cit., pp. 314-315.

overlooks the Caguas-Naguabo lowland (Fig. 10). This escarpment has every aspect of a fault scarp. Although for some miles east of Guarabo it coincides with the trend of the structural and topographic elements in the highland, elsewhere it truncates the upland topography at a low angle, in the manner of a normal fault scarp. It is oversteepened and

FIG. 10.—*The northern wall of the Caguas lowland*

Over 2000 feet high near Juncos, this scarp persists with scarcely a break from the western part of the district to Naguabo. The alluvial fans which have been built up at its base bury the floor of the basin, but here and there rock hills rise above them like islands.

young, and at its base coalescing alluvial fans spread far into the lowland, overlapping the floodplains of the large streams which parallel it (Fig. 10). The scarp persists in spite of radical changes in the rock types that compose it. Tuffs, andesites and andesite porphyries, granitoid intrusives, ashy and calcareous shales are found along successive portions of its imposing slopes; yet, notwithstanding local modifications which reflect the lithologic changes, it continues almost unbroken. Thoughts of the Quaternary and late Tertiary rift-faulting which has furrowed the Antillean region, and which has fashioned several of the lowlands within and marginal to Haiti and Santo Domingo, invoke the idea of comparatively recent faulting here. Certainly the youth of the escarpment and the recency of alluviation at its base give substantial support to the view.

South of the Caguas lowland the Sierra de Cayey upland rises in somewhat the same way as the Luquillo and western hill sections of the Fajardo district (Fig. 3). In a distance of eight or nine miles elevations increase from 300 to 3000 feet, and high altitudes continue as far as the southwestern coast. Between Yabucao and Patillas, cliffs rise 1200 to 1600 feet above the waters of the Caribbean. Shore forms that characterize other sections of the Porto Rican coastline are missing, and their absence indicates that this part of the coast was formed by faulting late in Quaternary time.[35] The inference that the escarpment north of the Caguas lowland is of similar origin and of similar date is all but irresistible.

This explanation of the Luquillo Mountains and the Caguas lowland, however, must disregard several features which point to a much longer and more involved history. As Lobeck has shown,[36] remnants of erosional surfaces surround the higher portions of the mountain range, against which they end with topographic discordance. Correlative erosional forms fringe the Sierra de Cayey upland at corresponding or slightly higher elevations; but in both uplands the low gradients of the erosional terraces are unrelated to the more rapid rise in elevation in the associated highland areas. The rise is not uniform but is made in three distinct steps, each of the three erosional levels present forming one of the treads, while comparatively steep scarps form the risers. If the Luquillo and Cayey uplands are tilted blocks, tilting must have occurred so long ago that the blocks have undergone the same erosional history as the rest of the island. In this case their elevation and relief are to be explained, not as the outcome of diastrophic processes, but as the result of their inherent resistance to the processes of denudation.

Equally serious objections to the hypothesis of recent block-faulting develop when some of the drainage features are studied. If eastern Porto Rico consists of two fault blocks tilted toward the north, the drainage from the southerly block would follow the linear depression along the fault plane between them, especially as the latter provides an unobstructed route eastward to Vieques Passage. The Caguas-Naguabo lowland, however, is not occupied by an east-flowing mainstream. On the contrary, the greater part of the lowland drainage is tributary to Rio Grande de Loiza, which cuts through the western hill section, fol-

[35] Meyerhoff, H. A.: Tertiary physiographic development of Porto Rico and the Virgin Islands. Bulletin, Geological Society of America, 1927, Vol. XXXVIII, pp. 572-575.
[36] Lobeck, A. K.: op. cit., p. 314.

lowing a long, tortuous course to the Atlantic. Scattered wind-gaps in the escarpment forming the northern boundary of the lowland show that other streams, which have since been captured by Rio Grande de Loiza, initially had a similar relationship to the upland, and that the behavior of the latter is normal. The measure of independence which the streams display toward the topographic features is a common phenomenon if it is related to a long erosional history of two or more cycles' duration; it is entirely incompatible with the development of consequent drainage in young block mountains. The superposition of Rio Grande de Loiza across the highland and the features of entrenchment within its course indicate clearly their genetic association with an early cycle of erosion and their lack of connection with a hypothetical Quaternary displacement.

A more speculative, yet interesting, line of evidence against the fault hypothesis is furnished by the distribution of granitoid intrusives in the Fajardo district. If it be assumed that stocks and apophyses that invade overlying rocks from a subjacent magmatic reservoir ordinarily taper upward, there should be a rough relationship between the depth of erosion and the areal extent of their outcrops. If the Caguas lowland and Luquillo upland were formed from a simple, peneplaned mass by displacement and tilting, the intrusives now exposed on their respective surfaces, in spite of the differences in elevation, would have been eroded to the same relative depths. Yet the numerous granitoid intrusives in the upland are invariably small in areal extent, whereas those in the lowland are characteristically large, a feature which suggests that deeper erosion has taken place in the latter. This general line of reasoning loses its force, however, when it is recalled that the source of the intrusives was the Humacao batholith to the south, and that their relative sizes are probably due as much to their proximity to the batholith as to the depth of dissection. On the other hand, three of the intrusives of the lowland area extend into the upland: an apophysis of moderate extent is present between the La Muda-Caguas carretera and Aguas Buenas; a small stock invades the margin of the upland near El Rio; and an intrusive tongue passes from lowland to mountains along the falls of Rio Blanco. No one of these cases could be exhaustively studied in the field, and to some extent the boundaries given them on the map are only approximate. All of them are alike, however, in beginning with broad bases in the lowland, and ending in much more restricted exposures in the highland. In the Rio Blanco intrusive, tapering can actually be

detected from bottom to top of the steep mountain slopes. Evidence of this kind has merely an incremental value; it is in harmony with an erosional origin of the Luquillo upland and Caguas lowland, and seemingly contradictory to a diastrophic interpretation.

It is unfortunate that a problem as elementary as this cannot be settled by direct observation, but the rocks of the lowland are exposed at the base of the northern escarpment at only one point—at the divide between the Rio Grande de Loiza drainage and the Rio Blanco drainage. Here the escarpment and lowland are both composed of a porphyritic intrusive. Although evidence of a structural or lithologic break is lacking, the character of the exposures forbids an unqualified assertion. Elsewhere the continuity of rock outcrops from scarp to lowland is interrupted by the alluvial outwash from the upland; but east of Gurabo the scattered rock "islands" in the alluvium, and the rock exposures along the southern margin of the depression afford little basis for postulating a normal fault of large displacement between them. On the contrary, in the magnetite belt east of Juncos a simple synclinal relation appears to exist between the rocks in the southern part of the lowland and those in the scarp on the north. West of Gurabo most of the basin is underlaid by quartz diorite. The tuffs to the north and south of the intrusive are much alike, and comparisons between them have little significance. Near Aguas Buenas the lowland seems to end with the diorite intrusive, and the entire country rises to an elevation of 700 or 800 feet; yet even here an east-west belt as wide as the Caguas basin, and continuous with it, forms a valley peneplane bounded both north and south by higher flat-topped ridges and uplands. The ridge on the north is continuous with the escarpment that bounds the Caguas lowland farther east and appears in every way to be analogous to it; but in the Aguas Buenas region the numerous and unbroken rock exposures reveal no structural break between the ridge and the floor of the valley peneplane.

Alluring as a theory of block-faulting may be to explain the juxtaposition of the Luquillo upland and the Caguas-Naguabo lowland, it clearly does not fit many of the facts. Suggested by the youth of the scarp between the highland and lowland, by the truncation of physiographic and structural elements, and by the alluviation of the Caguas basin, the hypothesis cannot account for the presence of the same erosional levels around the flanks of the mountains and the margins of the basin as occur in all other parts of Porto Rico; for the occurrence of the same, or of stratigraphically related, rocks in the lowland and on the scarp; for

the absence of convincing evidence of faulting where the base of the scarp is exposed; or for the superposition of streams across the northern upland, notwithstanding the existence of an unobstructed outlet to the east coast.

Lobeck suggests that the contrast in relief along the southern margin of the Fajardo district is the outcome of differential rock resistance.[37] He considers the Caguas lowland to be the result of rapid excavation of the underlying granitoid rocks; and, though puzzled by the diversity of rock types in the Luquillo range, he concludes a brief descriptive passage with the statement: "It is quite possible that a better knowledge of the rocks involved would show that the higher areas are actually made up of more resistant types."

In field and laboratory the authors have given Lobeck's suggestion very careful consideration, but the evidence assembled fails to support his opinion. Quartz diorite underlies only a part of the Caguas lowland, and where it is present, it has undoubtedly played an important part in facilitating denudation. In the vicinity of Caguas, where the depression is broadest, its limits are almost precisely determined by the extent of the quartz diorite. East of Gurabo, however, outcrops of other rock types are common, and at the divide between Rio Gurabo and Quebrada[38] Peña Pobre the granitoid intrusive is absent, yet the lowland persists. In the entire Naguabo section of the lowland outcrops of quartz diorite are scattered, and, notwithstanding the ease with which the streams working headward from the east coast have excavated them, they appear to have been subsidiary, rather than dominant, factors in the location of the drainage lines. At the falls of Rio Blanco the non-resistance of the diorite has unquestionably determined the position of the river; but the fact that the coarse-grained intrusive passes indiscriminately from valley to mountain mass without a structural break is of greater significance, and in following it Rio Blanco drops a thousand feet or more in a broken series of falls down the sheer mountain wall of the central range. The most prominent valley in this portion of the Luquillo Mountains is not that of Rio Blanco, which has barely notched the highland; it is the east-west valley of the much smaller stream which flows between the central range and the southern foothills (Fig. 11).

It must be admitted that wherever rocks of a non-granitoid character occur within the lowland, they tend to rise to elevations somewhat higher

[37] Lobeck, A. K.: op. cit., pp. 314, 318-319.

[38] The word "quebrada" may be translated "creek" or "brook."

than its floor, making prominent knobs, ridges, and spurs that protrude through the alluvium or form local stream divides. West of Caguas, where the quartz diorite ends, the entire country rises 600 feet or more; yet even here there is a topographic lowland between high ridges. From the persistence of this linear depression along the southern boundary of the Fajardo district in spite of changes of rock types, it must be con-

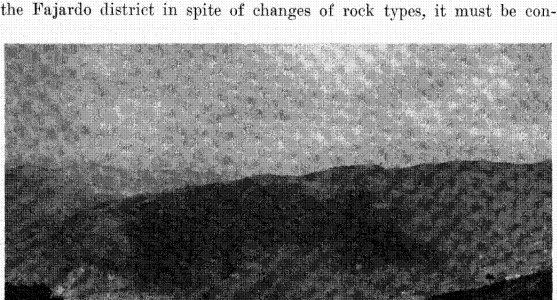


FIG. 11.—*The southern foothills*

This deep east-west valley has been opened out by a relatively small stream which worked headward along the anticlinal structure. The largest stream of the region, Rio Blanco, cascades down the high southern slope of the central range, from which the photograph was taken.

cluded that the non-resistant intrusives did not constitute a primal cause in localizing denudation, much as they may have accelerated its progress.

A somewhat similar conclusion must be drawn concerning the rôle of rock resistance in the origin of the Luquillo Mountains and of the ridge that extends westward from them, forming the scarp on the northern side of the lowland. Field traverses merely confirmed Lobeck's observation that almost every lithologic variety found elsewhere among the Cretaceous rocks of the district outcrops in the mountain region (cf. geologic map). If a few individual beds, like the conglomerate north of La Muda, be excepted, none of the varieties present exhibits noteworthy resistance in other parts of northeastern Porto Rico. The sediments on the southern flank of the central range display a greater degree of induration than those near the north and east coasts, but this characteristic is

attributable to the rapidity of dissection and to the consequent freshness of the exposures, rather than to an initial difference in composition. The marked tendency of the stratified tuffs and ashy shales to form subsequent valleys in every part of the island stresses the unlikelihood of abnormal elements of resistance in the sediments of the Luquillo Mountains. In the extensive areas of high elevation and relief where sediments are not present, moreover, superior lithologic resistance cannot be entertained as a means of interpreting the topography. The hypothesis must be rejected also as an explanation of the ridge that bounds the Caguas lowland, for this, too, is composed of many lithologic types.

Analysis indicates, therefore, that the Luquillo Mountains and the Caguas lowland have not been formed by recent diastrophic movements of any kind, because they have gone through the same phases of a long erosional development as the rest of Porto Rico; that they did not originate in consequence of geographic isolation, for they seem to have occupied a vulnerable position with respect to streams and ocean since early Miocene time; that they have not been etched into relief because of the differential resistance of their constituent rocks, for the same, or similar, formations are present alike in mountains and lowland, as well as in every other part of the Fajardo district. It is true that lithologic factors have proved important in the development of portions of the Caguas basin, especially near the town of Caguas, but they had at best a small part in determining its initial location.

There is available, however, another explanation of the origin of the Luquillo Mountains and the Caguas lowland, and although its applicability cannot be fully demonstrated at the present time, it is supported by all the data thus far assembled. The relative resistance of rocks to processes of erosion may depend upon their lithologic characteristics, or, on the other hand, it may be more directly related to their structures. Mass resistance, as contrasted with lithologic resistance, may, for example, be imparted to rock formations by the development of compressional structures. In nearly every region of folded mountains, especially if the folding is close, the synclinal troughs more effectively withstand denudation than any other kind of orogenic structure. In pitching folds the ends of both the anticlines and the synclines seem to possess the quality of mass resistance, as the canoe-shaped forms of the central Appalachian region so strikingly show. Anticlinal crests and the summits of domes are, in contrast, easily excavated, and not infrequently they serve to localize the formation of subsequent depressions.

There is some reason to believe that an explanation of this kind applies to the major topographic features in the southeastern and southern parts of the Fajardo district. It is unfortunate that concrete structural observations in these two sections were few and scattered; yet the evidence they supply is suggestive, if not conclusive. It may be summarized briefly:

(1) The steep southern flank of the central range is composed largely of ashy and tuffaceous shales which dip at a moderate angle toward the north. In spite of their somewhat darker color, which is due in great part to the fact that they have not undergone deep residual weathering, these stratified rocks are tentatively correlated with the beds found near the coast at Luquillo and other localities, where also they dip north. Repetition of the strata cannot be interpreted as the outcome of faulting in this case, and from the facts which follow, it appears definitely to be the result of folding.

(2) The presence of folds within the mountains is further indicated by the determinable structures at their eastern and western ends. Near Guzman Abajo at the northwest end of the central range the crest of a large anticline has been identified. Along the east coast from Fajardo to Naguabo two large folds involving several thousand feet of sediments and flows have been found, and they have been traced for several miles westward into the foothills of the Luquillo range. From the folds which have been differentiated, from the repetition of strata in the mountains, and from the distribution of the outcrops of other rock types, the structure from the north coast to the southern front of the central range is believed to consist of a synclinal trough, an anticline, and a syncline (Fig. 12). The latter is an eastward plunging structure, which seems to undergo partial closure at East Peak, but which opens broadly toward the east coast.

(3) The central range and southern foothills of the Luquillo Mountains and the Caguas lowland are all elongated in an east-west direction. Although they parallel the general structural trend of the underlying rocks, the occasional independence of strike and topography is noteworthy. The cases of independence can be readily understood if the topographic elements coincide with the axes of the folds rather than with the strikes of individual formations; and in the few localities which could be studied carefully, this relationship was found to exist.

(4) The elevated valley peneplane which lies west of the Caguas lowland beyond the outcrops of the non-resistant granitoid intrusive has already been mentioned. Semmes and Hodge have determined the anticlinal character of the underlying structure, and the field studies of the

present survey have made it possible to extend the anticlinal axis far into the Caguas basin. Further study may show that it is continuous with the anticline between the central range and southern foothills, thereby extending the structure the full length of the Fajardo district; but at present there is some doubt concerning its continuity between Gurabo and El Rio. In any case its presence in the western portion of the depression strongly suggests that the Caguas section of the lowland was initially an anticlinal valley, the excavation of which has been locally facilitated by the dioritic intrusives. The valley between the central range and southern foothills is also anticlinal, and its discontinuity and narrowness as compared with the lowland to the west reflect the greater compression of the structure and the scarcity of intrusives. The structure of the Naguabo section of the lowland was not determined carefully, but its development appears to depend more upon its proximity to the coast, and upon the free play of the lithologic characteristics of the rock formations than upon simple structural features. Its connection with the Caguas basin is due to the accidents of headward erosion.

(5) The origin of the El Yunque outlier can merely be conjectured. It lies somewhat north of the main range, almost isolated by a ramifying system of stream-heads which have cut deep gorges on nearly every side. A slender divide ties it to the central ridge, but the divide lies a thousand feet or more below the mountain crests. Although the principal drainage lines on the northern slopes of the mountains trend northward toward the Atlantic coast, the rapid extension of tributaries in an east-west direction be-

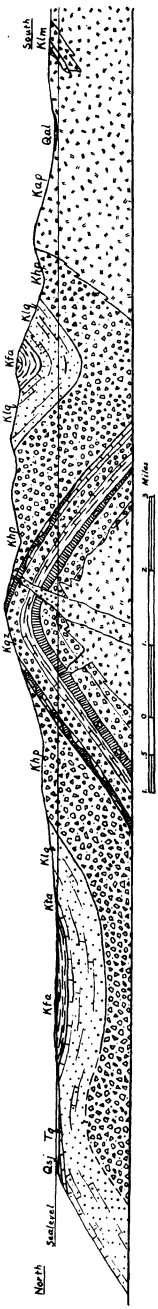



FIG. 12.—*Structure section from Mameyes to Torres*

This section across the Luquillo Mountains at El Yunque is generalized and partly interpretative. Horizontal and vertical scales are alike.

Qsj=San Juan formation; Tq=Quebradillas limestone; Kfa=Fajardo shales; Kta=Trujillo Alto limestone; Klq=Luquillo formation; Khp=Hato Puerco tuffs; Kgz=Guzman formation; Kap=andesite porphyry; Qal=alluvium; Klm=La Muda limestone.

tween El Yunque and the central range is suggestive of a zone of weakness, which the variety of rocks across the divide proves is not strictly related to the lithology. On the geologic map this belt is shown occupying the limb of a fold, where relative lithologic resistance would be the principal element affecting erosion, whereas theoretical consideration would lead one to expect that the east-west gorges are being opened out along the axis of an anticline. More thorough field study may show the map to be in error, notwithstanding the weak support given it by the physiography and the distribution of outcrops, which imply that El

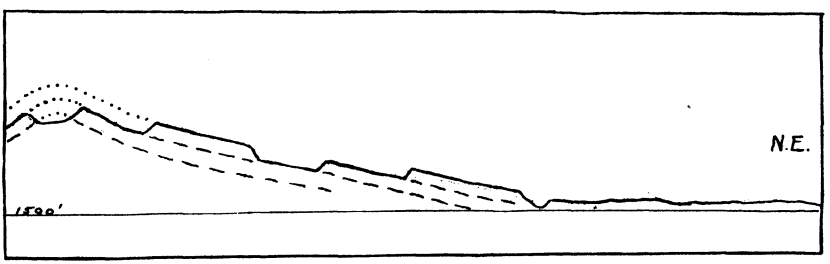



FIG. 13.—*Sketch profile of El Yunque*

As seen from Vieques Sound. The recurrent scarps facing southwest suggest a northeastern dip in the rocks that form this side of the mountain, but the structure at the summit is uncertain. The flat-crested spur approximating 1600 feet in elevation is conspicuous.

Yunque forms the crest of the anticlinal structure. The scattered readings that were obtained on the northern slope of the mountain are persistently to the north. An unusual profile view of the northeastern spur of El Yunque was sketched from the mail launch that plies between Fajardo and Isabel Segunda. The sketch, which is reproduced in Figure 13, suggests from the recurrence of scarps fronting southwest that this side of the mountain is a partly stripped dip slope, composed of northeastward dipping strata. If this interpretation be correct, El Yunque forms the end of an anticline which pitches east-northeastward, and which, because of its closure, has given mass resistance to the peak. The interpretation gains some support from the fact that Cape San Juan, which is structurally aligned with the northeastern spur of El Yunque, is anticlinal in character. The synclines which flank the cape, moreover, pitch east-northeastward and necessitate a similar pitch in the anticline between them.

Meager as the observations presented may be, they warrant several definite conclusions and permit a few inferences regarding the structural character of the Luquillo Mountains and the Caguas lowland. Both are

composed of folded strata, which include most of the formations that appear in all other parts of the Fajardo district. These formations have no peculiar lithologic properties affecting their ability to resist or to undergo erosion in the mountain and lowland belts, and the features of the topography exhibit a degree of independence of the rock types that makes a lithologic explanation of their origin untenable. To some extent, however, dioritic intrusives have accelerated erosion, but only where denudation was localized by other factors.

In general, the relief features are intimately related to the orogenic structures, but the relation is with the axes of the folds rather than with the formational outcrops associated with them. An anticlinal valley separates the southern foothills from the central range, and the presence of an anticline, which pitches at both ends, may be responsible both for the isolation of El Yunque and for its prominence. Between the two anticlines lies the pinched synclinal structure which forms the central range. Closure upon the west determines its limits at El Toro, the highest peak in eastern Porto Rico; partial closure on the east may also account for East Peak, and the compression of the fold between the two points of closure has made it possible for the central range as a whole to maintain an average elevation approaching 3000 feet. The Caguas basin offers difficulties in interpretation because the intrusives have obscured and to some extent distorted the original structures of the older rocks. In the west, however, its anticlinal character provides reason to believe that its excavation was due initially to the structure. If this interpretation of the structure be correct, supported as it is by a few measured dips, by the distribution of the fragmental rocks, and by the physiographic features, the Luquillo upland and Caguas lowland have been carved from two anticlines and a syncline, all with east-west axes that pitch toward the east (Fig. 12). Limiting them on the south is the syncline of the magnetite belt, which has already been mentioned; on the north lies an undulating synclinal trough, which will receive further study in a later section.

It may justly be claimed that the relief in southeastern Porto Rico has not yet been explained, even if the structural interpretations presented be correct. Along the western border of the district pitching folds are also present; yet, granting the excavation of the anticline at the southwestern corner of the district into a valley peneplane flanked by somewhat higher synclinal uplands to the north and south, the topographic effects are by no means comparable with those in the east.

Some factor other than simple folding must be found to explain the contrasts in relief which occur in the Luquillo Mountains region.

The additional factor is provided by the relative amounts of compression in the folds of the two localities. Along the western border of the district the folds are broad and open, and the processes of erosion have not encountered the mass resistance of tightly pinched structures. In the Luquillo Mountains the synclinal fold of the central range is narrow and compressed, and the anticline to the south is almost equally so. The mountains are wholly restricted to these two compressed folds and to the sharply creased end of the plunging anticline which seems to compose El Yunque. In every direction from the mountains the major folds shallow and broaden; the inherently low erosional resistance of the rocks comes into play; and the elevation subsides at the point where the change in the character of the structure first appears. A study of the east coast will make the significance of these statements clear.

*The structure of the east coast*

Confirmation of the inferences which have been drawn concerning the structure of the Luquillo Mountains and the Caguas-Naguabo lowland might logically be expected from the natural structure section exposed along the coastline at the eastern border of the district. Again, however, realization falls short of expectation, and it can merely be claimed that the rock section along the east coast partially confirms and nowhere contradicts the interpretations which have been advanced to explain the structures of the interior. Minor folding and faulting obscure the larger features; deep weathering makes field and laboratory identification of rock-types precarious; the appearance of thick volcanic sills and flows, not present in the western part of the district and not so conspicuous in the central part, makes stratigraphic determinations less certain. More serious than these partly surmountable difficulties which are of a positive character, are the wide gaps in the cross-section that have been caused by deep dissection, submergence, filling of the estuaries, and aggradation of the valleys. The unconsolidated deposits of the broad playas, which extend for moderate distances inland along the stream courses, bury many parts of the rock section—usually critical parts, because the larger aggraded valleys were excavated along the axes of folds and upon the less resistant stratified rocks, in which structural data are easily gathered. In consequence, most of the outcrops in the rocky divides between the playas consist of the more resistant, massive volcanics, which supply few structural details that are serviceable in

identifying the major folds of the region. The result is an incomplete set of facts, especially for the area south of Fajardo; and the conclusions presented in the following paragraphs and utilized in drawing the geologic map are provisional. Some revision will be necessary when a thorough investigation of the structure has been made.

From Playa de Fajardo to Cape San Juan outcrops are almost unbroken along the shoreline, and they are also very numerous inland. They display a bewildering succession of small folds, many of which are over-

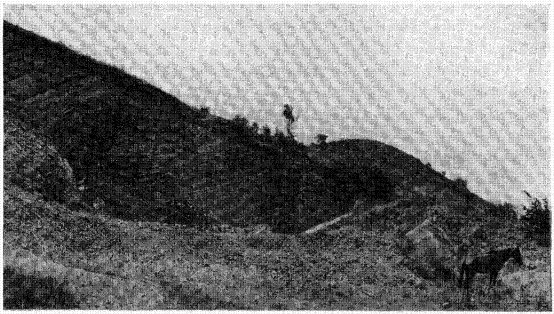


FIG. 14.—*Deformation in the incompetent Fajardo shales*
This small overturned anticline, its crest fractured and faulted, is exposed on the carretera at Kilometer 51, a short distance south of Fajardo.

turned from the south. Buff ashy shales, like those at Rio Piedras, dominate in the vicinity of Fajardo, and they continue southwestward along Rio Fajardo into the Luquillo foothills and northwestward along the route of the Fajardo Railroad to the Atlantic coast. North-northeastward toward the Cape and southward toward Ceiba, however, beds of tuff increase in number and in prominence, and in both these directions the tuffaceous strata ultimately replace the shales. The strikes of the sediments are as variable as the points of the compass, but a prevailing east-northeasterly trend that coincides with the direction of the Fajardo valley is apparent. The dips are even less constant than the strikes. The numerous small, sharp overturned folds, some of which involve thrust faults of minor displacement, show the extraordinary extent to which distortion of the rocks has proceeded. In the rocky knob that

protrudes above the alluvium a half-mile south of Fajardo, one of the quarries along the carretera has uncovered an overthrust which developed at the crest of a slightly overturned anticline (Fig. 14). The succession of anticlines and synclines exposed in the wave-cut cliffs north of Playa de Fajardo is the most striking structural display which the island contains. Many of the small folds plunge sharply, a feature which is well exhibited in the flexures and contortions that the strata undergo when exposed on horizontal surfaces, as along the Fajardo valley road about one kilometer southwest of Fajardo.

The prominence and obviousness of the structural details in the northeastern corner of the district, however, obscure the broader and more significant features, for the aggregate of many strike and dip readings fails to disclose the major structural elements of which the minor deformation is part. The larger structures have been determined only by plotting the distribution of the sedimentary formations. The buff shales which outcrop in the valley of Rio Fajardo give place to calcareous tuffs on the south; and to the north and northwest they partly encircle a similar series of tuffaceous sediments. The reappearance of the shales in scattered outcrops along the contact between the Cretaceous and Tertiary rocks shows that they were originally continuous with the ashy shales at Rio Piedras; and wherever they are exposed at the northern edge of the Cretaceous oldland they lie stratigraphically above the calcareous tuffs. Their position between the tuffaceous strata in the valley of Rio Fajardo seems, therefore, to be a reliable indication of the synclinal character of the main structure. The tuffs in the vicinity of Cape San Juan, on the other hand, are lithologically distinct from the calcareous beds which lie beneath the ashy shales. They are non-calcareous and contain a greater admixture of pyrogenic material, and their location at the northeastern extremity of the pitching anticline which has been traced from El Yunque to the Cape San Juan peninsula affords evidence of their younger age. This anticline is the northernmost structure which emerges at the east coast, and it provides one clearly defined boundary for the syncline of the Fajardo valley.

The village of Ceiba, four miles south of Fajardo, is situated upon tuffaceous deposits which include a large proportion of calcareous and shaly members. Weathering and deformation have so completely obliterated the structural features of the rocks that in the score, or more, of outcrops studied not a single reliable structural determination was obtained; in most exposures it was impossible to identify the bedding, even though petrographic analysis has shown the rocks to be sedimentary

in character. Here again, the lithologic succession must be utilized in forming a tentative conclusion regarding the structure. Between the tuffs of the Ceiba district and the ashy shales of the Fajardo valley is a band, one kilometer wide, of volcanic rocks, which range from microfelsite and typical andesite to a highly altered andesitic derivative. Their fine textures and flowage lines make their effusive origin certain. They were traced westward more than four miles to Rio Fajardo and throughout this distance they parallel the ashy shales and stratified tuffs to the north and the calcareous tuffs to the south. About half a mile south of Ceiba a similar band occurs across a zone with approximately the same width. It was not traced westward, and in showing its extent on the geologic map accompanying this report the writers have made some use of Fettke's brief notes concerning it.[39] On the map of the Humacao district it appears as a lens-shaped body which loses its identity in the extensive outcrops of porphyritic andesite surrounding it. The work of the present survey failed to disclose the presence of the porphyry north of the felsitic flows but discovered that, like those north of Ceiba, they come into direct contact with the tuffs. It seems highly probable from the limited evidence obtained that the two bands of extrusive material north and south of Ceiba are identical, and that they outcrop on the opposite limbs of an anticline. The structural alignment of the Ceiba spur with the anticline between the central range and the southern foothills of the Luquillo Mountains supports this opinion without proving it.

Interpretations of the structure south of the Ceiba anticline so nearly approach guess-work that none will be offered. Andesite porphyry predominates among the deeply weathered rocks, but a short distance north of Playa de Naguabo an area of felsite resembling the flow material near Ceiba, and a small patch of calcareous shale suggest duplication of the formations by folding or by faulting. The distribution and limits of the felsite and shale in the vicinity of Playa de Naguabo could not be determined in the field, and it is impossible to form any satisfactory opinion about them. Fettke, whose studies overlapped those of the Fajardo survey at this point, did not differentiate the sediments, and his map shows the felsite as an ill-defined lens within the porphyry. He makes no attempt to interpret the structure. The most puzzling feature in the Naguabo region is the huge mass of andesite porphyry which cuts the adjacent stratified rocks like a wedge, roughly paralleling their structure and stretching westward to the Caguas lowland, perhaps as far as

[39] Fettke, C. R.: Geology of the Humacao district, Porto Rico, op. cit., p. 148 and map.

the large plug-like mass at the head-waters of Rio Canovanas. In many places the porphyry maintains a sill-like relation to the surrounding strata, but in others it cuts irregularly through them. Some of the problems of its origin and structure will be reserved for consideration in an ensuing section, but its presence in the southeastern corner of the district creates a structural chaos that defies analysis. Its intrusion has isolated sedimentary areas, which have been further affected by the invasion of the Humacao batholith. In view of the extent of volcanism, it may be doubted if any of the sedimentary remnants in this area has retained a wholly normal relationship with the more regularly folded rocks to the north.

The character of the structure along the east coast suggests a tentative explanation of the lowland east of Porto Rico, which, as a result of submergence, now forms Vieques Sound. The sharp folds of the Luquillo Mountains plunge eastward; the two anticlines flanking the central range become narrower and lower; the syncline between them broadens, and within its trough non-resistant sedimentary rocks appear. Notwithstanding the development of sharp drag folds in the more thinly bedded strata, the general structure flattens, and in consequence the erosionally weak rocks are spread over a large area. Culebra, composed in part of horizontal tuffs, appears to lie in the center of this synclinal trough,[40] which, because of the coincidence of relatively flat structure and of non-resistant rocks, has remained an area of low elevation and relief throughout Cenozoic time. A second period of gentle folding or warping may have modified it during the diastrophic disturbances of the Miocene, for a remnant of the Tertiary coastal plain has been preserved within it in spite of its long erosional history.[41] It is clear, however, that the Vieques Sound lowland begins where the close folding ends. Not only is this statement true of its eastern end against the Luquillo Mountains, but also of its southern margin against Vieques, where the Cretaceous sediments and volcanics again possess high structures.

*The transverse folds of the northern border*

In the preceding analysis the structure of the Fajardo district has been studied in cross-section at its eastern and western boundaries and

[40] Meyerhoff, H. A.: The physiography of the Virgin Islands, Culebra and Vieques. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, 1927, Vol. IV, Pt. 2, pp. 204-205, including footnote 38, p. 205.

[41] Idem, pp. 195, 198-200.

across its center. The repeated references to plunging folds have indicated that there are additional complications in longitudinal section, some of which may be appreciated by a brief examination of the structures along the northern edge of the Cretaceous outcrops.

The carretera from Rio Piedras to Fajardo follows the contact between the Tertiary strata and the Cretaceous rocks rather closely until the former disappear. Rock cuts are numerous and, in spite of deep weathering, the predominating stratified tuffs and shales have retained their structural features sufficiently well to supply ample data for interpretation. From Bayamon to Rio Piedras the rocks strike southeast, and their dips are steep to the northeast. Between Rio Piedras and Carolina the strike changes to due east-west, and the dips become lower but remain persistently northward. At Carolina the sediments swing to the northeast, and from this point to Cape San Juan northeasterly strikes prevail. The exceptions are few but noteworthy. At the valley of Rio Grande de Loiza, at the town of Rio Grande, and again a short distance southeast of Luquillo the strikes veer in a direction at right angles to the general trend exhibited elsewhere, and the stratified rocks swing inland. In these three localities structural observations were difficult to obtain, because igneous intrusions, uncommon elsewhere in the section, cut the strata. In the Rio Grande-Mameyes region porphyritic and granitoid masses have completely engulfed the sediments except for one or two small patches that accidentally escaped destruction.

Throughout most of the section from Carolina to Cape San Juan the dips are very low—locally even horizontal or gently undulating. In many places at the extreme northern edge of the Cretaceous outcrops, the strikes turn from northeast to due north, and, if the strike readings be plotted on a map, the impression is inescapable that the massive pyroclastic rocks of the interior pass into the Atlantic and in their passage suffer conversion from massive to stratified types. A more careful evaluation of the facts must alter this alluring hypothesis. There is no other evidence that the unstratified tuffs and agglomerates grade laterally into sedimentary equivalents to this extent. On the contrary, part of the same sedimentary succession that is present in the neighborhood of Rio Piedras and Trujillo Alto persists without interruption to Cape San Juan, in spite of its apparent tendency to move out to sea. Explanation of the seemingly contradictory facts must be sought in the structural character of the three belts in which the rock section swings back into the interior.

Once again the critical features are not entirely clear in the field, and interpretation must supplement direct observation. The rocks that strike northeast and north have gentle dips and are relatively free of minor deformation and the effects of igneous intrusion; but those that strike southeast have high dips, which are locally complicated by faulting and contortion. The intrusives associated with them appear to have been localized by the intensity of deformation at these points, and they have the unfortunate effect of confusing or obscuring the significant orogenic structures. The igneous bodies near Carolina and Luquillo are comparatively small, but the granitoid mass near Rio Grande is of considerable size, and its invasion destroyed a large and important area of sediments. In each of the three localities, however, enough of the sedimentary succession remains to supply some structural data, on the basis of which an explanation of the larger orogenic features may be postulated: (1) The major structure along the northern edge of the Cretaceous exposures comprises an east-west syncline, which extends from a point two miles east of Rio Piedras to a point about three miles east of Luquillo. The contact between the Tertiary and the "Older Series" roughly coincides with the axis of the fold. (2) Strongly asymmetric transverse folds in the trough cause undulations which sink gradually toward the west and drop sharply toward the east. (3) Diastrophic conditions on the steep limbs of the cross-folds favored magmatic penetration of the stratified rocks. The second and third of these features are illustrated in the accompanying generalized structure section (Fig. 15). The geologic map shows the peculiar areal distribution of rock types which has prompted the interpretation outlined above.

Transverse folding of a less pronounced character affects every portion of northeastern Porto Rico, as may be judged from the number of plunging folds which have been described. The writers are not prepared to read any final meaning into these cross-structures, for their significance can be gauged only after a careful structural analysis of the entire Porto Rico-Virgin Islands region has been made. The intimate relation existing between intrusives and the asymmetric folds in the northern part of the Fajardo district, however, implies that all the deformation occurred in a single period of orogenesis, and that it involved strong torsional stress, which was relieved by movement along transverse lines. Folding may have occurred in two distinct pre-Oligocene cycles, as Hubbard suggests, but this supposition receives little unqualified support from the structural features in the northeastern part of the island.

# OVERSIZED PLACEHOLDER

FILE NAME_____

*Summary*

Despite the many problems which the foregoing discussion of the structure has left unsettled, it is clear that the formations of the Fajardo district are systematically folded. The main system of folds extends in an east-west direction across the district, but it is complicated by several well defined flexures which cross it from north to south. Subsidiary systems of the drag fold type are found among the incompetent rocks, but they are genetically related to the larger structures with which they are associated.

The major folds are few in number, and their distribution may be briefly reviewed. Two anticlines enter the corners of the district from the west and merge into a single large structure in the hill section, a short distance west of Rio Grande de Loiza, thereby crowding out the syncline between them. The enlarged anticline rises into a dome-like structure on the northern flanks of the Luquillo Mountains and then pitches moderately toward Cape San Juan. A narrower anticline appears on the south near the eastern end of the Caguas lowland, passing eastward between the central range and southern foothills and plunging into Vieques Passage. Between these two folds lies a tightly compressed syncline, the rocks of which acquired through folding a mass resistance that has enabled them to form the high central range of the mountains. On the north the district is enclosed by an asymmetrically undulating syncline, the northern limb of which is buried beneath Cenozoic deposits or lies upon the submarine platform beyond the limits of observation. The southern border of the district is complicated by the dioritic outliers of the Humacao batholith and by older intrusives of andesite porphyry. From Gurabo eastward the structure is anticlinal in character, but in the Naguabo lowland the vestiges of structure still remaining appear to be synclinal or monoclinal. The folds of the interior flatten eastward; the two anticlines narrow and disappear, whereas the syncline of the central range broadens at their expense, forming the basinal expanse that underlies Vieques Sound. Within the syncline minor folding and thrust faulting have developed to a marked degree in the incompetent shales, but the small folds show convincingly their genetic relation to the major structure.

The regularity of the folded structures is surprising in view of the heterogeneous character of the rock section. There is some basis for believing that the variations in the widths of the folds are related closely to the relative massiveness and competence of the rocks involved

within them; and that the characteristic features of cross-folding which all of them display were in some instances, at least, localized by the presence of competent intrusives or volcanic masses, which rose through the rocks of the normal stratigraphic section. Further analysis will undoubtedly reveal a very intimate connection between the competence of the lithologic elements and the form of the orogenic structures. The work of unraveling the structure has also brought out two additional features, the significance of which is of more immediate importance in the present study; namely, the strong influence which the structure has exerted upon the development of the topographic forms; and the possibility of differentiating the confused and variable rocks of the region into an orderly stratigraphic series. The first of these points has already been discussed; the second may appropriately be considered in the following section.

## THE STRATIGRAPHY OF THE "OLDER SERIES"

### *Problems in nomenclature*

The development of stratigraphic nomenclature in most regions is inevitably haphazard because of the piecemeal differentiation of lithologic units on which it is generally based. The law of priority cannot always be rigidly applied, for stratigraphic subdivisions acquire final validity only when the rock section of a given locality is fully understood, and when the individual units and the groups of which they are part have been traced to their farthest geographic limits. The names assigned to well defined formations are likely to prove permanent unless there has been inadvertent duplication, but the names given to formational series usually need revision as knowledge of the stratigraphic section grows.

This preface to an examination of the Cretaceous stratigraphy of the Fajardo district outlines the situation which must be met in delineating the lithologic sequence. The problems may best be understood from an historical résumé. In 1899 R. T. Hill briefly described the limestones which outcrop prominently in parts of the interior, and which form the crests of several of the more conspicuous ranges,[42] referring to them as the mountain limestones, to distinguish them from the younger Tertiary strata of the coastal plain. Hill did not regard his designation of these rocks as a formational name, nor did he apply it to a specific strati-

[42] Hill, R. T.: Mineral resources of Porto Rico. U. S. Geological Survey, Annual Report, 1899, Vol. XX, Pt. 6, pp. 771-772.

graphic unit;[43] yet Hodge definitely assigned the name to the shaly limestones in the vicinity of Barranquitas and included them as one of the members in his Barranquitas-Cayey series.[44] Berkey, too, has suggested that the name be retained in the stratigraphic nomenclature.[45] Such a course seems decidedly unwise, because the name has no definite geographic connotation in Porto Rico, hence a type locality must arbitrarily be chosen, and because the application of the term to a specific part of the Cretaceous section was not Hill's intention. What is more, the name is pre-occupied. In this report, therefore, no attempt will be made to fix the term "mountain limestones" upon any of the calcareous strata which occur in the district, notwithstanding the fact that the shaly limestones of the Barranquitas-Cayey series are probably present.

As an outcome of his geological reconnaissance Berkey assigned names to several well defined and conspicuous stratigraphic horizons located in different parts of the island. Those which lie within the limits of the Fajardo district include the La Muda limestone and Trujillo Alto limestone, and the Fajardo shales. Berkey differentiated these beds before their stratigraphic relationships were known, and he foresaw the possibility that any of them might prove to be equivalent to the formations elsewhere in Porto Rico, for which names were simultaneously proposed. The only possibility of this kind which the present survey has developed has not been proved; but a careful study of the pitching syncline which extends from Aguas Buenas to Toa Alta may show that the Corozal and La Muda limestones are identical beds exposed on opposite limbs of the fold.

Semmes added few names to the short list proposed by Berkey. He applied the term "Aguas Buenas limestones" to the two calcareous beds that outcrop in the southeastern corner of the San Juan district; but the two formations are apparently equivalent to the La Muda and Trujillo Alto limestones, in spite of their separation from the latter by an interposed porphyritic intrusion, and in spite of the discordance in their direction of strike, a feature which Semmes and Berkey thought indicated their unconformable position beneath the rocks to the north and northeast.[46] The name "Aguas Buenas" must, therefore, be placed in synonymy.

[43] Hill, R. T.: personal communication.
[44] Hodge, E. T.: op. cit., p. 135.
[45] Berkey, C. P.: Introduction to the geology of Porto Rico, op. cit., pp. 17-18.
[46] Ante, pp. 231-232.

The "Juan Ascencio Chert Beds" near Aguas Buenas were also named by Semmes. As stated in the preceding section,[47] the material in these strata is laumontite rather than some form of silica, and, according to R. J. Colony, the rock was probably derived from beds of calcareous tuff by alteration, perhaps of the hydrothermal type, like that postulated by Hodge for two comparable rocks found in the south-central part of the island.[48] Notwithstanding the fact that the Juan Ascencio beds did not originate as Semmes believed, the name is still a useful appellation for the banded strata to which he gave it, and it will be retained in the present report. So little is known about the lateral and vertical extent of the beds, however, that it seems safer to treat them as one of the members within the associated and genetically related calcareous tuffs and ash beds, rather than as a distinct formational unit, at least until more information concerning them is obtained.

The name "Collores limestone" was given by Fettke to the two bands of limestone that outcrop in the magnetite belt east of Juncos.[49] He believed that both bands are parts of the same formation exposed on opposite limbs of a synclinal fold, but the two are lithologically different and bear more striking resemblances respectively to the La Muda and Trujillo Alto limestones than they do to each other. The indeterminate character of the structure in the magnetite belt makes it necessary to attach greater significance to the physical differences in the two beds, and in the present report they will be regarded as separate formations. Provisional correlation with the La Muda and Trujillo Alto limestone is made on the grounds that the lithologic similarities are definite, and that these two formations are the only persistent calcareous beds in the eastern part of the island. The names "La Muda" and "Trujillo Alto" will be used for the Collores limestones, therefore, although the isolation of this narrow belt of sediments makes complete verification of the writers' opinion difficult, if not impossible.

In his report on the geology of the Coamo-Guayama district, Hodge has divided the Cretaceous rocks into seven more or less arbitrary "series," in each of which he has endeavored to group genetically related materials. The tendency to restrict the word "series" to the complete sequence of sediments accumulated in a single geological epoch makes its employment for the indefinite lithologic divisions in Porto Rico inappropriate, because the latter reflect fluctuations in the vigor of volcanic activity

[47] Ante, p. 234.
[48] Hodge, E. T.: op. cit., pp. 208-209.
[49] Ante, pp. 236-238.

rather than progressive changes in life and environment during well marked divisions of geologic time. In a rock succession characterized by rapid alternation of hydroclastic, pyroclastic, and pyrogenic elements, moreover, any grouping is likely to have severely limited application, and it is significant in this connection that neither Mitchell nor Fettke saw fit to extend the "series" of the Coamo-Guayama district into the contiguous areas to the west and east. The validity of Hodges' stratigraphic succession may also be questioned on more serious grounds. He has assumed that successively younger beds are exposed from north to south across the Coamo-Guayama district; but Mitchell's studies in the adjacent Ponce district show that the structure of southern Porto Rico involves a series of folds, in which the strata are repeated several times. Hodge has given little information concerning the structure, and it is difficult to reconcile the few statements he has made with the superposition of beds he has assumed in dealing with the stratigraphy. Until the nature of the structure is determined with some degree of finality, it seems unsafe, therefore, to accept the succession which Hodge has proposed, for it is probable that some of its parts are equivalent.

Of the seven lithologic divisions differentiated in the Coamo-Guayama district, the two oldest, at least, extend into the Fajardo district. The basal division, the Rio de la Plata, consists chiefly of massive tuffs, whereas the overlying Barranquitas-Cayey series is composed predominantly of sediments. Both are mixed lithologic series rather than simple formational units, however, and, as Hodge indicates, the contact between them is intergraditional and rather vague in character. To employ these indefinite group names for any of the clearly defined formational subdivisions which can be recognized in the Fajardo district would inevitably create confusion in what is otherwise an orderly and differentiable sequence. In the present work, therefore, Hodge's names for the stratigraphic divisions of the Coamo-Guayama district which extend into the Fajardo district will not be accorded recognition, because there is no point in utilizing broad group terms based on questioned structural interpretations, when definite formational names can be applied.

Recently C. J. Maury has proposed the following stratigraphic succession for the "Older Series" in Porto Rico:[50]

Upper Eocene: Rio Descalabrados and La Muda deposits
Middle Eocene: Rio Jueyes beds

[50] Maury, C. J.: Porto Rican and Dominican stratigraphy. Science, N. S., 1929, Vol. LXX, p. 609. See also, Science, N. S., Vol. LXXII, 1930, p. 254.

Upper Cretaceous: San German deposits, Ensenada shale, Fajardo and Cape San Juan limestones
Lower Cretaceous (?): Limestone south of Cidra

For the most part the sequence suggested utilizes formational names that are already in use for strata in the several districts, although it erroneously refers to the Fajardo shales as limestones. It introduces one new term for a lithologic unit in the Fajardo district; namely, the "Cape San Juan limestones." This designation cannot be accepted for the rocks of the Cape San Juan region because, in the first place, they are not limestones, and, in the second, the name "San Juan" is already in use for the Quaternary dune sands of the north coast.[51] Based upon the work of Berkey, Semmes, Hodge, Mitchell, and Vaughan, the stratigraphic succession proposed by Maury is vitiated by the lack of correlation among their several studies. The limestone south of Cidra is equivalent to the La Muda, and both lie stratigraphically below the Fajardo shales. Mitchell has shown that Hodge's Rio Jueyes and Rio Descalabrados series are not simply superposed members of the rock succession, but that they comprise the same closely folded formations. His discovery of Cretaceous fossils in the limestone strata, moreover, indicates the need of caution in assigning them to the Middle and Upper Eocene.

*The stratigraphic sequence*

The writers approach the task of offering a geologic column for northeastern Porto Rico with some hesitation. Although the earlier studies of the Scientific Survey imply that this area contains the most ancient members of the "Older Series," the rock system has no base in the true sense of that word. The younger Cretaceous formations, moreover, have been eroded; hence the succession presented is but a slice from the middle. Its exact place in the entire system cannot be determined until the whole of the "Older Series" in Porto Rico has been resolved into an orderly sequence of superposed or graditional and interfingering units. The only defense that can be offered for publishing a new table of formations at this time rests upon the fact that the data obtained within the limited area of the Fajardo district make it possible to place part of the Cretaceous system in order. The chaotic condition which exists as a result of the contradictions and lack of correlation among the earlier studies is evident

[51] Meyerhoff, H. A.: The pre-Oligocene stratigraphy of Porto Rico. Science, N. S., 1930, Vol. LXXI. pp. 322-323.

from Maury's attempt to construct a much needed stratigraphic section from them. As the foregoing discussion has shown, Berkey gave names to several lithologic units whose relative positions were unknown; Semmes and Fettke duplicated his work to some extent but did not fill in the gaps which Berkey left for the more detailed district surveys; Hodge presented a stratigraphic column composed of generalized units, but based it upon too simple a view of the geologic structure; his stratigraphic conclusions are contradicted both by Mitchell and by Semmes.

The determination of the structural relationships of the rocks along the western border of the Fajardo district has made it possible not only to fix the positions of the formations which Berkey segregated, but also to differentiate the associated rocks into definite formations. The entire section has been correlated throughout the Fajardo district and has been traced into the immediately adjoining areas, and some of the discrepancies in earlier reports have been settled. Obviously the section given in the accompanying table and discussed in the following pages will need revision and correction when correlation can be extended still farther west, for some of the strata may prove equivalent to formations in other parts of the island which have already been named. It is not likely that the succession will apply in every part of Porto Rico. In fact, the geologic sections at opposite ends of the Fajardo district are not identical, as the restored section (Fig. 16) shows, and it is to be expected that lateral changes of as great magnitude take place westward. The sequence proposed, therefore, does not purport to be regional in application, for its utility has not been tested outside the northeastern portion of the island.

## THE CRETACEOUS FORMATIONS

### *The Guzman formation*

The oldest rocks exposed in the Fajardo district have been named from their occurrence in the western part of Barrio Guzman Abajo, where they outcrop along Rio Canovanas about nine kilometers south of the village of Canovanas. They embrace an imperfectly understood series of slate-blue calcareous shales and tuffaceous limestones, massive tuffs, volcanic breccias, and andesite flows. Their differentiation as a formation distinct from the overlying Hato Puerco tuffs is based upon their stratification and upon the presence of calcareous members, for these features indicate circumstances of genesis that contrast with those under which the superimposed tuffs were formed. The Hato Puerco tuffs rest upon the calcareous

TABLE OF THE CRETACEOUS FORMATIONS IN NORTHEASTERN PORTO RICO

| Formational name | Estimated thickness (in feet) | Lithologic characteristics | Synonyms | Possible equivalents |
|---|---|---|---|---|
| San Diego formation | 600+ (top not present) | Interstratified ashy shales, tuffaceous sandstones, and fine-grained conglomerates, with intercalated sills of andesite and andesite porphyry | Cape San Juan limestones (Maury) | |
| Fajardo shales | 750–1000 | Ashy shales, somewhat calcareous in composition, buff to black, or slate-blue in color | | Comerio ash beds and tuffs (Berkey)<br>Mayagüez shales (Berkey) |
| Juan Ascencio member | | Strongly banded hematitic strata, probably derived from calcareous tuffs by hydrothermal alteration | | |
| Figuera formation | 0–500 | Andesite flows at or near the top of the Luquillo formation in the southeastern part of the district | | |
| Trujillo Alto limestone | 0– 200 | Dark gray to slate-blue shaly and tuffaceous limestone, merging northeastward with the calcareous tuffs of the Luquillo formation | Upper member of the Aguas Buenas limestones (Semmes)<br>Upper member of the Collores limestones (Fettke) | Barranquitas shaly limestones (Berkey) |

| | | | | |
|---|---|---|---|---|
| Luquillo formation | 2500 ± | Interbedded calcareous and non-calcareous stratified tuff, with thin intercalated flows and sills. Textural and compositional range wide | | Barranquitas-Cayey and Rio de la Plata series (in part) (Hodge) |
| Rio conglomerate | 0– 500 | A coarse, massive, tuffaceous conglomerate or agglomerate | | |
| La Muda limestone | 0– 300 | Light gray to white cavernous limestone, which appears to end by overlap northeastward | Lower member of the Aguas Buenas limestones (Semmes)<br>Lower member of the Collores limestone (Fettke) | Barranquitas-Cayey and Rio de la Plata series (in part) (Hodge) |
| Guaynabo formation | 0–1000 | Undifferentiated section of calcilutytes, ashy shales, tuffaceous sandstones, and conglomerates, which outcrop along the western border of the district but thin and disappear eastward by overlap or by gradation into the massive tuffs of the Hato Puerco formation | | |
| Hato Puerco tuffs | 3000–5000 | Massive, unstratified tuffs, agglomerates, and flows intruded extensively by andesite porphyries | | Sierra de Cayey tuffs (of Berkey, not Sierra de Cayey series of Hodge)<br>Rio de la Plata series (in part) (Hodge) |
| Guzman formation | 300+ | Undifferentiated breccias and tuffs, with blue-gray calcareous shales at the top. Basal position not fully confirmed | | |

shales of the Guzman formation directly, and evidence of a disconformity is absent; but the change from conditions favoring the accumulation of pyrogenic, pyroclastic, and hydroclastic materials in shallow water, to those favoring extremely rapid subaërial deposition of ill-assorted explosive products may well have involved a temporary break in deposition, even if erosion did not intervene.

The stratigraphic position of the Guzman formation has been determined from its situation at the crest of the pitching anticline which underlies the northern slopes and foothills of the Luquillo Mountains. In consequence of its structural position the strata composing it have low dips, which undulate gently in the exposures along the carretera that follows the valley of Rio Canovanas. Comparatively little of the formation is exposed, for both to the north and to the south it passes beneath the overlying tuffs, which are cut off southward within a short distance by an extensive intrusion of andesite porphyry. The areal extent of the Guzman formation is unknown. The limits shown on the geologic map can lay no claim to accuracy, for the ruggedness of the country, the absence of roads and the scarcity of trails proved insurmountable obstacles in the efforts to trace it toward the east. It has been projected as far as El Yunque partly on the basis of the geologic structure, the details of which are none too certain, and partly on the strength of a brecciated limestone which outcrops high on the northern flank of El Yunque. There fragments of gray, coarsely crystalline limestone are embedded in an andesitic sill or flow. Although the limestone bears little or no determinable relationship to the darker calcareous sediments in the Rio Canovanas valley, it has no demonstrable affinity with the two higher limestone members in the stratigraphic section,[52] both of which appear to be absent in the northeastern part of the district. A correlation made on as flimsy evidence as this, how-

[52] In making this statement the authors disregard a resemblance which appears in microscopic sections among the limestone fragments of the El Yunque breccia, one of the zones in the La Muda limestone, and a bed of limestone in the Barranquitas-Cayey series (cf. Hodge, op. cit., pp. 134-135). These three rocks are composed of rolled and abraded particles, many of them consisting of small fossils, cemented in a recrystallized calcium carbonate matrix. This mutual resemblance may prove more important than the writers believe, but the feature appears to be local in its development and is not one that can be used safely in regional correlation. The other zones in the La Muda limestone, for instance, are genetically different, and on the basis of physical characteristics exhibited in thin sections might easily be thought to belong to a different formation. The coincidental occurrence of limestone and volcanic brecciation, and the structural position of the breccia on El Yunque are features which relate this and the associated beds with the Guzman formation, and which appear to be of greater significance than an accidental resemblance to other strata.

ever, is worth little, and the Guzman formation needs more careful field study before it can be accurately mapped and adequately defined; or before the possibility of its correlation with younger beds in the section can be entirely eliminated.

In Barrio Guzman Abajo the lithologic characteristics of the formation are distinctive. Massive andesitic breccias predominate and are characterized under the microscope by pronounced flow structure in a cryptocrystalline matrix, which is but rarely interrupted by phenocrysts of plagioclase feldspar. The included fragments are invariably volcanic. Alteration processes have involved the development of chlorite, epidote, and zoisite, and the rocks are considerably indurated by introduced quartz. Secondary calcite is so abundant in the fracture planes and pore spaces that in the field some of the thinner layers were mistakenly called limestone breccia. Clearly the secondary calcite was derived from the intimately associated tuffaceous limestones and calcareous shales. The latter vary from medium-bedded to thinly stratified blue-gray rocks, all of which have undergone extensive recrystallization and induration. In relative abundance and importance they are second only to the breccias. Non-calcareous tuffs occur, but in Barrio Guzman Abajo they comprise but a minor portion of the section, whereas andesite flows, containing large amygdules rimmed with chlorite and filled with calcite, occupy a somewhat more conspicuous place. In the type locality the Guzman formation has escaped extensive intrusion, but it is penetrated by a small number of porphyry dikes.

The outcrops along Rio Canovanas do not constitute an ideal type section, because the base of the formation is not revealed and only the upper 300 to 400 feet are exposed. Whether a more satisfactory section is to be found elsewhere in Porto Rico is unknown. It is possible that the formation outcrops near the border of the San Juan and Coamo-Guayama districts along the axis of the anticline which brings the Rio de la Plata "series" to the surface; but Hodge's account of the geology of this area contains no mention of rocks that can be correlated with it. Unless the genetic conditions which gave it its distinctive characteristics changed laterally at the time of origin, it can be easily recognized from its stratified calcareous members and its brecciation. Apparently the anticline near the headwaters of Rio de la Plata has not been eroded deeply enough to bring it to the surface, and there is no information available on which its occurrence in the western half of the island can be postulated.

*The Hato Puerco tuffs*

Approximately half of the rocks of the Cretaceous section in the Fajardo district consist of massive tuffs, in which there is practically no vestige of structure, except in one thin member of bedded ash exposed in the valley of Rio Grande de Loiza, two miles due south of Trujillo Alto. In the northwestern part of the district, however, the upper portion of the formation contains an increasing number of crudely stratified layers, which grade vertically into the overlying Guaynabo formation; and the fact that the latter thins eastward and finally disappears south of Trujillo Bajo, whereas the massive tuffs thicken, indicates the probability of lateral gradation as well. Southwestward the massive tuffs can be traced into the Rio de la Plata series of the Coamo-Guayama district, but they form only part of the latter, in which Hodge has also included some of the overlying stratified rocks. In the accompanying table it has been suggested that the massive tuffs of the Fajardo district may be equivalent to those which Berkey described and named from their occurrence in the Sierra de Cayey between Guayama and Cayey,[53] but this conjecture can be substantiated only by additional field work of a structural character. Until the rocks of the two localities are proven to be identical, it seems necessary to propose a provisional formation name which will include the unstratified tuffs which lie between the Guzman formation and the Guaynabo formation in the western part of the Fajardo district and in the northeastern corner of the Coamo-Guayama district; and between the Guzman and Luquillo formations nearer the eastern end of the island. The tuffs outcrop throughout such a large part of the Fajardo district that many satisfactory type localities are available. Barrio Hato Puerco, situated on Rio Canovanillas midway between Barrio Guzman Abajo and Trujillo Bajo, has been chosen because here the formation attains what is believed to be its maximum development, and because its base and top are exposed or can be very closely approximated. The Guaynabo formation is either thin or absent, and the Hato Puerco tuffs give way abruptly to the overlying sedimentary series. The estimate of thickness which has been given is at best a rough one, based on the width of outcrop and the dips of the subjacent and superjacent strata, with a conservative allowance for duplication by faulting. Even in those few places where the dips of the

[53] Berkey, C. P.: Geologic reconnoissance of Porto Rico, op. cit., pp. 25 and 61.
Unfortunately the name "Sierra de Cayey" was later used by Hodge for a thick conglomerate which appears not to have been embraced in the formation differentiated by Berkey.

associated rocks are steep, the Hato Puerco tuffs outcrop in a band considerably more than one mile wide; hence, the maximum figure of 5000 feet ascribed to the formation seems neither too little nor too much, although the great areal development which the tuffs attain gives an impression of a much greater thickness.

The competence of the formation under lateral compression is everywhere apparent, for major fractures are far more abundant than in any other lithologic unit in northeastern Porto Rico. Some fractures have been filled by dikes; others show from associated slickensides the effects of displacement, although the simple character of the faults implies that the amount of movement was not great in any single case.

The rocks comprising the formation have been called tuffs, and certainly the monotony of the deep, reddish residual soils or of the scattered gray-green outcrops gives an impression of the lithologic homogeneity which a single descriptive name implies. But the impression is completely dispelled by the microscope. Perhaps four-fifths of the formation consist of tuff, which ranges in texture from ashy to agglomeratic. The large fragments in the coarser varieties are invariably volcanic in character but were obviously derived from several distinct sources. They include glass, felsites, and porphyries of several kinds, but the majority of the pieces consist of andesite porphyries of different textures and compositions. In many parts of the formation the pieces are angular, but in others definite rounding may be noted, and some outcrops were described in the field as conglomeratic. In the medium and fine-grained horizons the determinable fragments usually consist of crystal grains, of which altered plagioclase feldspars are the commonest. Among the components that are conspicuously absent from the assemblage of explosive materials are bombs, lapilli, and other ejectamenta that result from the subaërial consolidation of molten matter. The few glass fragments identified appear to have been secondarily derived. It is quite possible that a more thorough search and a more careful selection of specimens will reveal some primary fragments; for in a formation as prevailingly pyroclastic as the Hato Puerco tuffs, a considerable amount of this kind of material is to be expected. Its scarcity, or absence, raises a question whether the formation represents an old volcano, or whether the whole was formed by the accumulation of fragments transported fluvially from a nearby highland composed of diverse volcanic rocks. The angularity of so much of the material casts some doubt on the second possibility, but in itself does not constitute conclusive evidence in favor of the first. In any case, the

included fragments offer a means of surmising some features of the pre-Hato Puercan history of the region. Although the earlier development need not have been geologically long, it was exclusively volcanic, and the extrusive activity was essentially of the same type as that which occurred in Guzman and Hato Puerco times. An epoch or period antedating volcanism cannot be envisioned from any of the second-hand evidence supplied by the rocks represented in the Hato Puerco tuffs.

The remaining fifth of the formation comprises volcanic flows. Perhaps some sills are present, for not a little of the volcanic material is massive and porphyritic; some porphyry intrudes the tuffs as dikes, but much of it cannot be oriented with respect to structural lines, and its original form is unknown. The proportion of volcanic rocks mentioned above is not claimed to be mathematically accurate, for the amount of flow material present varies greatly from place to place and in some localities makes up a larger percentage of the whole. Furthermore, alteration and weathering have so changed the appearance of the volcanics that without careful microscopic analysis it is difficult to distinguish them from the tuffs; and a final opinion regarding the pyroclastic or pyrogenic origin of a small number of specimens has not been reached even by microscopic study. The greater number of the flows consists of amygdaloidal or vesicular andesites that exhibit a moderate compositional range, chiefly in a subsilicic direction, for several augite andesites and a few basalts have been identified. Alteration has been extensive and was dominated as a rule by the process of chloritization, some of the specimens having been changed almost completely to that mineral. In a moderate number of the rocks flowage lines are apparent not only in thin-section but also in outcrops, and when visible in the exposures of the formation, they furnish one of the few clues to its structure.

The great thickness of the formation and its occurrence in the broad anticlinal structures which underlie so large a part of the Fajardo district combine to make the outcrops of the Hato Puerco tuffs very extensive. Massive tuffs underlie nearly all of the hill section east of Rio Grande de Loiza, and from this central area they follow the crests of the anticlines to the northeast toward Cape San Juan, to the east into the Luquillo Mountains, to the west-southwest beyond Aguas Buenas into the Coamo-Guayama district, to the northwest as far as Barrio Cupey. In the last direction the steep pitch of the structure and the gradation of the tuffs into the Guaynabo formation cause them to disappear beneath younger formations within a relatively short distance. They also occur in the hills south of the Caguas basin. Despite a moderate amount of

induration, the formation is deeply weathered, partly in consequence of long exposure, partly as a result of the alteration which took place during the later igneous history of the island. The brick-red soils which its rocks yield are more characteristic than its gray-green outcrops in the large areas over which it is exposed; but in the fresh rock surfaces, which may be found along the streams and in a few road cuts, its unrelieved massiveness is its most diagnostic property; for in no other formation in the district is evidence of resorting and stratification so completely absent.

*The Guaynabo formation*

The name "Guaynabo" is proposed for the succession of sediments which lie below the La Muda limestone and above the Hato Puerco tuffs in the northwestern part of the Fajardo district. The town of Guaynabo lies near the southwestern edge of the broad formational outcrop, which extends beyond the limits of the district to Bayamon, where the sediments lose their identity in the deep residual soils. The formation thins rapidly southward and somewhat more gradually eastward, where a slender wedge of it may be identified as far as the camino from Carolina to Gurabo. Along the carretera south from Canovanas, four miles farther east, it was not found.

The thinning and disappearance of the Guaynabo formation may be interpreted in one of two ways: either it rests disconformably, or unconformably, upon the Hato Puerco tuffs, against which it ends eastward by overlap; or, it grades laterally into the massive tuffs by replacing overlap. The problem of interformational relationship was not appreciated when the field studies were made, and data on which a choice between the alternatives might be based were not collected. Coarse water-worked pyroclastic sediments are numerous enough throughout the Guaynabo section to suggest a close genetic relation with the Hato Puerco, but not necessarily a contemporaneous origin. The abundance of stratified ash, ashy shales, and bedded tuffs suggests that the northwestern corner of the district lay on the periphery of an eruptive center, where the explosive products were smaller, save during short sporadic outbursts, and where the fragments were sorted and rounded in shallow marine waters as they fell. The volcanic center appears to have been situated toward the southeast and may have been located in the area of andesite porphyry between Barrio Guzman Abajo and Juncos. Many of the features of the Guaynabo formation foster the view that its deposition was modified and controlled by its proximity to a large volcanic

cluster, but the view must seek its support from too many untested assumptions. Until the field relationships of the Hato Puerco tuffs are studied more critically, there is little to be gained by discussing the hypothesis at greater length.

Lithologically the Guaynabo formation is more heterogeneous than any of the other sedimentary units in the district. In the exposures along the carretera from San Juan to Caguas by way of Guaynabo, and along the old military road between Rio Piedras and La Muda, no one rock type can be said to dominate. Beds of ash, tuff, and shale, ranging from buff to dark gray and green in color, increase in relative abundance northward, but in the central and southern outcrops, beds of coarser material are numerous. Interstratified with the tuffaceous sandstone, ashy shales, and agglomerates are some calcareous shales and shaly limestones. A more discriminating field analysis may resolve the formation into several members, possibly into separate formations; for notwithstanding the marked vertical and lateral changes that occur, there are zones in which one sedimentary type is predominant. The authors' collections and field notes are not adequate to the task of subdivision, however, and it will not be attempted. The stratification of the materials, their position beneath the La Muda limestone and above the unstratified Hato Puerco tuffs, and their gradational or overlap relationship to the latter imply sufficient kinship among the many lithologic types for inclusion in a single formation in the present report.

*The La Muda limestone*

The name "La Muda" was proposed by Berkey [54] for "a rather heavy development of limestone in the vicinity of La Muda." He described the rock as having a coarse fragmental structure almost completely obscured by healing, and he noted also the cavernous character of its outcrops. Berkey was not aware of the presence of two limestone formations in the vicinity of La Muda, but his brief description applies more fully to the calcareous bed situated one mile north of the village than to the shaly, or tuffaceous, strata situated to the south. The latter have been correlated with the Trujillo Alto limestone, and the name "La Muda" will therefore be used for the more northerly of the two calcareous beds. Semmes likewise restricted the use of the term to the light gray crystalline limestone which he found a short distance south of Guaynabo and traced northwestward toward Bayamon, where it becomes undifferentiable in the deep residual soils; but in the type locality he failed to discover

[54] Berkey, C. P.: op. cit., p. 22.

the corresponding limestone and erroneously applied the name to the higher Trujillo Alto. As the structural studies presented in the preceding section have shown, the La Muda limestone is to be correlated with the cavernous limestone which outcrops prominently along the track of the Porto Rico Railway, Light, and Power Company between Rio Piedras and Trujillo Alto (Fig. 7); with the cavernous member of the Aguas Buenas limestones, which were differentiated by Semmes;[55] and with one of the two limestones south of Cidra. On the basis of physical characteristics, the authors have also suggested its equivalence with the more southerly of the two limestones in the magnetite belt east of Juncos.

The La Muda formation is exposed in relatively narrow bands on the limbs of the several folds which furrow the western part of the Fajardo district. It measures from 275 to 300 feet in thickness at several widely scattered localities, and the constancy of these figures implies that the irregularities which have been observed within the strata, as well as the discontinuity noted in some of its outcrops, are secondary features that have developed since its deposition. In the outcrops near La Muda and south of Aguas Buenas, as well as in those east of Juncos, it is severed by intrusives. In these and other localities the extensive solution of the calcium carbonate has led to slumping in the overlying pyroclastic material, which now fills many of the older caves. Obscured by weathering, features of this kind may too easily be interpreted as evidence of lateral variation; but the purity of the formation, which in hand specimen and in thin-section reveals no pyroclastic content, makes such an interpretation untenable. On the other hand, the limestone disappears at some point east of Rio Grande de Loiza, and projection suggests that it ends either unconformably or by replacing overlap against the Hato Puerco tuffs. Its lateral passage into massive fragmental rocks, as well as the presence of tuffaceous beds beneath it and of a thick pyroclastic conglomerate immediately above it, makes its purity all the more remarkable. It seems to have been formed during an exceptionally long lull in the volcanic activity of the time.

It is a highly fossiliferous formation, in which the megascopic forms have been less commonly preserved than the smaller types, for the latter, with fragments of larger fossils, make up the chief constituents of many of the beds. In one of the zones the fossils have been worn and rounded, and under the microscope the rock looks not unlike the much younger San Juan formation; but the greater part of the formation contains algæ, Foraminifera, Radiolaria, and other organic types, some of which

[55] Ante, pp. 234-236.

have been broken but not rounded. The organic remains are set in a calcareous matrix which has undergone thorough recrystallization, and locally the fossils, too, have been destroyed by recrystallization. In the outcrops east of Juncos extensive metamorphism and replacement have taken place where the limestone comes in contact with intrusives, and here the rock consists of an aggregate of calcite, garnet, chlorite, quartz, and pyroxene, with occasional crystals or crystalline masses of magnetite and hematite.[56]

One of the most striking traits of the La Muda limestone is its susceptibility to solution. In its outcrops along the railroad between Rio Piedras and Trujillo Alto large and extensive caverns have been opened up within it, and the caves which occur in it south and southwest of Aguas Buenas are well known among the caverns of Porto Rico.[57] Partly filled caverns are also present at the type locality. The recurrence of this striking erosional habit, combined with the formation's comparatively constant lithologic characteristics, make the La Muda limestone an ideal key horizon in the western part of the Fajardo district and in the adjacent portions of the San Juan and Coamo-Guayama districts. It has no counterpart in the eastern part of the Fajardo region, where presumably the horizon is represented by some of the higher members of the Hato Puerco tuffs, unless the fragments in the flow breccias on El Yunque belong to this formation instead of the older Guzman.

*The Rio conglomerate*

In all the localities where the La Muda limestone has been identified, except in Barrio Collores in the eastern part of the Caguas lowland, it is succeeded by relatively massive beds of conglomerate. Berkey was under the impression that the conglomerate lies stratigraphically beneath the limestone at the type locality, but his interpretation of the relative positions of the two formations is at odds with their physiographic expression. The resistant conglomerate stands as a prominent linear ridge which crosses the Rio Piedras-Caguas highway at the northern limits of La Muda, presenting a steep scarp toward the northeast and a comparatively gentle slope toward the southwest. The scarp is erosional in character and cuts across the beds, whereas the gentler southwestern slope appears to be the dip-slope. The La Muda limestone emerges from beneath the erosional cliff on the northeastern side of the ridge.

[56] Cf. Fettke, C. R.: Magnetite deposits of eastern Porto Rico, op. cit., p. 1028.

[57] Dinwiddie, W.: The great caves of Puerto Rico. Harper's Weekly, March, 1899, Vol. XLIII, p. 293.

The southerly dip of the two members can be seen and measured in their exposures along the San Juan-La Muda carretera, immediately south of the village of Guaynabo, where the limestone is succeeded by a well exposed section of the conglomerate, which outcrops continuously for nearly two kilometers along the road. In this area the formation appears to be very thick, and it is perhaps of greater thickness than the 500 feet which have been assigned to it in the table; but the impression obtained may err because of the fact that the strike of the beds cuts the road at a low angle, and the dips are gentle and undulating. The conglomerate is also associated with the La Muda limestone near Aguas Buenas and along the railroad west of Trujillo Alto, but in Barrio Collores intrusion and metamorphism have occurred so extensively that a corresponding horizon was not differentiated. Its persistence in the other localities where the La Muda is found entitles it to recognition as a separate member of the stratigraphic section. Some difficulty has been experienced in selecting a formational name for it, because its narrow outcrops form linear ridges that have not been conducive to the development of settlements upon them. The name "La Muda" would be most appropriate, but it cannot be used; hence Barrio Rio, a small community situated about one mile southeast of La Muda, has been chosen as the type locality.

The rocks of which the formation is composed are coarse in texture, but not uniformly so. Some of the beds consist very largely of boulders, usually of andesite porphyry, embedded in a tuffaceous matrix; in other strata the tuffaceous matrix is the dominant feature, and the boulders are small and scattered; a few layers are almost wholly tuffaceous. The Rio conglomerate is stratified throughout, although some of the individual beds are very thick; and its marine origin is indicated by the minute fragments of fossils it contains. In its stratification and in the rounding of the constituent fragments it can be readily distinguished from the coarser horizons of the Hato Puerco tuffs, and it is to be differentiated from the coarse-textured strata in the Guaynabo formation by reason of its greater thickness and the persistence of its conglomeratic characteristics. Like the Guaynabo and La Muda formations, it passes westward into the Hato Puerco tuffs, or ends unconformably against them.

*The Luquillo formation*

The Rio conglomerate is succeeded by a thick section of stratified tuffs and tuffaceous shales which are characteristically calcareous. They con-

stitute a formation which is one of the most persistent in northeastern Porto Rico, and its outcrops cover large areas in many localities. In the western part of the Fajardo district both the upper and lower limits of the tuffaceous beds are clearly defined, and here they form an easily distinguishable unit in the stratigraphic section. Along the Trujillo Alto carretera the formation is exposed from top to bottom, but deep weathering makes a careful study and analysis of its characteristics impossible. In most of its outcrops, in fact, it displays the trait of non-

FIG. 17.—*The Luquillo formation*
An exposure of the stratified calcareous tuffs at the type locality.

resistance, and in many places has been carved into a subsequent lowland or valley by local streams. Because of the weathering and erosion it has undergone in most inland regions, it has been named, not from any of the areas in the western part of the Fajardo district, but from the town of Luquillo, where it forms low but prominent cliffs both along the shoreline and along the banks of Rio Sabana near its mouth (Fig. 17). In this region the Rio conglomerate, the La Muda limestone and the Guaynabo formation are absent, and the stratified Luquillo tuffs rest directly upon the massive Hato Puerco tuffs. Because of the depth of weathering it is difficult to determine the exact position of the contact between the two formations, but the change from the massive non-calcareous pyroclastics to the stratified calcareous beds can be detected within

a short distance by the slight yet significant changes in the topography, soils, and outcrops. Luquillo and its environs do not furnish an ideal type section, because the upper part of the formation has been destroyed by fluvial and marine erosion. On the other hand, the freshness of all but the basal outcrops and the clarity of the geologic structure make it possible to learn more about the strata than can be learned elsewhere; and the prominence which these calcareous tuffs attain along the northern margin of Cretaceous rocks furnishes another reason for selecting a formational name from a town within this belt.

From the type locality the Luquillo formation extends in a continuous band southeastward almost to Fajardo and thence southward along the east coast. A synclinal prong carries it far into the Luquillo Mountains, but elsewhere the bedded tuffs occupy a position in the eastern foothill belt. They are also present near the southern margin of the district, but here the outcrops are discontinuous, and their textural and compositional features are profoundly modified by contact metamorphism. Except in the central range of the Luquillo Mountains and in the vicinity of La Muda, where synclinal structures carry the beds into the district, the Luquillo formation serves as a jagged frame for the older deposits which have been described above. It encloses the underlying Cretaceous rocks so completely, that the younger formations in the "Older Series" have succeeded in retaining a place within the district borders in very few localities. In the west the evenness of the outcrop bands indicates a constant thickness, which has been estimated with a fair degree of accuracy at 2500 feet. In the east, too, its thickness seems to undergo little, if any, change, notwithstanding the tendency of all the underlying members to thin and disappear in this direction. The relation of the Luquillo sediments to the Hato Puerco tuffs suggests that its deposition occurred when the rapid accumulation of the continental pyroclastic rocks ceased, and that it was formed by the sorting and redistribution of the finer materials in the highest portions of that massive series of explosive products. The relative quiescence which existed throughout Luquillo time is attested by the abundance of calcareous material in the strata. The calcium carbonate, although somewhat irregularly distributed, increases in the higher beds and culminates in the Trujillo Alto limestone, which forms the top. The calcium carbonate content also increases laterally to the west, away from the Hato Puercan mass, which seems to have served as the source for the clastic material in the Luquillo formation.

Petrographic study reveals a moderate range in texture and composition among the members of the formation. Some of the beds are massive and coarsely tuffaceous, but a much larger proportion of the strata exhibits an arenaceous texture, and in thickness the individual beds range from a fraction of an inch to one or two feet. In both the coarse and medium-grained layers, the individual particles consist almost wholly of rounded volcanic fragments, chiefly of andesite and andesite porphyry, with minor amounts of glassy lava and pumice. Some of the beds in the middle of the formation and many of those toward the top are shaly in texture and tuffaceous, ashy, and calcareous in composition. The original calcium carbonate content of the individual beds varies in quantity in inverse proportion to the grain-size. Commonly it is present in the form of microscopic organic remains, especially Foraminifera. In the shales it also consists of finely comminuted shell fragments, in which all semblance to specific forms of life has been lost. Secondary calcite has been introduced into both the calcareous and non-calcareous layers; but, as the latter contain a large amount of interstitial pore space, the secondary calcite is usually more conspicuous in them. The abundance of marine life at the time these tuffs were deposited is further indicated by the dark gray or slate-blue colors of the fine-grained beds; in the coarser beds, as might be expected, organic material was less often preserved, and these rocks have the characteristic greenish hue that is imparted to them by the volcanic fragments.

Calcareous tuffs have been described from many parts of Porto Rico, and at present it is difficult to correlate those reported in localities outside the Fajardo district with the Luquillo formation. In the present survey the formation has been traced for a short distance into the San Juan district, where it forms a broad band paralleling the outcrops of the La Muda limestone as far as Bayamon. It has also been followed across the southeastern corner of the San Juan district into the northern part of the Coamo-Guayama district, where it forms part of Hodge's Barranquitas-Cayey series, and perhaps a small portion of the Rio de la Plata series. It seems probable that the Luquillo formation is partly or wholly equivalent to the Barranquitas shaly limestones of Berkey, and if future field work should prove these two formations to be correlates, it will be necessary to discard the name "Luquillo" for the prior name "Barranquitas," which was given by Berkey in 1915. Correlation of the Luquillo with the calcareous tuffs described in the districts still farther west is not yet possible.

*The Trujillo Alto limestone*

Berkey gave this name to the dense bluish limestone which outcrops on the carretera about one mile north of the settlement of Trujillo Alto. He did not know that the formation is present also a short distance south of La Muda, where its outcrops are nearer the village than those of the La Muda limestone. Because of the geographic relation of these two limestones to the localities from which their names were derived, there is some danger of confusing them, but their physical characteristics are so entirely distinct that there is little risk of mixing them once they are differentiated. The Trujillo Alto limestone is invariably dark in color, the La Muda light; the former is visibly tuffaceous, the latter chemically and mineralogically pure; the former displays few effects of the solvent action of ground water, whereas the La Muda limestone is perforated with caves and solution channels wherever its beds come to the surface.

The Trujillo Alto limestone grades downward into the calcareous tuffs and shales of the Luquillo formation, and in most places its lower beds are so extremely tuffaceous that it is impossible definitely to establish its base. The limestone is clearly a gradational phase of the Luquillo formation, representing the end point of the sedimentary cycle which started with the deposition of the Rio conglomerate. Because of its relation to the underlying rocks, the Trujillo Alto may be considered merely as a member of the Luquillo formation; but the formational status given it in the present report seems preferable in view of its distinctive lithologic characteristics and its geographic distribution, features which make it one of the most satisfactory stratigraphic horizons in the eastern two-thirds of the Fajardo district. From the type locality it may be traced westward toward Rio Piedras, although its identity is lost in the deep residual soils near the town. Eastward it extends at least as far as Canovanas, and it is probable that the calcareous beds exposed along Rio Sabana about one mile south of Luquillo are to be correlated with it (Fig. 9). It has not been found along any portion of the east coast, in spite of the fact that the calcareous tuffs and shales of the Luquillo formation occupy a conspicuous place in this area. In the southern part of the district it reappears as a short band truncated by igneous intrusives not far from the village of Torres (the Collores limestone of Fettke). Its exposures on both flanks of the plunging syncline at La Muda have been followed for short distances into the San Juan district and into the northeastern corner of the Coamo-Guayama district, where it may form one of the members of the Barranquitas shaly lime-

stones of Berkey (Barranquitas-Cayey series of Hodge). Its correlation with the latter, however, was not fully established.

The Trujillo Alto limestone seems to have attained its maximum development in the type section north of Trujillo Alto, where its exposures measure not more than 200 feet in thickness. In other parts of the district the gradation of its lower layers into the underlying calcareous shales and tuffs reduces the thickness of the limestone beds. Eastward along the north coast the thinning of the horizon is appreciable, and beyond Rio Sabana, as has been pointed out, it no longer acquires separate lithologic expression. In spite of slight variations, the physical characteristics of the formation are dependably constant. Normally, the beds are microfossiliferous, and Foraminifera, algæ, and Radiolaria have been identified within it. For the most part, it is a fine-grained, somewhat recrystallized lime-mud, or calcilutyte, in which the evenness of texture is occasionally broken by crystal fragments, including feldspar, augite, and other mineral grains from the associated volcanic rocks. Near Torres the fossils have been obliterated by contact metamorphism, and a suite of metamorphic minerals has been developed. In other parts of the district induration and partial recrystallization have occurred but have not obscured the primary features which the strata possessed.

*The Figuera formation*

Along the east coast in the vicinity of Ceiba a series of volcanic flows is intimately associated with the calcareous tuffs and shales of the Luquillo formation. From the distribution of the flows and their position with respect to the Fajardo shales, they appear to be intercalated with the higher strata of the Luquillo formation. They may, in fact, form the top, although they are succeeded by more tuffaceous layers, which seem to pass by insensible gradations into the basal portion of the Fajardo formation. The flows may, therefore, be regarded either as a local volcanic member of the Luquillo beds, or, if the same line of reasoning be followed as was used for the Trujillo Alto limestone, as a distinct formation. In the latter case the tuffaceous beds above them must be grouped with the Fajardo shales. The second alternative is adopted in this report, but the disappearance of the Trujillo Alto limestone in this region makes it impossible to determine whether the limestone and the flows occupy wholly analogous positions in the stratigraphic section.

The geographic extent of the extrusive rocks is unknown. Two parallel bands occur near Ceiba, one of them beginning at the east coast at Punta

Figuera, from which the formation has been named; the other extending from Puerto Medio Mundo into the interior for an undetermined distance. The more northerly of the two bands has been traced inland for a distance of four miles, but it has not been followed west of the valley of Rio Fajardo. The more southerly band has not been differentiated from the associated andesite porphyries west of the Fajardo-Humacao carretera, which it crosses one and a half miles south of Ceiba. A third occurrence of the volcanic flows was found near Playa de Naguabo, but its limits could not be determined.

The material comprising this formation has suffered intense alteration and deep weathering, yet in many of its greenish outcrops flow structure is clearly visible. A mile and a half north of Ceiba an isolated boulder resembling pitchstone or obsidian was discovered in association with the flows. Under the microscope the rock was found to be microcryptocrystalline, spherulitic, and amygdaloidal, with cavity fillings of hematite and a colorless mineral which has been tentatively identified as quartz. Although unlike the andesitic material that constitutes most of the Figuera formation, it appears to be genetically related. The more common andesite is fine-textured but entirely holocrystalline. Some of the individual flows are amygdaloidal, but many of them lack vesicular cavities; and the few scattered phenocrysts, usually of orthoclase feldspar, indicate a relatively narrow compositional range, varying between andesite and trachyte. Alteration has introduced large quantities of epidote and chlorite, and subordinate amounts of quartz and kaolin, into the rocks, and a few specimens contain serpentine. Weathering has converted the ferro-magnesian minerals partly or wholly to limonite, which colors many of the more deeply weathered exposures brown. In a few respects the Figuera flows resemble the extrusive rocks identified at several points within and marginal to the Caguas basin, and in a more detailed survey the possibility of their equivalence should be given careful study. In the western part of the district the Juan Ascencio member of the Fajardo formation occupies a stratigraphic position which is so nearly analogous to that of the Figuera flows that the two may prove to be related upon more thorough investigation. At present the scant evidence favoring the correlations suggested is not sufficient for the expression of a definite opinion.

### *The Fajardo shales*

The town of Fajardo is almost completely surrounded by low hills of buff-colored ashy shales, which form the valley walls of Rio Fajardo

for several miles above its mouth. The name "Fajardo" which Berkey gave these sediments is therefore doubly appropriate; and in spite of the complexity of the structure, which makes accurate stratigraphic analysis difficult, a better type section could not have been chosen. In the Fajardo region the base of the formation has been arbitrarily extended downward to the top of the Figuera flows, notwithstanding the fact that, as thus defined, it includes a moderate amount of calcareous tuff which might with equal propriety be placed in the Luquillo formation. In the localities west of Rio Sabana, the designation of the Trujillo Alto limestone as the lower limit of the Fajardo shales raises the same problem. The writers believe that it is more satisfactory to use well defined horizons for the base, at the expense of including material genetically related to an underlying formation, than to try to discover a non-existent boundary in the interstratified and intergraded tuffs and shales that mark the passage into the homogeneous strata in the middle and upper parts of the formation. The top is exposed in the Cape San Juan peninsula north of Fajardo, where the shales lie conformably beneath the San Diego formation and to some extent intergrade with the tuffs that belong to the latter.

From the Fajardo valley the ashy shales appear to extend west-southwestward into the Luquillo Mountains, where they make up part of the crest and southern front of the central range. Other occurrences of the Fajardo formation are restricted to the sags in the synclinal structure which forms the northern limit of the Cretaceous exposures in the district. Outcrops are found along the Rio Piedras-Fajardo carretera between the valley of Rio Grande de Loiza and Canovanas; they occur again in the section between Rio Piedras and Carolina, and in the environs of Rio Piedras the tilted beds of the formation outcrop conspicuously. The Fajardo shales have been differentiated in the San Juan district, notably in the large area of stratified ash included between Bayamon, Toa Alta, and La Muda. Probably some of the ashy sediments in other parts of the San Juan district can be correlated with the Fajardo shales as soon as the geologic structure is more fully known, and their identification in the Coamo-Guayama district is also to be expected. In fact, it is possible that these beds continue to the west end of the island, where, as Berkey has suggested, the Mayagüez shales look suspiciously like those which occur at Fajardo.

The Fajardo formation has proved extremely incompetent under the compression of post-Cretaceous deformation. In the northeastern part of the district it is closely folded and thrust-faulted to such an extent

that accurate measurement of its thickness was impossible, and the figures given in the table (750-1000 feet) are little more than a rough approximation. In other areas the upper beds have been removed by erosion, and the present thickness is considerably less even than the minimum figure given. If the basal strata be left out of consideration, the physical characteristics of the formation are relatively uniform. The beds are thinly stratified, and the closely spaced joints normal to the bedding planes give them a blocky fracture (Fig. 18). Few of the

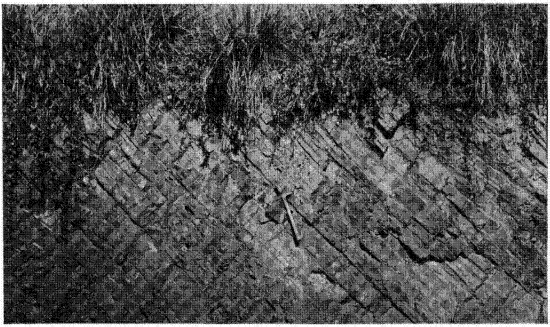


FIG. 18.—*The Fajardo shales*
A quarry face at the type locality, one kilometer south of Fajardo.

layers exceed four inches in thickness, and most of them average about two. The rocks are exceedingly fine-grained, and under the microscope the individual particles which can be isolated consist chiefly of angular fragments of volcanic glass and, to a less extent, of mineral fragments. The minute grains which compose the groundmass exhibit the polarization of quartz, and, if the mineral is correctly identified, its presence and abundance are indeed puzzling, unless it be assumed that it has been introduced into the rocks by processes of alteration—an assumption which could not be verified. The buff color, which is such a striking feature of the formation in its deeply weathered exposures in the coastal areas, is due to the presence of interstitial hematite. Weathered specimens have an unusually low specific gravity, a feature which, in micro-

scopic sections, may be traced to the abundance of cavities, formerly occupied by minute Foraminifera that have been dissolved in the course of rock decomposition.

In the Luquillo Mountains the strata which have been referred to this horizon do not resemble superficially the beds in the coastal region, save in their shaly structure. The former are dense, slate-blue rocks, which look more like the calcareous shales of the Guaynabo and Luquillo formations than they do like the buff shales in the vicinity of Fajardo and Rio Piedras. The differences exhibited appear to be due largely, if not wholly, to the freshness of the outcrops on the steep flanks of the mountains, and not to differences in the initial chemical or mineralogic composition. The mountain sediments lack the cavities but contain the Foraminifera and so have a higher calcium carbonate content than the beds at the type locality. The organic material has not been oxidized, and its presence prevents the iron oxide from imparting color to the rocks. In other more fundamental respects, however, they are identical with the buff shales at lower elevations. Berkey, too, has pointed out the evident genetic relationship between the weathered buff shales and the unweathered bluish shales;[58] but in view of the need to verify the correlation of the coastal strata with those in the Luquillo Mountains and other elevated portions of the interior, it is important that the identity of the two types of material be more fully confirmed by additional studies. At present the possibility that the beds in the mountains which have been referred to the Fajardo shales may prove to be a more shaly phase of the Luquillo formation, has not been wholly eliminated.

*The Juan Ascencio member*

Closely associated with the calcareous tuffs that lie above the Trujillo Alto limestone in the western part of the district is a series of deposits of distinctive lithologic character, but of uncertain derivation. Semmes called them the "Juan Ascencio chert beds," from Barrio Juan Ascencio at the eastern edge of the San Juan district, not far from Aguas Buenas. It has already been pointed out that these rocks are not cherts, but that they consist largely of the mineral laumontite, with hematite filling the interstitial spaces and giving the rock a reddish color and a strongly banded appearance. R. J. Colony suggests that they may have been formed by hydrothermal action upon calcareous tuffs, and Hodge has

[58] Berkey, C. P.: Geological reconnoissance of Porto Rico, op. cit., p. 19.

postulated a somewhat similar origin for petrographically related rocks on the southern slopes of the island.

The Juan Ascencio beds bear some physical resemblance to a series of flows which outcrop near the village of Torres and again in the escarpment on the north side of the Caguas basin a little more than a mile from Juncos. Correlation of the latter deposits with the Juan Ascencio member cannot be made from the data collected in the course of the field survey, but the possibility is sufficiently strong to warrant further investigation. The fact that the Figuera flows occupy an analogous stratigraphic position along the east coast suggests the idea that they, too, may be related genetically to the processes that formed the banded, laumontitic rocks along the western border, but this conjecture completely lacks substantiation. Because of the striking lithologic character of the Juan Ascencio beds, as well as their clearly defined stratigraphic position and their persistence in the La Muda-Aguas Buenas region, it seems desirable to accord them recognition as a basal member in the Fajardo shales. Future study may show that the horizon represents a phase of widespread volcanic activity that assumed different modes of expression in various parts of the island.

*The San Diego formation*

This name has been applied to the series of stratified tuffs which form much of the Cape San Juan peninsula and the tied island that now constitutes Punta San Diego (Fig. 19).[59] The validity of the formation depends wholly upon the accuracy with which the authors have interpreted the structure of the Cape San Juan area. Along the rugged shoreline on the eastern side of the peninsula where exposures are best, the Fajardo shales appear to pass beneath the tuffaceous deposits; but critical sections of the shoreline were found difficult of access, and a re-examination of the region is desirable to prove with greater certainty that an unobserved reversal of the dip has not brought the Luquillo formation back to the surface. If the writers' interpretation is right, the San Diego formation occurs in no other part of the district, for its high stratigraphic position has led to its removal by erosion. Pyroclastic beds which are tentatively referred to it outcrop extensively in the pitching syncline which stretches from Aguas Buenas to Toa Alta. Near the center of this structure a complete section is undoubtedly present, and had time permitted, it is probable that a better type locality could

[59] Meyerhoff, H. A.: The pre-Oligocene stratigraphy of Porto Rico, op. cit., p. 323.

have been discovered in this part of the San Juan district. It may be questioned, however, whether the deeply weathered exposures in the interior are as suitable for study as those in the imposing cliffs of the northeastern coast. The principal disadvantages which the latter area possesses as a type region lie in the fact that the top of the formation does not occur, and the upper beds are considerably modified and confused by the dioritic intrusions which cut them. If these disabilities are overlooked, the exposures are unrivaled and they reveal more of the

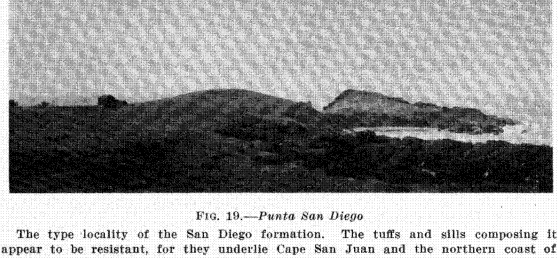


FIG. 19.—*Punta San Diego*

The type locality of the San Diego formation. The tuffs and sills composing it appear to be resistant, for they underlie Cape San Juan and the northern coast of Culebra, where, too, they are exposed to the vigorous attack of the Atlantic.

stratigraphic details than those of any other locality in northeastern Porto Rico.

The conformable relation of the San Diego formation with the underlying Fajardo shales, and the intergradational character of the contact are features which have already been mentioned. The strata are composed of thin to medium bedded tuffs with some interstratified shales and intercalated sills. A few of the fragmental layers are calcareous, but the greater part of the calcium carbonate is secondary, and there is much less of it than there is in the Luquillo formation. The greenish andesite fragments, which give many of the beds a coarse sandy texture, impart a characteristic color to the entire formation. These physical and chemical features, the associated sills, and the absence of horizons corresponding to the Trujillo Alto limestone and the Figuera flows are facts which give the writers grounds for believing that the San Diego formation is the youngest stratigraphic unit in the district, and not the Luquillo formation resurrected on the limb of an unidentified fold.

*Conclusions*

In the foregoing description of the Cretaceous system, the persistence of the several formations has been especially emphasized, but a broader view of the rock section reveals the marked lateral changes that occur. From the western border of the Fajardo district to the east coast the change is little less than a transformation; for along the former, stratified materials comprise nearly three-quarters of the total section; along the latter, three-fifths, or more, consist of unstratified pyroclastic rocks and volcanic flows (Fig. 16). The vertical change that occurs in the 10,000 to 12,000 feet of material is of a similar nature. At the bottom the unstratified tuffs of the Hato Puerco formation are found resting upon limestones and volcanic breccias. Except for the interpolation of an occasional flow or a sill, the coarse fragmentals continue upward with scarcely a break for 5000 feet in the east, and for at least 3000 feet in the west and northwest. When eruptive activity and rapid accumulation ceased, marine conditions followed, and the upper part of the Hato Puerco tuffs was reworked into the sediments of the overlying Luquillo formation. For the development of the highest formations, the Fajardo shales and the San Diego tuffs, new accessions of pyroclastic materials from remoter sources must be postulated.

The full significance of the lateral and vertical changes cannot be grasped until more information about the distribution of the several formations in adjacent areas is obtained. The Fajardo district obviously does not embrace the whole of the picture which the stratigraphic section suggests, but provisional inferences are irresistible. The Hato Puerco formation appears to have been a huge volcanic cone or cluster, the profile of which was materially lowered by the contemporaneous effects of marginal wave action; and on its northwestern margin, at least, strata composed of sorted and water-worn fragments either interfinger with the massave tuffs of the volcano or end against its flanks. Eruption was intermittent, and in the quiescent intervals calcareous strata were formed. The episode ends with complete submergence and renewed volcanic activity, which this time emanated from a more distant center.

The reconstruction of the Hato Puerco tuffs into a volcanic cone or cluster may, it must be admitted, involve more imagination than fact. The disappearance of the Guaynabo, La Muda, and Rio formations, a part of the sedimentary section involving 1500 to 1800 feet of material, takes place within the space of ten miles, and in the same distance the

Hato Puerco tuffs seem to thicken a corresponding or greater amount. If these estimates are at all accurate, replacement or overlap of 200 feet per mile is required. A slope of this declivity is, of course, too low for a normal volcanic cone composed of fragmental materials; but, on the other hand, it is too high for a graded marine platform, unless a rapid rate and an abnormal amount of subsidence are postulated. The available data are thus not wholly consonant with the interpretation offered, or with any other reasonable hypothesis; and only a better acquaintance with all the facts can lead to a sound and acceptable interpretation.

### UPPER CRETACEOUS AND POST-CRETACEOUS VOLCANISM

In the preceding pages repeated mention has been made of volcanic activity and of igneous intrusion. In fact, it has been seen that the accumulation of the thick stratigraphic section was controlled throughout Upper Cretaceous time by eruptions which varied in intensity and duration, and which produced effects that were closely dependent upon the remoteness of the active vents. During the early part of the period which is represented by the fragmental and organic deposits, explosive activity took place at close range, but later it was more distant. The change is recorded in the lithologic contrasts between the lower and upper parts of the stratigraphic section, which likewise mirrors every minor igneous and diastrophic pulsation that occurred. Volcanic activity started before the oldest sediments in the Fajardo district were deposited, and it did not entirely cease until the youngest Cretaceous rocks had been formed. Volcanism ended, however, some time before the Oligocene and Miocene marls and limestones of the coastal plain were laid down, stopping, apparently, with the orogenic disturbances that preceded Tertiary deposition. Whether this happened in the Cretaceous or in the early Tertiary is unknown; for, like the stratigraphic history, the beginning and end of igneous activity fade into the obscurity which veils so many of the pre-Oligocene events.

Notwithstanding the imperfection of the record, more has been learned about the volcanism than about any other phase of Mesozoic history. Events centered around the activity of a dioritic magma; and pyroclastic materials, flows, and intrusives approach this composition as the norm, though differentiation gave rise to many local compositional varieties. A few distinct tendencies are apparent: Among the microcrystalline and porphyritic rocks rhyolitic types are scarce, whereas basalts

are more abundant. Among the granitoid rocks, on the other hand, granites are commoner than gabbroic differentiates. A study of the forms which the igneous material assumed when it came to rest within the older rocks or upon the surface, indicates that few important structural types are missing. Among the surface forms, volcanoes were indubitably present during Cretaceous time. Throughout the 200-miles' length of the Porto Rico-Virgin Islands platform, the recurrence of thick sections of unmodified tuff and agglomerate implies the existence of several large and vigorous eruptive centers. Dissected by fluvial agencies, planed or modified marginally by marine erosion, and folded, none of the cones has retained its initial shape, and the few that can still be identified must be isolated by inferences based upon dike systems and plug-like masses that suggest the positions of ancient vents. Only rarely does a feature like the replacing overlap which has been discussed in connection with the stratigraphy make partial reconstruction of a specific form possible.

Sills are so often intercalated with the strata of the sedimentary formations that the presence of flows has generally been overlooked. Berkey wrote: "On the whole, evidence of lava flows on a large scale are wanting. This kind of product seems to have been very much more rare than the fragmental type." [60] Semmes spoke of the scarcity of flows in the San Juan district,[61] and Mitchell [62] stated flatly that "all of the igneous rocks in the Ponce district have an intrusive relation to the Cretaceous sediments." But Mitchell apparently missed one of the largest single lava flows which the senior author has seen in Porto Rico—a striking amygdaloidal basalt that outcrops continuously for several miles along the road connecting Adjuntas with the Yauco-Lares carretera, not far from the northern boundary of the Ponce district. Hodge mentioned but a small number of flows in the Coamo-Guayama district; Hubbard described only one in the Lares district; and Fettke was unwilling to commit himself as to the intrusive or extrusive origin of the felsitic rocks in the southeastern corner of the island.[63]

It is possible that the outpouring of lava was accidentally concentrated in the Fajardo district, but in view of the abundance of flows there, the writers must take issue with Berkey's general statement. Lava was extruded in every part of the district, and it is present in most of the bedded formations of clastic origin. The authors have, in fact, found it neces-

[60] Berkey, C. P.: Geological reconnoissance of Porto Rico, op. cit., p. 26.
[61] Semmes, D. R.: Geology of the San Juan district, op. cit., p. 76.
[62] Mitchell, G. J.: Geology of the Ponce district, op. cit., p. 261.
[63] Fettke, C. R.: Geology of the Humacao district, op. cit., pp. 142 and 147.

sary to differentiate a series of fine-textured andesites that outcrop near the east coast as a separate formation, under the name "Figuera flows." The extrusive origin of the latter is scarcely less certain than that of the other felsitic rocks which comprise parts of the Hato Puerco, Luquillo, and Fajardo formations; for in nearly all of them their amygdaloidal character, strong megascopic flowage lines, columnar jointing, and relation to the superjacent and subjacent strata furnish a body of evidence concerning their eruptive character that leaves no room for question. The importance of this kind of product is still further emphasized by the common, if not abundant, occurrence of flow fragments in the tuffs and agglomerates. The majority of the extrusive sheets may have been comparatively local in extent, yet in the aggregate they form a large fraction of the rock section.

Even in the Fajardo district, however, the effusive rocks do not acquire the importance exhibited by the intrusives. Sills invade the sediments in every part of the island, some hovering on the lit-par-lit injection type, others attaining large proportions, a few shading into laccoliths. Dikes are probably the most numerous of the intrusive forms and display a remarkable petrographic range. The eroded granitoid bodies of deeper origin are more scattered than the shallow intrusives and are exposed in irregular apophyses and stocks, and in a few batholithic masses.

So many petrographic varieties are present among the igneous rocks of the Fajardo district, that a systematic treatment of all the species which have been differentiated in the preparation of this report could easily furnish material for another of equal length. Systematic studies have already been made of the igneous rocks in the adjoining San Juan and Humacao districts by Semmes and Fettke, and their petrographic descriptions and general conclusions apply equally well to the igneous geology of the Fajardo district,—the more because many of the rocks which they classify and describe extend into the district without undergoing any detectable change. A similar treatment of the same or like products would be in large part repetitious.

On the other hand, the igneous phenomena have an historical significance which may appropriately receive consideration, for they require correlation with the stratigraphic details which the Fajardo district reveals. To this end they may be grouped, first, into those features which were more or less contemporaneous with Upper Cretaceous sedimentation and, second, into those which were concomitant upon the orogenic disturbances that later caused deformation in all the older rocks. The members

of these groups differ slightly in composition, and markedly in texture and form. The contemporaneous types invariably possess finer textures, and they may be less silicic than the phanerocrystalline intrusives of later origin. The latter invade the stratified rocks as irregular apophyses, stocks, and batholiths. The former, on the contrary, assumed simpler shapes which were more intimately related to the original sedimentary structure: sills are abundant; the dikes are simple, tending to fill single, well defined fractures; other intrusives are, with few exceptions, small, compact masses, which have upon and within them the marks of later deformation and magmatic alteration. Gradational varieties that link the two groups are not present, and in the field and laboratory it has been found consistently possible to classify the igneous products on this twofold basis. On the geologic map which accompanies this report the contemporaneous intrusives, which in some localities are so intimately associated with the sediments as to be inseparable from them, are accorded a degree of prominence and distinctiveness that is not encountered in the field, whereas the deeper intrusives which invaded the stratigraphic section at a later date are as sharply set off from the surrounding rocks as the red color employed to represent them on the map implies. A brief examination of the igneous rocks will make their similarities and differences more apparent.

*The early volcanic rocks*

The igneous rocks which were formed during the period of Upper Cretaceous sedimentation may be subdivided into surface types and intrusives. Obviously the intrusives in this group were later in origin than the rocks they invaded, but they were formed at shallow depths while higher members of the stratigraphic section were being deposited, and before the orogenic movements occurred. Except for their unfailing porphyritic habit and their usual lack of flowage lines they differ little from the closely related flows.

(1) *Surface types.* Pyroclastic rocks cover about three-quarters of that portion of the Fajardo district which is underlain by the "Older Series." A large quantity of the fragmental material was ejected, or washed, into shallow marine waters, where it underwent sufficient resorting and modification to assume the stratified structures, as well as the textures, of normal sedimentary rocks. So completely have the explosive features of many of the finer pyroclastics been modified by wave action that they are usually described under sedimentary names, and their ultimate volcanic

origin is indicated at most by a qualifying adjective. The ashy shales of the Fajardo formation, the tuffaceous sandstones and calcareous tuffs of the Guaynabo and Luquillo formations, the pyroclastic conglomerate of the Rio formation are among the examples which the Fajardo district contains. Of the several stratigraphic units that have been differentiated, only the Hato Puerco tuffs seem to be subaërial in origin. Even in this formation, the diversity exhibited among the constituent particles and the rounding which the fragments locally display suggest that water action played some part in assembling the materials. The salient features and problems of the pyroclastic rocks have already been briefly discussed, however, and attention may more appropriately be turned to the flows which are intercalated with them.

Extrusive sheets have been found in association with most of the clastic formations which have been differentiated within the boundaries of the district. In the Guzman formation amygdaloidal andesite flows are interbedded with the tuffs and limestones, and on the northern flank of El Yunque, at an elevation of 2400 feet, one of the flows has brecciated a bed of limestone. The recrystallized and partly absorbed fragments of the limestone have weathered more readily than the andesite in which they are embedded, giving the outcrop a deeply pitted surface, in which the white or light gray calcareous remnants afford a striking contrast with the weathered greenish exposure of the volcanic matrix. It is not known to what extent flows characterize other portions of the Guzman formation, for along the northern flanks of the Luquillo Mountains, where it is believed to acquire its maximum extent, its outcrops could not be visited. Until this area is studied, a more exact statement concerning its constituent members cannot be made.

In the overlying Hato Puerco tuffs the percentage of flow material is extremely variable, but in every section which was examined flows were found to compose a moderate proportion of the whole. Practically all of them are andesitic in character; most are amygdaloidal, and flowage lines are commonly exhibited. In the southwestern corner of the district a typical extrusive belonging to this horizon is exposed about one kilometer from the Caguas-Aguas Buenas carretera along the trail to the caves in the La Muda (or Aguas Buenas) limestone. The rock is a vitrophyric flow breccia with the composition of a dellenite. The small phenocrysts of feldspar, altered biotite, and magnetite are embedded in a groundmass

composed largely of glass. Fragments of an older glass, which exhibits strong flow structure, are also present, but megascopic and microscopic flowage lines are equally prominent in the younger glassy matrix. Veinlets of sericite and epidote penetrate the rock, and alteration has materially affected the phenocrysts. The biotite has been all but destroyed; the magnetite has undergone partial alteration to leucoxene; and secondary quartz has been introduced into every cranny in the rock.

Across the western hill section on the caminos from Trujillo Alto to Gurabo and from Trujillo Bajo to Juncos flows are very common. Most of them are so extensively altered that scarcely an original mineral remains; but vestiges of plagioclase phenocrysts can usually be detected, and the prominent amygdules and flowage lines have not been much disguised. Perhaps as many as 1000 feet of these amydaloidal andesites are present in the central portion of the district. Grouped tentatively with the Hato Puerco formation on the geological map are two related rocks which are somewhat more silicic in composition than the majority of volcanic products in the district. One outcrops at the summit and on the higher slopes of the escarpment that forms the northern wall of the Caguas lowland near Juncos; the other occurs in the two conical hills that rise conspicuously above the lowland floor not far from the village of El Rio. Both are composed in great part of secondary hematite and quartz, including jasper and vein quartz, and the distribution of these minerals has given the rocks a strongly banded appearance. In the exposures north of Juncos the nature of the banding is suggestive of flowage, and petrographic analysis of the specimens confirms the impression of their effusive origin by revealing a pronounced vesicularity and a large quantity of glass. Professor R. J. Colony suggests that the rock was initially a scoriaceous lava of felsitic or rhyolitic composition. The rocks near El Rio consist in part of similar material but also comprise associated fragmental rocks that have been identified as rhyolite tuffs. In some respects the specimens from both localities bear an arresting resemblance to the Juan Ascencio member of the Fajardo shales, and it is possible that additional field study will show the latter to be a correlate of the Caguas lowland deposits. The authors have not found sufficient evidence to justify the correlation. It would require the presence along the escarpment north of the lowland of a deep synclinal fold in which a considerable portion of the stratigraphic section must occur. As has already been stated,[64] the

[64] Ante, pp. 236-238.

FIG. 20.—*A flow in the Luquillo formation*

**A tilted extrusive sheet exposed on the carretera about three kilometers south of Canovanas.**

structure of this belt probably is synclinal, and if the Collores limestones have been correctly correlated with the La Muda and Trujillo Alto formations, the basal portion of the Fajardo shales in which the Juan Ascencio member occurs may also be present. But in this case the entire section should be repeated in the upland, and in the field studies in this region it was not found. Its absence can too readily be attributed to the porphyritic intrusives which penetrate the formations along the trails, and the missing strata may be present in less accessible parts of the upland. Until they are discovered, opinion regarding the correlation suggested is reserved.

In the comparatively small area underlaid by the Guaynabo formation in the northwestern corner of the district, the majority of the igneous rocks that came under observation are sills. In a few cases the possibility of an extrusive origin was noted in the field, but none of the specimens in the collection which has been studied microscopically shows convincing signs of having cooled at the surface. The Luquillo formation, however, contains one of the two most striking flows in the district, and perhaps others which were not differentiated are present. The flow in question (Fig. 20) is a tilted sheet about 30 feet thick, intercalated with the bedded tuffs and ashy shales that outcrop on the carretera nearly three kilometers south of Canovanas. Like the sediments with which it is associated, it dips 25 degrees north-northwest, and its regular columnar joints are inclined an equal amount from their original vertical position. A similar tilted flow in the lower portion of the Fajardo shales has been used as a bridge abutment where the carretera crosses Rio Canovanillas between Carolina and Canovanas. The rocks composing both these extrusives are amygdaloidal and aphanitic. Marked flowage lines have been preserved by the oriented lath-shaped feldspars, which are set in a glassy matrix. The amygdules, as a rule, exhibit reaction rims of chlorite which envelop a calcite filling, but in the specimens from the Fajardo formation a zeolite, probably heulandite, fills some of the cavities. Both rocks possess too fine a texture for accurate classification, but the extinction angles of the small feldspar laths suggest a composition intermediate between basalt and andesite. The nature of the volcanic material in the Figuera formation has already been described.[65] In the middle and upper part of the Fajardo shales and in the San Diego tuffs no flows were found.[66]

[65] Ante, pp. 282-283.

[66] Vaughan (Journal, Washington Academy of Sciences, Vol. XIII, 1923, p. 307) mentions a folded basalt flow at Cape San Juan, but the writers' field observations and microscopic studies indicate a probable sill origin for the andesitic rocks of this locality.

From this summary statement of the areal and geologic distribution of volcanic flows in the Fajardo district, it is clear that their importance in the Porto Rican section must be re-evaluated, for locally they comprise as much as 1200 to 1500 feet of the total geologic column. Effusion took place sporadically during most of Upper Cretaceous time, but two particularly vigorous cycles are noteworthy: one in Hato Puerco time, another during Figuera time. If the puzzling rocks of the Juan Ascencio member and of the central and eastern Caguas lowland were not formed correlatively with the Figuera flows, a third cycle must be recognized. Although the eruptive rocks are typically andesitic, local differentiation gave rise to the less silicic varieties near Canovanas and to the more silicic variety north of Juncos.

(2) *Intrusives.* Igneous intrusions are more numerous than flows among the rocks of Cretaceous age, and, as might be expected, the older and lower formations have been more extensively invaded than the younger. If it be assumed that the greater number of intrusives in the older rocks is the outcome of continuous igneous activity throughout the depositional period represented by the stratigraphic section, wide textural variation in the intrusions might be expected in view of the differences in the thickness of the overburden as successive invasions occurred. To an extremely limited extent this assumption is substantiated by a study of the dike systems which penetrate the formations, especially the Hato Puerco tuffs. Textural variation is almost wholly restricted to the dikes, however, for in other kinds of igneous bodies the textures are monotonously felsophyric. The cryptocrystalline matrix which characterizes most of the intrusives implies that they cooled at relatively shallow depths, and that their formation followed close upon the deposition of the rocks which they invade. A more critical analysis also shows that the large number of intrusives penetrating the Hato Puerco tuffs is due rather to the greater vigor of volcanism in Hato Puerco time than to the cumulative effect of igneous activity over a long geological period. The time factor was of slight importance only in the development of the younger dikes, through which the magma was supplied to higher stratigraphic levels. Description of a few of the intrusive types, chosen to illustrate their relationships to the surrounding rocks and their compositional range, will serve to show their historical significance, as well as a few of the problems they present. On the geologic map all are represented by a single symbol, and only those which attain moderate proportions, or which appear to have especial significance, are shown.

Dikes occur in all the Cretaceous rocks, but they attain their best development in the massive and relatively competent tuffs of the Hato Puerco formation. Rio Grande de Loiza and Rio Canovanas have cut excellent natural sections across this formation in the center of the district, and in the steep valley walls and in the beds of these two streams the scattered dikes form conspicuous outcrops (Fig. 21). Most of them consist of altered andesite porphyry, to which the white, or light gray plagioclase phenocrysts, set in a dull green microscrystalline groundmass,

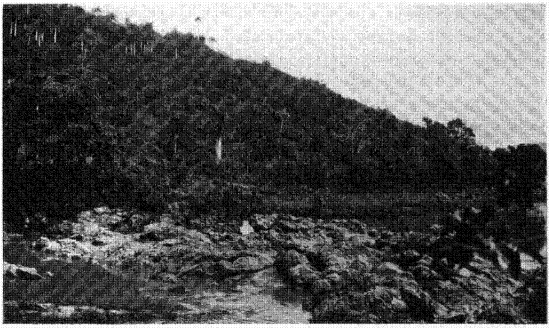


FIG. 21.—*A dike cutting the Hato Puerco tuffs*

Harder than the surrounding tuffs, this andesite prophyry intrusive forms a narrow zone of falls along Rio Grande de Loiza at Kilometer 19.8 on the line of the Porto Rico Railway, Light, and Power Company.

impart a mottled aspect. A few dikes are more silicic than the andesitic norm.[67] At kilometer 21.6 along the track of the Porto Rico Railway, Light, and Power Company, a band of rock with dike-like characteristics cuts across Rio Grande de Loiza, forming a narrow zone of rapids. It has been classified as a dike, although its contacts with the surrounding tuffs are buried beneath a thick soil cover and could not be studied. Uniquely enough, the mass is composed of two closely related igneous rocks, one intrusive into the other. The older is a bostonite, inconspicuosly porphyritic, and composed of primary quartz, anorthoclase, and andesine or oligo-

[67] In this statement no account is taken of the dikes associated with the diorite and quartz-diorite intrusions of later date. These will be discussed in the following section.

clase. The younger rock, which is more distinctly porphyritic, parallels the older and has sent narrow stringers into the fractures that had formed within it. The plagioclase feldspars of the later intrusion are higher in soda than those of a normal andesite, and except for accessory magnetite, biotite is the only determinable ferro-magnesian mineral it contains. It has been classified as a porphyritic trachy-andesite. Dacite porphyries have also been encountered in a small number of dikes in the western third of the district. One comparatively unweathered occurrence was noted at kilometer 15.5 along the railroad in the valley of Rio Grande de Loiza, where the intrusive cuts a series of indurated shales. Quartz and andesine compose both phenocrysts and groundmass, and biotite constitutes the ferro-magnesian component.

Other kinds of chemical and mineralogic variations among the dike rocks are more common than those responsible for the differentiation of the trachy-andesites and dacites. One type is to be found in the relatively common hornblende andesite porphyries, such as occur in the dike which outcrops on the carretera eight and one-half kilometers south of Canovanas. In this rock moderate-sized phenocrysts of plagioclase, ranging from andesine to bytownite, occur with huge phenocrysts of greenish black hornblende in a matrix of aphanitic andesite. In most porphyries of similar character the hornblende phenocrysts are relatively inconspicuous, and in several intrusives they are difficult to distinguish megascopically from augite, which is a common essential mineral. Among the older intrusive dikes a graded series of rocks ranging from bostonite to augite andesite porphyry could easily be arranged, but beyond these extremes lithologic representatives are rare. Fragments of basalt and diabase, including olivine-bearing varieties, are locally so abundant in the tuffs and agglomerates as to compose the major part of some of the minor pyroclastic members. These, together with the scattered basaltic flows and sills in various parts of the district, make it necessary to postulate the existence of feeder dikes of similar composition, which escaped detection in the field. The single body of olivine basalt which was found in the district about four kilometers north of Gurabo on the Trujillo Alto trail, does not seem to have a dike-like relation to the surrounding tuffs, and it may upon further study prove to be a flow.

In the foregoing discussion no emphasis has been placed upon the textural features of the dike rocks, other than to stress their general porphyritic habit. As phenocrysts have little value in indicating the relative position in which the magma ultimately crystallized, attention must

turn to the groundmasses. With no important exceptions the latter are uniformly cryptocrystalline, and a few contain small quantities of glass. None of the specimens is truly phanerocrystalline. It must be concluded, therefore, that nearly all the older dikes consolidated near the surface, and that they do not represent an unbroken series which links the earliest manifestations of volcanic activity with the deep-seated intrusions that followed the Cretaceous. On the contrary, the facts suggest a distinct hiatus between Cretaceous and post-Cretaceous volcanism.

There is little need to enlarge upon Berkey's general description of the occurrence of sills:[68] "The smaller intrusives are chiefly andesite porphyry in composition and have everywhere penetrated the shale and ash beds. The commonest occurrence is in the form of small sills or sheets conformable to the bedding structure and varying in thickness from only a few inches to many feet. These sills are so perfect in form, have so little disturbed or modified the adjacent beds, and are so similar in general composition and appearance, after weathering, to the associated sedimentary beds that it is quite impossible to determine in all cases how much intrusive and how much original sedimentary rock are involved. The only thing noticed as a rule is the uniformity of petrographic structure that seems to be characteristic of the intrusive as compared with the associated beds. The simplest occurrences of sills of this kind, which at the same time show their igneous intrusive character, were seen near Fajardo, near Rio Piedras and in the vicinity of Comerio."

The two examples mentioned by Berkey as occurring within the limits of the Fajardo district are typical of many other similar intrusions in the strata of the Guaynabo, Luquillo, Fajardo, and San Diego formations. Locally it proved possible to isolate the sills by the perfection of the spheroidal weathering affecting them, but where this method of differentiation failed, identification was possible only by means of petrographic analysis, save in the rare unweathered exposures along a few streams and along parts of the northeast coast. The uniformity in texture and in composition which the sills exhibit is certainly a more arresting feature than their elusive occurrence in the field. Nearly all of them consist of andesine or labradorite phenocrysts in greenish cryptocrystalline matrix, in which hornblende or, less commonly, augite may be identified. In a few sills the extinction angles of the plagioclase indicate

[68] Berkey, C. P.: Geological reconnoissance of Porto Rico, op. cit., p. 26.

a composition that approaches bytownite, but basaltic varieties are extremely scarce. Their texture, their thinness, and their conformance with the sedimentary structures are characteristics which at once indicate their contemporaneity in origin with the formation in which they are found and set them apart from the phanerocrystalline sills of much later origin.

Other kinds of porphyritic intrusives present in the district are difficult to classify, and only the larger and more important bodies have been represented on the map. Many consist of plug-like masses with circular, oval, elongate, or irregular ground-plans. They usually appear suddenly in the midst of a section of sediments, their outcrops covering, in some cases, but a few acres; in others, from one to two square kilometers. The dikes associated with a few of them suggest that they mark the sites of subsidiary volcanic cones, and at least one that came to attention near La Muda has the aspect of a volcanic plug. Marginally some of the intrusives have incorporated such large quantities of country rock that several of them could scarcely be distinguished in thin-section from the pyroclastic rocks, but in the field their intrusive contacts with the surrounding formations make their origins clear.

The nature of the larger intrusive bodies of andesite porphyry is indeed perplexing. Semmes mapped a large mass north of Aguas Buenas, and it has been traced for some distance into the Fajardo district, although its boundaries could not be determined with any degree of precision. It is composed of andesite and andesite porphyry and is cut locally by irregular dikes or apophyses of diorite, some of which appear to be direct offshoots of the granitoid intrusives of the Caguas basin. The areal distribution of the porphyry and its location at the end of the pitching syncline that crosses the western border of the district, suggest a sill-like origin, yet wherever its contacts with the surrounding sediments were observed, they have been found to cut the structures. Its ground-plan and structural relations are much like those of a stock, yet its comparatively fine texture, grading from felsitic at the margins to felsophyric nearer the center, casts serious doubt upon such a mode of origin. It is possible that the mass developed as a subsurface feature in association with one of the younger volcanic vents in the interior of the island, but the erosion of the higher members of the stratigraphic series has destroyed whatever evidence of concomitant eruptive activity there may have been to support such a postulate.

The large porphyritic intrusion near Mameyes is associated with sediments that have relatively low dips, and it occupies a stratigraphic and structural situation almost identical with that of the Aguas Buenas porphyry. Its development in the trough of the undulating syncline that underlies this region again suggests a sill-like relationship to the surrounding rocks, but such an assumption is precluded in view of the nature of its intrusive contacts. Were it not for the unmistakable signs of deformation that are revealed when this and the Aguas Buenas porphyry are studied under the microscope, it might be postulated that both entered the zones of minimum pressure in the troughs of the synclines as folding occurred, much as incompetent clays are squeezed into the axial portions of folds whenever strong compression takes place.

Fettke has already called attention to the large areas of andesite porphyry in the northeastern part of the Humacao district and in the adjacent portion of the Fajardo district,[69] but he has left their origin unexplained. As the geologic map accompanying the present report shows, these intrusives display a tendency to parallel the structures of the sedimentary rocks, yet in many places they cut indiscriminately across them. Minor petrographic changes in the rocks imply that the extensive area which Fettke and the present writers have mapped as a continuous body of porphyritic andesite along the southern edge of the Luquillo Mountains may prove to be a more complex series of intrusives. At the western limits of the mountains the igneous rocks occur at the end of the pitching syncline that forms the central range, and from the meager data obtained in the field it has been inferred that they do not penetrate the overlying sediments of the Luquillo formation, which are present in the structure. This assumption is based partly on the form of the intrusive and partly on the associated dike system, both of which indicate that the area was the locus of explosive activity during Hato Puerco time. The inference was not supported by direct field observation of the contact between the porphyry and the sediments, and if the intrusive is continuous and contemporaneous with the one in the eastern part of the Caguas lowland and in the Naguabo region, the hypothesis is incorrect, for the latter is associated with the younger rocks in the stratigraphic series. If two distinct intrusives are present, as the geologic map implies, the older was formed during Hato Puerco time and involved the development of a plug-like volcanic core of moderate size at the western end of the Luquillo Mountains. The younger involved the

[69] Fettke, C. R.: Geology of the Humacao district, op. cit., pp. 136, 144-147.

injection of thick sheet-like masses of andesite porphyry into the strata of the Luquillo formation. By postulating two cycles of intrusion the contrast between the forms of the intrusive in the upland and of that along the southern border of the district can be explained; but no physical evidence was disclosed in the field to justify the recognition of two distinct periods of invasion at different times, and microscopic analyses of the specimens from the two localities are non-committal.

The essential petrographic features of the irregular and unclassified intrusives have been described by Semmes and Fettke. Most of them are normal andesite porphyries with andesine or labradorite forming the phenocrysts. Several of the smaller masses show a slightly higher content of silica and have crystallized as dacite and trachy-andesite differentiates. In the larger masses an opposite tendency is locally exhibited. The plagioclase shades toward bytownite, and augite replaces hornblende. None of the rocks quite reaches the composition of diabase, although stray diabasic fragments among the coarse pyroclastic rocks show that differentiation proceeded to this extreme in a few cases. In all the intrusives of this group, irrespective of size and composition, the felsophyric texture shows no sign of gradation into the phanerocrystalline textures of the younger granitoid intrusives. The gap between the two types is broad, even though they occur in bodies that are comparable in form and size.

*The granitoid intrusives*

The coarsely crystalline igneous intrusives have a wide distribution in the Fajardo district, and it is probable that there are even more outcrops than the geologic map shows. The majority of those which lie north of the Caguas-Naguabo lowland are small, yet, irrespective of their size, they are composed of rocks with phanerocrystalline textures and mineralogic characteristics that set them clearly apart from the porphyritic intrusives. In thin-section the latter exhibit the effects of extreme alteration and of mechanical strain and chemical healing. The granitoid igneous rocks, on the other hand, are relatively unaltered, and, although a few specimens possess a faintly gneissoid structure, suggestive of crystallization under compression, none exhibits the features of strain, shattering, and healing, which develop if pressure is applied after crystallization has taken place. The relation between some of the smaller granitoid intrusives and the folded structures of the surrounding sediments also indicates that the movement of the magma was

locally governed by the structures the rocks assumed when folded, and that invasion took place as the period of orogensis was drawing to a close. The textural hiatus between the porphyries and the granitoid rocks thus reflects the gap in time that separated the earlier from the later intrusions, as well as the vastly different physical conditions under which the two invasions occurred.

In both epochs of volcanism the source of the magma was evidently the same, for each porphyritic variety can be matched by a corresponding granitoid variety. Yet, if the aggregate of coarsely crystalline rocks be compared with the aggregate of the finely crystalline types, the former are found to be somewhat more silicic. Subsilicic species occur in the Fajardo district, but they are not common. One of them Fettke designated by the name "Juncos gabbro,"[70] from its exposures along the carretera from Naguabo to Juncos, a little more than a mile from the latter town, where its contact with the younger diorite that cuts it may be studied. According to Fettke the rock is composed of labradorite and augite, with hornblende forming reaction rims around the latter. The writers' specimens were undoubtedly taken from a point nearer the contact, for hornblende comprises a very abundant constituent throughout the rock, and the pyroxene consists of colorless diopside. In its fine-grained, inequigranular texture it resembles a gabbro boulder which was picked up in the bed of Rio Blanco a short distance below the falls. Mineralogically, however, the fragment represents a normal gabbro, and the abundance of boulders like it in the stream bed indicates an outcrop of unknown extent somewhere along the upper reaches of the river. At the time the field work was done there were no trails in this section, and it was impossible to ascend the water course beyond the falls, so nothing further was learned about the source of the gabbroic fragments.

Although none of the other rocks in the district was classified as a gabbro, several of the diorites exhibit mixed characteristics. A few carry augite as a primary constituent. Specimens from one locality about three kilometers west of Caguas were found to contain no other ferro-magnesian mineral. They were taken near the contact with the country rock, and to what extent the presence of augite is due to endomorphic reactions is uncertain. The abnormal composition of the rock as a whole suggests modification of this kind, for both andesine and orthoclase are constituent feldspars. The intrusive exposed along the carretera between Rio Grande

[70] Fettke, C. R.: Geology of the Humacao district, op. cit., p. 153.

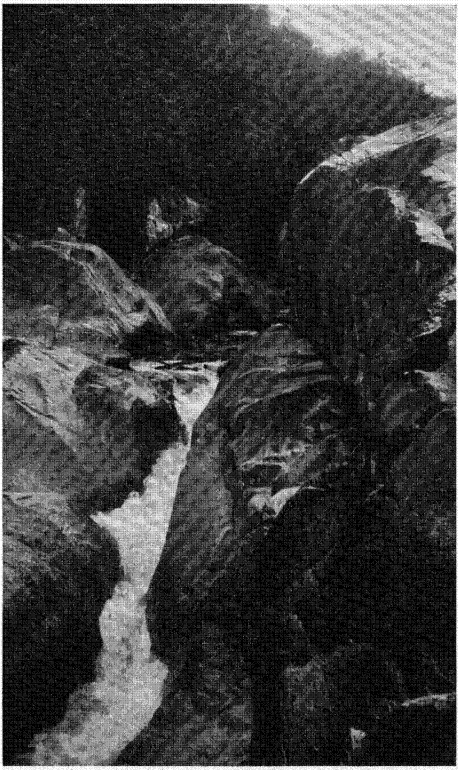


FIG. 22.—*The Rio Blanco quartz diorite*

This exposure in the lower falls of Rio Blanco shows the use to which the river is putting the joints of the massive intrusive in its precipitous drop down the southern front of the central range.

and Mameyes is another in which augite plays a primary rôle, but the calcic character of its plagioclase indicates that the composition of the entire rock is normal. The diorites composing part of this intrusion and one of the smaller apophyses that penetrate the San Diego tuffs near the Cape San Juan lighthouse exhibit the closest approach to gabbro which was observed. The relations of both to the surrounding strata indicate an origin contemporaneous with the other dioritic masses in the district, and their compositional deviation from the norm is apparently the result of simple differentiation.

In the diorites elsewhere in the northeastern part of the island the feldspars range from andesine to bytownite, but generally have the composition of labradorite; hornblende is invariably present, and magnetite, titanite, and apatite are the usual accessory minerals. In the majority of the smaller intrusives and in the western part of the stock underlying the Caguas basin no other minerals are present; but in the San Lorenzo batholith, in the Rio Blanco stock (Fig. 22), and in a few other dioritic masses, quartz becomes so abundant that the rocks must be classified as quartz diorites. Andesine is commoner than the more calcic plagioclase, and in a few places biotite appears in small quantities among the ferromagnesian constituents. As Fettke's excellent account of the San Lorenzo batholith and the associated intrusives shows,[71] careful sampling will reveal in each of the large granitoid intrusives the presence of hornblende granites, grano-diorites, quartz diorites, normal diorites, and augite diorites, so perfectly intergraded as a result of relatively slight geographic differentiation that sharp delineation between the species is not only impossible but pointless. These graded variations in single masses provide an ideal demonstration of the unity which must exist among the small granitoid intrusions in the district, irrespective of their present accidental isolation and divergence in composition. Only the Juncos gabbro exhibits a distinctly older origin, and a few granitic rocks, which are described below, appear to have been formed at a later date.

Two silicic differentiates, probably products of relatively late magmatic processes, have been noted in the district. In the valley of Rio Grande de Loiza, at kilometer 23.3 along the railroad, an exceedingly coarse-grained, almost pegmatitic, granite dike cuts through the surrounding tuffs, forming a band fifteen or twenty yards wide on both sides of the river. Shreds of bleached biotite are distributed among the large crystals of quartz and

[71] Fettke, C. R.: Idem, pp. 153-159.

kaolinized feldspar, the rock forming at once the nearest approach to normal granite and to pegmatite which the district affords. A stock-like body of graphic granite is situated at the southern edge of the area included in the present survey, about two kilometers southwest of Torres. Mixed with the graphically intergrown quartz and pink orthoclase are minor amounts of albite and scattered shreds of biotite. The rock as a whole is easily differentiable from the quartz-diorite with which it is associated, but the character of the contact could not be determined. Fettke regards this granite as a phase of the analogous Yabucoa granite, which at Playa de Yabucoa is intrusive into the diorite.[72] There is every reason to believe that the relation holds in the occurrence near Torres, and that the dike in the valley of Rio Grande de Loiza is an essentially contemporaneous injection.

About five kilometers east of Caguas on the carretera to Gurabo a road-cut reveals a small intrusive of quartz monzonite situated between outcrops of diorite and tuff. Fettke has recorded similar patches of quartz monzonite in the magnetite belt east of Juncos, but they were not differentiated by the authors; two other small areas, respectively three and one-half and seven kilometers west of Naguabo, are shown on Fettke's map, but a restudy of the material collected from them has indicated that the rocks must be classified as quartz diorite. Although the quartz monzonite near Caguas is finer grained than the large body of diorite in the Caguas basin, mineralogically it falls within the range of variation which the dioritic intrusion displays, and the authors were inclined to regard it as a marginal phase of the main mass, in spite of the prevalence of less silicic differentiates in situations of this kind. Fettke, however, found quartz monzonite cutting the Yabucoa granite along the coast two miles southeast of Patillas, and, on the assumption that all occurrences of monzonite were formed at the same time, he believes the intrusives along the southern border of the Fajardo district to be younger than any of the other kinds of granitoid rocks. The writers do not have sufficient information to support or to refute his hypothesis, but some of their conclusions differ from his and at least indicate the need for supplementary studies of the quartz monzonites in the Caguas-Naguabo lowland.

[72] Fettke, C. R.: Idem, pp. 159-161.

If Fettke's chronology of post-Cretaceous igneous activity be applicable in the Fajardo, as well as in the Humacao, district, the four stages of granitoid intrusion which he distinguished may be recognized. Gabbroic differentiates of limited size and extent were intruded early in the cycle and were succeeded by the widespread invasion of dioritic magmas, the later products of which were decidedly granitic. Perhaps as an aftermath, small masses of quartz monzonite were formed in, or near, the areas affected by the earlier invasions. The center of igneous activity was obviously in the Humacao region, where the San Lorenzo batholith, the largest batholithic mass in Porto Rico, appears to have played a parental rôle to the smaller intrusives to the north. Even the older gabbros near Juncos and on the southern slopes of the Luquillo Mountains are closely associated, and the younger granites either cut through the batholith or outcrop in the peripheral areas. The more remote intrusives are invariably dioritic, and their deployment over so wide a region bespeaks the intensity of igneous activity when it reached the climax of its development.

The textural features of the granitoid intrusives require mention, although their variety makes it impossible to give them extended treatment. All are phanerocrystalline, but the crystal size is invariably small in the gabbros and is usually small in the quartz monzonites. Among the rocks of the dioritic group fine textures occur along their contacts with the country rock, and in a few of the smaller masses the crystals remain small throughout the entire extent of the exposures. In the majority of cases, however, the crystals become larger away from the contacts, except in the granites, where they maintain about the same relative sizes in all parts of the intrusive. Although the constituent crystals have sometimes grown to moderate proportions, none of the rocks is very coarsely crystalline, with the notable exception of the granite dike along Rio Grande de Loiza, which is almost pegmatitic.

In nearly all of the intrusive specimens which were studied microscopically the fabric is inequigranular. Generally the inequigranularity is seriate, but in a few specimens it is sufficiently hiatal to warrant the application of the term porphyritic. The gabbro specimens found in the stream boulders near the falls of Rio Blanco, for example, contain a few enormous phenocrysts of augite, which have undergone more marked alteration than the augite in the equigranular groundmass. A diorite porphyry containing large hornblende phenocrysts in a finer matrix is exposed in the low ridge which rises above the alluvium of the Caguas basin

between Caguas and Gurabo. The rock is clearly a marginal phase of the diorite, for its contact with the associated tuffaceous strata is well exposed in another part of the ridge. These two cases are exceptional, for the inequigranularity rarely goes to these extremes.

The forms which the granitoid rocks assumed upon crystallization were seldom influenced by the structures of the strata they invaded, but a few exceptions to this statement may be noted. About two and one-half kilometers east-southeast of the village of Luquillo a lens-like intrusion of diorite rises above the deeply weathered tuffs, attaining a maximum breadth of 200 to 300 yards and tapering gradually toward the ends in the manner of a tilted laccolith. No strata are exposed in its immediate vicinity, and it is possible that the diorite fills a pinching fracture that parallels the sedimentary structures; but its unique and distinctive shape has led the authors to classify it provisionally as a thin laccolith. Four kilometers south of Rio Grande a slender wedge of diorite conforms with the structural trend of the subjacent and superjacent agglomerates and tuffs. It has been classified as a sill, although on the map it has not been differentiated from the larger stock-like intrusive with which it is closely associated. At Cape San Juan a network of small intrusions cuts the San Diego formation, and a few of them conform somewhat crudely to the bedded structures. In the fine-grained diorite porphyry which protrudes above the alluvium between Caguas and Gurabo, a faintly gneissoid structure appears to parallel the bedding planes of the associated ashy and tuffaceous shales. Here the intrusive mass cuts through the sediments, but marginal offshoots interfinger for short distances with the beds.

So far as could be determined, the other granitoid rocks cut jagged swaths through the formations of the stratigraphic section. The San Lorenzo batholith truncates nearly all the formations and their structures indiscriminately. The irregular apophyses which radiate outward from the stock beneath the Caguas basin, apparently filling the joints that penetrated the surrounding country rock, illustrate clearly the magma's intrusive course through the clastic rocks on every side. The Rio Blanco stock [73] is elongated in a direction normal to the trend of the regional

[73] Fettke called this intrusive the "Luquillo stock," on the basis of erroneous information that it forms a considerable part of the Luquillo Mountains (op. cit., pp. 154, 158-159). The senior author was unable to determine the exact limits of the quartz-diorite in the central range, but he at least found that it is restricted to the relatively small area drained by the headwaters of Rio Blanco. Its close association with this stream and the anomalous part it plays in the mountain mass render the name Luquillo inappropriate, and the name "Rio Blanco" is therefore proposed to replace it. (Cf. Fig. 22.)

structure. The smaller intrusives in the district are similarly related to the older rocks which they invade, but their movement into these rocks seems to have been in part occasioned by the development of lines of easy penetration during the period of folding. The crests and steep flanks of the asymmetric cross-folds in the northern part of the Fajardo region served as particularly favorable sites for invasion, although by no means all of the intrusive masses can be definitely correlated with specific orogenic structures. Most of them have stock-like forms, but only the large mass near Rio Grande is of sufficient size to be classified as a stock. It appears to be a complex intrusion, composed of several closely related, and perhaps detached, elements, the relations and distribution of which were not determined in the field. The other small granitoid bodies in the northern and eastern part of the district penetrate the rocks as irregular apophyses, to which the names stock and dike can scarcely be applied. They are usually xenolithic, a few strongly so, and they give the impression of being the summits of stocks that have just been uncovered by erosional processes. Only one normal dike was identified in the district—the pegmatitic granite dike which cuts through the Hato Puerco tuffs along Rio Grande de Loiza near the southern limits of the western hill section.

The foregoing account of the granitoid rocks does not pretend to add much that is new to a subject which has been ably and more fully presented by other workers in Porto Rico, especially C. R. Fettke. The post-Cretaceous igneous activity in the district was, in fact, but a smaller edition of the profound invasion that took place simultaneously in the Humacao district. A statement of the conclusions which may be drawn from the studies in both these areas at the eastern end of the island seems pertinent:

(1) A comparison of the older andesites and the younger diorites with respect to composition, texture, degree of alteration, and form, shows that the two rock groups cannot be regarded as early and late products of the same uninterrupted cycle of volcanism. On the contrary, they represent two wholly distinct cycles of igneous activity, and their respective developments took place under different sets of conditions, although the magma was unquestionably derived from the same source.

(2) The dioritic invasions appear to have been started by the orogenic movements which followed the accumulation of the stratigraphic section. Judging from the relations between intrusions and folds, the dim traces of gneissoid structures, and the lack of strain effects, shattering, and

alteration in the diorites, the magma made its way into the overlying rocks toward the close of the period of diastrophism.

(3) It seems likely that intrusion took place at moderate, rather than at great depths below the surface, for the chilling effects which the diorites exhibit near their contacts, and the fine textures of the early gabbroic and later monzonitic intrusives, are facts which indicate that the molten masses penetrated relatively cool rocks. It is unnecessary to imagine, therefore, that the stratigraphic section was very much thicker than it is now, and the character of the folds furnishes ample reasons for believing that there was not a heavy overburden that has since been removed by erosion.

(4) The magmatic invasions were cyclic in character, involving the evolution of more silicic types as time went on. Chronologic differentiation is pronounced, whereas geographic differentiation is relatively slight.

(5) If the geographic distribution of the granitoid rocks may be used as a criterion, intrusion was as extensive in the Fajardo district as in the Humacao district. The molten material did not rise to the same elevation, however, and subsequent erosion has not been deep enough to expose the igneous rocks which probably underlie the entire area. To what extent post-Cretaceous volcanism may have been responsible for the structural anomalies in the stratigraphic section is unknown.

(6) The scarcity of veins of magmatic origin is a feature which must sooner or later come to the attention of the investigator who is studying the igneous geology of eastern Porto Rico; and a brief enquiry into the disposition of the mineralizers during the closing stages of volcanism may appropriately conclude the present section.

*Mineralization and contact metamorphism*

In an island as large as Porto Rico, where volcanism dominated its early geological history, the scarcity of pegmatite dikes and the practical absence of veins are surprising features, especially when the silicic character of the later magmatic differentiates is considered. In all of the Fajardo district one pegmatitic dike was found, and a single specimen of vein material was discovered in a boulder along the trail between El Yunque and El Toro, under circumstances that made location of the vein itself impossible. Assumptions that the mineralizers escaped without leaving a sign of their departure, or that pegmatites and veins were formed at higher levels and have been lost through erosion, are entirely gratuitous. It is logical, therefore, to look for the effects of mineralization in other

situations, and the search need not go far. In every member of the stratigraphic section, in all the andesitic intrusives, and even in some of the earlier granitoid intrusives, the subtle effects of mineralization are evident. Scarcely a rock in the "Older Series" has completely escaped alteration, and in a few, little of the original material remains. About thirty minerals of secondary origin have been identified among the Cretaceous specimens, and twenty-five or more of them were characteristically introduced by late magmatic activity.

The processes which produced the most widespread effects were silification, chloritization, and epidotization. Secondary silica is present in the volcanic rocks and sediments in the form of quartz; less commonly, opal and jasper may be detected. Rarely the quartz has replaced older constituents, but in the majority of instances it infiltrated through the intergranular spaces, where it serves as an important cementing agent. In a few specimens it forms veinlets that ramify through fracture and crush zones, but this type of occurrence was observed at very few localities. The comparative scarcity of quartz as a primary mineral in the rocks of Upper Cretaceous age makes its presence more notable and its magmatic origin more certain. Silica, it is true, may be derived from feldspathic rocks by normal weathering, and it may be deposited in the interstices of fragmental rocks by ground water; but petrographic study of the specimens shows that such a theory of origin is inadequate to explain its distribution in the sedimentary and andesitic rocks of northeastern Porto Rico.

Chlorite is an equally common alteration mineral, and, although usually a product of replacement, it was formed under a large variety of conditions. It fills the vesicular cavities in some of the andesitic and basaltic flows; in others it forms reaction rims around the calcite which occurs in many of the amygdules in the effusive rocks. In most of the porphyries and coarse tuffs the process of chloritization involved selective replacement of ferro-magnesian minerals, but in some of the cryptocrystalline and stratified rocks partial or complete replacement appears to have gone on without much regard for mineral or chemical composition. Although quantitatively less abundant, epidote is scarcely less common than chlorite, being present in a majority of the Cretaceous specimens which have been studied under the microscope. It is found both as an interstitial mineral and as a replacement product, and it also occurs in veinlets and in irregular aggregates of anhedral grains. Sericite and zoisite were like-

wise noted in a large number of specimens, but the remaining secondary silicates are only sparingly present and are seldom important.

Locally mineralization involved the introduction of sulphides, including pyrite, pyrrhotite, and chalcopyrite, and of the iron oxides, magnetite and hematite. About three miles northwest of Florida estate in the southeastern portion of the Luquillo Mountains, the country rock has been exploited for copper.[74] The old mine, located high above the anticlinal valley that separates the central range from the southern foothills, has not been re-opened since the hurricane of 1898, and the trails are so completely overgrown that the senior author was unable to reach it, or to find guides willing to undertake the several days' labor of opening a trail. The geology of the deposit is therefore unknown, but, judging from information supplied by Sr. David Noble, it is like that of most of the copper prospects in Porto Rico, which usually occur in veinlets that penetrate fracture zones in shattered andesite or andesite porphyry. In the area drained by Rio Blanco andesite porphyry is abundant, and it seems safe to guess that an intrusive of this character has cut the folded sediments which make up most of the central range, and that ore formation has been localized within it. According to Sr. Noble, the principal mineral is chalcopyrite, the higher grade material assaying six to eight per cent. copper, in addition to small values in gold. It is unlikely that ore of this quality continues either laterally or vertically for any distance, but even though the chances that the Rio Blanco deposit will prove richer and more extensive than the other copper prospects in Porto Rico are not very great, it deserves a careful field study to evaluate its possibilities.

A second and less important showing of copper was found 31.1 kilometers east of Rio Piedras on the carretera near Mameyes, where malachite conspicuously stains the weathered surface of an andesite porphyry. The primary sulphide, probably chalcopyrite, was present in such small quantities in the minute veins in which it was formed that it has undergone complete conversion to the copper carbonate. Other small sulphide deposits occur within the limits of the district, for the senior author has seen specimens of copper ore that had been collected from three unvisited localities, but in none of them was the tenor of the ore high enough to have encouraged serious prospecting. Sulphide replacement has also taken place to a moderate extent in some of the sediments, but in the

[74] Colony, R. J., and Meyerhoff, H. A.: The copper prospect at Barrio Pasto, Porto Rico. Econ. Geol., Vol. XXIII, 1928, pp. 515-516. On the location map in this article (Fig. 1) the mine is incorrectly shown to the east of Rio Blanco, instead of to the west. Cf. also, Low, Bela: The mineral deposits of Porto Rico. Engineering and Mining Journal, 1929.

cases studied the minerals are disseminated through the rocks in amounts too small to warrant economic exploitation.

With the possible exception of the Rio Blanco copper deposit the features of mineralization which have thus far been discussed are widely distributed and affect large masses of rock of diverse origins and kinds. Very few of the lithologic elements, the formation of which antedated the granitoid intrusives, completely escaped alteration, and even some of the latter were mildly affected. Mineralization is so general that it can rarely be attributed to any specific intrusive mass, and in many places it is by no means clear whether part of it occurred during the volcanic activity of Upper Cretaceous time, or whether all of it occurred as an aftermath of the later period of dioritic invasion. The changes which all the sedimentary, pyroclastic, and pyrogenic rocks have suffered are distinctly metamorphic in character; and, if the word "regional" may be used in its literal sense, they may appropriately be designated as regional, to set them apart from the local and more intense changes which are found in the rocks that come in direct contact with the larger dioritic intrusives of the district.

Comparable in many particulars with the regional alteration which has taken place, the local, or contact, metamorphic phenomena differ principally in degree. The magnetite belt east of Juncos exhibits the most spectacular results of local metamorphism which the district contains. Here, not only have large masses of magnetite and smaller quantities of hematite been introduced into the La Muda and Trujillo Alto (Collores) limestones and the closely associated calcareous tuffs of the Luquillo formation, but the calcareous beds have been converted to aggregates of garnet, epidote, chlorite, amphibole, pyroxene, and talc, whereas calcite has become a relatively unimportant constituent. Contact metamorphism occurred when the San Lorenzo batholith and the contemporaneous dioritic stocks and apophyses invaded the region, for intense alteration is directly related to these intrusives, and its intensity diminishes away from the contacts. Fettke has studied the deposits of the magnetite belt quite carefully,[75] hence a restatement of the geologic details and of the economic importance of the iron ores is unnecessary.

Local metamorphism occurs elsewhere along the southern border of the Fajardo district in association with the dioritic intrusions. Endomorphic changes are numerous, and some of them have already been mentioned;[76] attention may be turned, therefore, to a few of the exo-

[75] Fettke, C. R.: Magnetite deposits of eastern Porto Rico, op. cit., pp. 1028, ff.
[76] Ante, pp. 305, 309-310.

morphic modifications which a number of the rocks outside the magnetite belt have suffered. At Casa de la Mina, in the valley 1000 feet below the abandoned copper mine in the Rio Blanco region, an altered tuff illustrates some of the processes that undoubtedly occasioned the introduction of chalcopyrite in the vicinity of the mine. The tuffaceous origin of the rock is evident from its fragmental texture, but none of the initial pyroclastic material remains. Stout but minute crystals of diopside are scattered profusely through the entire rock, the other constituents of which include a colorless chlorite, orthoclase, soda plagioclase, and an undetermined amphibole. Zoisite, calcite, and epidote are common, and chalcopyrite, pyrrhotite, magnetite, and titanite form prominent, though less abundant, constituents. This one rock seems to epitomize most of the features of magmatic alteration which are present in somewhat milder and less varied form in the other lithologic types of the district, especially in, and around the edges of, the Caguas-Naguabo lowland, where the dioritic intrusions are large and numerous. In a few places the country rock is distinctly schistose for short distances from igneous contacts, and in one locality the intrusive itself has assumed a gneissoid structure. Structural changes of this kind are, however, less common than they are in the adjoining Humacao district, where similar phenomena have been studied and described at length by Fettke.[77]

In the foregoing discussion contact and regional metamorphism have been differentiated; but, as has been pointed out, the difference is chiefly one of degree rather than one of kind, for in the field the two types are completely gradational. Minerals diagnostic of one or the other cannot be distinguished, because the whole gamut of alteration products occurs indiscriminately in both regional and contact situations. The fact that the products of mineralization are so widely disseminated in the Cretaceous rocks leads to one possible explanation of the alteration phenomena. The comparative scarcity of dikes, especially in the higher members of the stratigraphic section, has already been mentioned, and the abundance of thin sills in the shales and stratified tuffs has also been noted. From the nature of the shallow intrusions, as well as from the lithologic characteristics of the rocks themselves, the several formations of the stratigraphic section appear to have been relatively impervious to the magma which essayed to rise through them, and their unconsolidated condition seems to have made them too incompetent to fracture. The consolidation which the rocks now exhibit was acquired primarily as a result of the induration which the magmatic emanations effected. There were

[77] Fettke, C. R.: Geology of the Humacao district, op. cit., pp. 170-176.

thus no easy channels through which the mineralizers could make a ready escape, and in consequence they permeated the entire rock section. Their action was often highly selective, for strongly altered types occur in proximity to rocks that suffered mildly or scarcely at all, a feature strikingly illustrated by the silicated Juan Ascencio member of the Fajardo formation, which lies between beds that have been but slightly modified.[78] Usually selective alteration was fostered by the chemical composition of the individual strata and their relative susceptibility to mineralogic changes, but in some cases it was clearly due to contemporaneous activity of a hydrothermal character.

The enforced dissemination of the mineralizers had, beyond question, a deleterious effect on metallic ore concentration, except in a few of the limestones, in which replacement could readily occur. The local concentration of copper sulphides in the andesites is natural, for the latter were the only rocks in the section competent enough to fracture; but, engulfed in incompetent pyroclastics and sediments, the shallow igneous intrusives were compelled to yield to compression by flexure more often than by fracture, and crush zones are few and extremely limited in extent. In the other rocks sulphides are commonly present, but in such low concentrations that the prospects for economic development are not promising.

*Conclusions*

The preceding sketch of the igneous features of northeastern Porto Rico has aimed merely to add areal details to a phase of the island's geological history, the main features of which have been known for some time. It departs from the conclusions advanced in the earlier reports of the Scientific Survey in but one respect; namely, in insisting that the sharp textural differences between the surface flows and shallow intrusives, on the one hand, and the later dioritic intrusions, on the other, indicate not only the contrasted conditions of depth and pressure which existed when the two cycles of volcanism occurred, but also the probability of a long lapse in time between the earlier and later periods of igneous activity. Early volcanism was explosive in nature and was causally related to the development of the stratigraphic section. In Hato Puerco time a volcano appears to have been built up subaërially in the southern or eastern part of the district, although its geographic position is unknown. Several subsidiary vents were opened on its flanks, and flows and dikes gave strength to the fragmental materials that composed it,

[78] Ante, pp. 286-287.

while marginally the fragments were resorted by an overlapping sea. Activity waned and finally ceased, but more remote centers remained, or became, active. Encroaching seas planed and buried the old volcano beneath sediments of pyroclastic and biogenic origins, although a few submarine flows and sills, and local cinder cones were mingled with the sedimentary deposits. Later, after several thousand feet of sediments had accumulated, volcanism was revived, probably as a result of the orogenic disturbances that compressed and folded the rock section. Resurgent magmas, which became increasingly silicic in composition, rose to various levels, forming the granitoid series of rocks, and concomitant mineralization produced telling effects upon the entire mass of older rocks.

In chemical compositions the older and younger igneous rocks are essentially alike, although the latter are somewhat more silicic than the former. Among the felsitic types differentiation produced both basaltic and trachytic, or rhyolitic, varieties, but the differentiates are complementary, the average or norm approximating the composition of andesite. Among the granitoid rocks time played a more important part than space in effecting differentiation, for the first intrusives of this cycle were gabbroic, and the later, if not the last, were granitic. Again the aggregate is more or less complementary, the whole approaching the composition of quartz-diorite. The pyroclastic rocks, too, are dominantly andesitic, for silicic and subsilicic variants occupy but little place in the stratigraphic section. It was this assemblage of andesite-diorite materials that formed the mountainous oldland around which the subsequent Cenozoic events have centered.

### EROSIONAL FEATURES OF THE CRETACEOUS ROCKS

The erosional history of the "Older Series" will be treated in a later section on the physiography of the district, but the various lithologic types react to the processes of weathering and erosion in ways that are sufficiently characteristic to merit brief exposition. In a humid tropical region decomposition normally predominates over disintegration, but in the mountainous parts of Porto Rico the high relief and youthful topography accelerate some of the mechanical phases of destruction, and the resultant erosional forms which each kind of rock assumes depend upon the balance between the chemical and mechanical forces which are acting upon it.

Chemical processes of rock decay are affecting every type of rock which the Fajardo district contains, and the results are especially striking in

the low coastal sections and in the interstream areas of the moderately elevated uplands. Lateritic soils characterize so much of the island's surface that, in the intensely cultivated districts where the soils are often bared by the plough, their red and brownish red colors are an inseparable part of every landscape. Lateritization has proceeded most extensively in the areas underlaid by the andesitic rocks. Limonite forms early in the process, and the development of residual clay products soon follows. In spite of their felspathic content, the patches of diorite, quartz diorite, and granite, on the other hand, exhibit negligible decompositional effects, and are commonly exposed in relatively fresh outcrops, even where they have been eroded to greater depths than the surrounding andesitic materials.

One of the most widespread results of the hydration which accompanies chemical weathering is exfoliation. Although operative on practically every lithologic variety in the "Older Series," it affects the relatively dense rocks to a greater degree than the coarser and more porous types, in which there is more latitude internally for this kind of katamorphic change. In the andesite porphyries exfoliation is most marked, and it is often displayed to best advantage in fresh road cuts and in stream gorges, sometimes as much as six and eight feet below the natural surface of the land, notwithstanding the protection afforded by the thick blanket of residual soil (Fig. 23). In several localities in the Fajardo district and in other parts of the island, the limits of an outcrop of andesite porphyry can be accurately determined from the extent of the comparatively fresh exfoliation boulders scattered thickly over its surface. Berkey called attention to this feature, and the resemblance between the boulders and glacial erratics led him to postulate glaciation as a possible explanation of their origin.[79] In the cases which came to Berkey's notice, the process of exfoliation has produced spectacular results because of the extremely irregular spacing of the fractures which governed its operation; in other rocks, where the joints are closely and more evenly spaced, this mode of weathering is no less effective, even though residual boulders do not endure. Its workings are revealed, however, in the rounded edges and minute scaling of joint blocks displayed in road cuts and in quarries. The depth beneath the surface at which exfoliation may occur, and the equable climate of Porto Rico are factors which indicate clearly that the process is the result of normal decomposition rather than of disintegration. Blackwelder has argued

[79] Berkey, C. P.: Geological reconnoissance of Porto Rico, op. cit., p. 35.

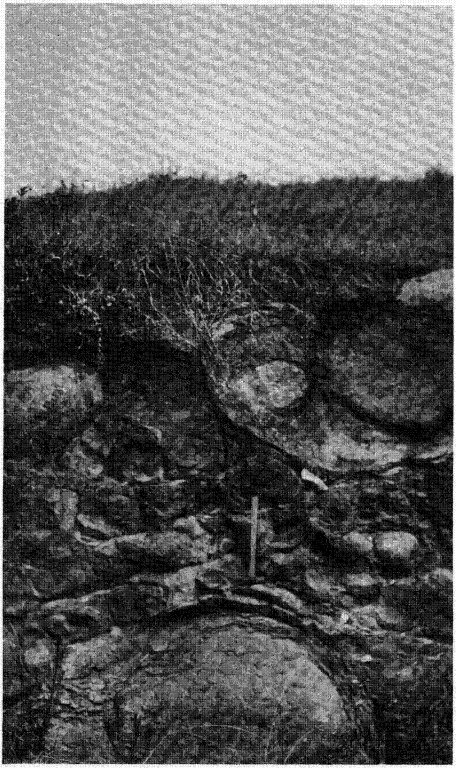


FIG. 23.—*Exfoliation in an andesite porphyry*

This new cut on the road from Rio Piedras to Barrio Cupey illustrates the depth to which the processes of decomposition have penetrated.

that exfoliation is more characteristically a chemical process than one dependent on thermal or mechanical phenomena.[80] Certainly the exfoliation which is taking place in every part of Porto Rico is open to no other interpretation.

Two anomalies in the effects of weathering come to attention rather early in a field study of Porto Rican geology. In many localities the purer crystalline limestones in the "Older Series" exhibit greater resistance to weathering and erosion than any other kind of rock, whereas diorites usually exhibit less. The limestones of the Fajardo district are thin and do not exert a strong influence on the topography, yet the La Muda limestone forms a distinct linear ridge in a number of its interstream outcrops (Fig. 7). In the interior of the district the granitoid intrusives have proved so non-resistant that stream erosion and gullying are usually localized upon them, and the outcrops of all the larger masses have become the sites of topographic basins or lowlands. In the low coastal areas, however, the relationships are not infrequently reversed: The limestones have been baseleveled, but the granitoid intrusives rise above the graded levels to which the other types of rocks have been reduced. Within the limits of the present report the many details of weathering cannot be described, but a brief summary and explanation of the outstanding features and anomalies seem pertinent.

Aside from the regional precipitation, humidity, and temperature, four special, or local, factors are exerting an important influence upon the weathering processes at work. These include, (1) the degree of magmatic alteration which the rocks underwent before exposure; (2) relative solubility and porosity of the several lithologic types; (3) present relation between the land surface and the water table; (4) relief.

(1) All the Upper Cretaceous rocks were altered to a greater or less extent by the processes of mineralization which were attendant upon the formation of the younger dioritic intrusives. Except in the few rocks which were silicified but not otherwise altered, susceptibility to chemical weathering appears to have been increased in direct proportion to the amount of alteration which took place. Because of the similarity of the changes that occurred within them, the andesites, the andesite porphyries, and the massive and stratified tuffs, all exhibit analogous erosional forms, in spite of the initial differences in their respective abilities to withstand weathering and erosion. Conversely the superior resistance of the grani-

[80] Blackwelder, Eliot: Exfoliation as a phase of rock weathering. Journal of Geology, 1925, Vol. XXXIII, pp. 793-806.

toid rocks in regions of low relief may be traced to the comparatively small amount of alteration which they suffered.

(2) The factor of relative solubility acquires expression chiefly where limestones, shales and andesitic rocks of both pyroclastic and pyrogenic origins are juxtaposed. In areas of low relief and low elevation where the water-table is near the surface, the rate of decomposition reflects quite accurately the proportionate solubilities of the varieties of rock present. The limestones are rapidly reduced; the shales, slowly; the andesitic rocks, at an intermediate rate. The simple operation of this rule may be modified by the porosity of the rocks, a factor which retards solution, though not appreciably in the areas of low relief.

(3) In the regions of moderate and high relief, on the other hand, permeability becomes a factor of increasing importance. The water-table is situated at a greater depth beneath the surface, and the downward movement of meteoric waters becomes too rapid for them to exert their maximum solvent effects upon the porous rocks. Under such circumstances both the initial porosity and the development of solution channels and caverns retard the rate of solution in the limestone strata, and they are in consequence relatively resistant elements in many parts of the interior. Conglomeratic rocks like the Rio formation may, too, if they have not too impervious a matrix, display their superior ability to resist decomposition in comparison with the tuffs and porphyries around them.

(4) High relief also accelerates mechanical weathering and erosion to such a marked degree that in many parts of the island they assume leading rôles in the reduction of the land surface. There is little disintegration in the stricter sense of the word, for most of the work is accomplished by rainwash and by landslides on oversteepened slopes. Decomposition initiates the process by loosening the minerals or fragments of which the rocks are composed, but thereafter the work is carried on by rain and gravity. Every downpour, from the short showers of the summer season to the occasional deluges of sporadic hurricanes, precipitates a host of earth slides, involving the shifting of vast quantities of material in the youthfully dissected regions. Where the rocks are andesitic, the natural tenacity of the residual clay soils slows the process markedly, but in the areas underlaid by diorite or granite it proceeds unchecked. Decomposition speedily loosens the interlocked crystals, as even a slightly weathered exposure shows, and rainwash or, under proper topographic conditions, a slide, removes the crystal fragments before they have the chance to undergo further decay. The arkosic sands that

cover much of the floor of the Caguas basin, as well as the comparative freshness of the diorite exposures, provide eloquent testimony concerning the efficacy of these mechanical processes. In this manner depressions have been excavated in dioritic areas, while nearby andesitic outcrops, seemingly more deeply weathered, have been etched in relief. On the other hand, in places where the relief is not great, whatever their elevation, removal of loosened crystal grains takes place at a more moderate pace. Here the feldspars of the granitoid rocks are undergoing thorough decay, and weathering is progressing at a slower rate than in the associated volcanic rocks.

The minor features of rock weathering are too complicated and too manifold to be covered in the present report, and the foregoing statement does little more than outline a few of the principles and explain some of the paradoxes. Though granitoid rocks may underlie the Caguas basin and form the peaks of the Sierra de Cayey, though the La Muda limestone may form the valley of Rio Grande de Loiza at Trujillo Alto and make the strong linear ridge just a few miles to the west, the erosional expression which each lithologic variety acquires is perfectly adjusted to the set of factors operative in the topographic situation that exists where it comes to the surface. None of the rocks can be rated on a scale of absolute resistance to katamorphic change, for their respective resistances vary from one type of environment to another. The climate governs merely the general aspects of weathering, but the behavior of the individual rock types depends almost wholly upon the minor factors which characterize different environmental conditions. Discussion has therefore centered upon the latter.

## The Tertiary Coastal Plain

by

Howard A. Meyerhoff

### Distribution of the coastal plain in Porto Rico

The Cretaceous oldland of Porto Rico is flanked both upon the north and south by overlapping coastal plain deposits of Middle Tertiary age. Along the south coast these deposits form a relatively narrow and irregular strip between the Cordillera Central and the present shoreline, extending with one or two breaks in their continuity from Santa Isabel to Cabo Rojo. Two formations have been differentiated: a basal shale, called the Juana Diaz formation, the occurrence of which is limited to a

small area near the eastern extremity of the Tertiary outcrops; and the Ponce formation, essentially a limestone, in which chalky marls, semi-crystalline and fragmental strata, calcarenytes, and reefs are interbedded, although the marls predominate. Both formations display a physical and faunal detachment which has made their correlation with the Tertiary strata along the north coast one of the perplexing problems in the Cenozoic geology of Porto Rico. The northern Tertiary is much more extensive, stretching from the western extremity of the island to Loiza in the north central part of the Fajardo district, and occupying approximately five-sixths of the entire coastal area. It acquires its maximum width of fourteen miles in the longitude of Lares, narrowing westward to less than eight miles in the vicinity of Aguadilla, and eastward to a minimum of three miles at Loiza. At the latter locality the strata make their easternmost appearance in the hills lying east of Rio Grande de Loiza. Several lines of evidence indicate, however, that they originally extended some five or six miles farther east to Punta Miquillo, and that even now they continue still farther east upon the submarine platform. The increasing breadth of the latter, the presence of typical coastal plain topography upon its drowned surface north of Culebra and the Virgin Islands,[81] and the low angle of tilt which carries all the landforms of Porto Rico downward toward the east, the lower ones to positions below sea-level, are facts which leave little room to question the presence of the Tertiary rocks immediately off-shore in the northeastern portion of the Fajardo district.

The Tertiary coastal plain not only acquires its greatest width in the Lares district in the northwestern part of the island, but also its maximum thickness and stratigraphic range. Here it is divisible into five distinct formations, to which Hubbard has given the following names and estimates of thickness:[82]

5. Quebradillas limestone, 700-785 feet
4. Los Puertos limestone,[83] 550-1000 feet
3. Cibao limestone,[83] 250-1000 feet
2. Lares formation, 350-1275 feet
1. San Sebastian shale, maximum, 700 feet

[81] Meyerhoff, H. A.: The physiography of the Virgin Islands, Culebra, and Vieques, op. cit., pp. 107-119; 194-207.

[82] Hubbard, Bela: The Tertiary formations of Porto Rico. Science, 1920, Vol. LI, pp. 395-396. Geology of the Lares district, op. cit., pp. 38-49 and Table 3.

[83] Maury (Amer. Jour. Sci., 4th Ser., 1919, Vol. XLVIII, pp. 209-215) proposed the name "Aguadilla" for the strata which lie between the Lares and Quebradillas formations, on the basis of faunal studies. Two very distinct formations are present, how-

Where all five formations are present the Tertiary series averages not less than 3000 feet in thickness, and along the valley of Rio Camuy a maximum of nearly 4000 feet is attained.[84] East and west from this stream the section thins; westward, because the rate of accumulation was less rapid, and the individual formations decrease in thickness; eastward, because the younger stratigraphic members progressively overlap the older.[85] Thus the San Sebastian shales pinch out near the eastern extremity of the Lares district. The other four formations continue into, and across, the Arecibo district, but the Lares limestones become extremely thin and, not far from the western border of the San Juan district, they disappear. The Cibao formation extends but little farther, and the Los Puertos limestone gradually ends against the Cretaceous rocks in the eastern part of the San Juan district. Only the Quebradillas formation passes into the Fajardo district.

### THE QUEBRADILLAS LIMESTONE

The Quebradillas limestone has already been described by Hubbard and by Semmes,[86] but the formation undergoes gradational lithologic changes from west to east, and its characteristics in the Fajardo district are sufficiently different from those exhibited in the type locality to merit brief supplementary description. The calcareous strata of the formation are exposed in a relatively small proportion of the coastal area in the northeastern corner of the island. They are found in widely scattered patches that rise as isolated conical hills or hill clusters, the bases of which are buried by overlapping lagoonal and fluvial deposits of recent

---

ever, and in none of Maury's work is it clear whether the term "Aguadilla" as originally employed embraced one or both of them. The rocks at Aquadilla are referable to the higher formation, the Los Puertos of Hubbard, and the lower, or Cibao, outcrops within a mile of the center of the town. The Los Puertos is faunally allied with the Quebradillas and is Miocene in age, whereas the Cibao's fauna is distinctly Oligocene. Maury's early studies placed the "Aguadilla" formation in the Oligocene, associating it with the Cibao rather than with the Los Puertos. Recently, however, she has placed the Aguadilla in the Miocene (Science, 1929, Vol. LXX, p. 609), apparently accepting the opinion of Woodring. It is not clear, however, whether this change is based upon a re-evaluation of the paleontologic evidence, or upon the restriction of the term "Aguadilla" to the higher of the two formations. In view of Maury's failure to define the formational name at the time it was proposed, or to state the basis for her recent change, its validity cannot be established, although its equivalence to the Los Puertos, as employed in her recent statement, is clear. In the present report, therefore, Hubbard s carefully defined names, "Cibao" and "Los Puertos," are retained.

[84] Hubbard, Bela: Geology of the Lares district, op. cit., Pl. II.

[85] Ibid. Fig. 23, p. 75.

[86] Ibid., pp. 46-49.
Semmes, D. R.: Geology of the San Juan district, op. cit., pp. 55-57 (in part).

origin. As may be seen from the geologic map which accompanies this report, the formation is exposed in four principal areas:

(1) in the clustered hills lying between San Juan harbor and Bayamon (Fig. 24);
(2) in the conical hillocks to the east of Lago San José;
(3) in the scattered eminences which rise above the plain between Lago San José and the Rio Piedras-Carolina carretera;
(4) in a comparatively large, maturely dissected area on either side of Rio Grande de Loiza, extending from the Carolina-Canovanas carretera northward to the coast.

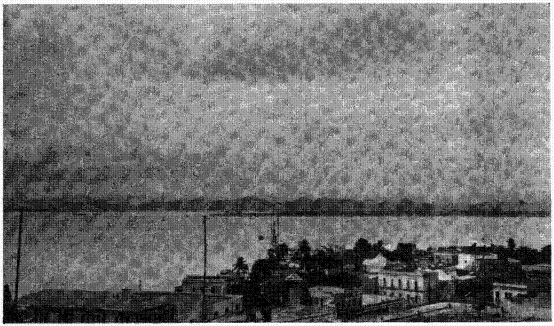


FIG. 24.—*The pepino hills of the Quebradillas limestone*
A view south across San Juan Harbor, showing the slightly upraised lagoonal deposits at Cataño (center right) overlapping the erosional remnants of the Tertiary strata.

Other isolated exposures occur within the district, but their size is small, and most of them are so remote from roads and trails that they were not visited in the course of the field survey.

In all of its occurrences in northeastern Porto Rico the limestone has been reduced by subsurface solution, and the irregular, jagged hills that characterize its outcrops are undissolved residuals that have thus far escaped destruction. In the type locality at Quebradillas the formation consists in large part of impervious marly beds which have yielded to solution but slowly. Here, in consequence, the strata have been reduced primarily by the usual processes of subaërial weathering and surface

erosion, and they form smooth, rounded hills and flat upland expanses, in which sink-hole topography is not especially prominent. These lithologic and erosional characteristics persist throughout the Lares district and across the greater part of the Arecibo district, but near the eastern boundary of the latter the lithology undergoes minor changes, which become more pronounced farther eastward. The marls give place to an increasing percentage of reef limestone, calcarenytes, and beds of recrystallized limestone, all of them types which readily succumb to subsurface solution. Sink-holes become abundant, and as their numbers increase toward the east, conical hills become the outstanding topographic form marking the presence of the Quebradillas formation. These erosional pillars, called "haystack hills" by Berkey, and "pepino hills" by R. T. Hill, who used the local term applied to them, formed the supports of caverns in an earlier stage of the present erosion cycle and have attained their prominence by the collapse of the cave-roofs around them.

The extent to which solution has proceeded in the limestone increases markedly eastward until, in the northeastern portion of the San Juan district, the formation appears above the surface of the overlapping lagoonal and fluvial deposits in bunched pepino hills. In the Fajardo district the groups of pepinos become more widely spaced, and in some localities the formation is represented by solitary erosional pillars of diminutive size. The varied effects of solution are striking. All the outcrops are exceedingly cavernous; in the reef limestone some of the caverns are original or primary, but most of them are of secondary origin, and each cave is lined with a thick encrustation of travertine. Even the arrangement of the clusters is obviously the outcome of subsurface channeling. The easternmost outcrops of the formation consist of a series of aligned pepinos, the trend of which reflects the influence of north-south subsurface drainage lines. The pepinos and sink-holes on the west bank of the Rio Grande de Loiza have a checkered pattern, in which north-south main channels and east-west tributary channels can be distinguished. The three detached hills of Quebradillas limestone between Lago San José and K. 3.6 on the Rio Piedras-Carolina carretera are similarly in north-south alignment, and in other parts of the coastal plain the plan of the original underground drainage, although more complex, can still be deciphered from the erosional remnants which are present. In the Fajardo district the cycle of subsurface erosion reached the penultimate stage of development, for the Quebradillas formation has been reduced to a perfectly graded peneplane above which the pepinos rise as monadnocks. Since the

erosional plane was formed, the recent changes in level at the coast have caused some aggradation to occur, and its surface is buried beneath a veneer of alluvial and lagoonal materials.

In the Fajardo district the lithology of the Quebradillas formation is about as varied as the lithology of limestones can be. Cavernous reef limestones and crystalline or semi-crystalline types predominate, and interstratified with them are beds of marl and a few layers of impure calcarenyte. Two and one-half miles northeast of Carolina an exposure of breccia, consisting of fragmented reef materials in a clay matrix, was noted. The reef members characteristically consist of scattered coral heads and recrystallized coral bases, with coral and shell fragments, rounded sand-grains, and, more commonly, marl filling the spaces between the heads. Most of the original cavities in the reef limestones have been filled in this way, and, from this characteristic, can generally be distinguished from the younger solution cavities. As a rule, the reef and crystalline beds are massive, varying in thickness from two to twelve feet, and the predominance of these two types in the section has governed the erosional development which the formation has undergone. The marls and calcarenytes, typical exposures of which may be seen in the railroad cut about one kilometer west of the Canovanas Sugar Central, are habitually thin-bedded. In several of the pepino groups beds of marl appear to have furnished local basements above which the erosional remnants rise. In the limestone hills between Carolina and Loiza, for example, drainage ditches in the bottoms of the sink-holes reveal impervious marls, through which the underground drainage was unable to penetrate by solution. The haystack hills which surround the sinks on every side consist almost wholly of massive beds of pure calcium carbonate, some of it partly recrystallized, in which marly strata either are absent or are limited to beds of negligible thickness.

## STRUCTURAL AND STRATIGRAPHIC RELATIONS OF THE QUEBRADILLAS FORMATION

The structure of the Quebradillas formation appears to be simple, but the character of its outcrops made it impossible to obtain an unequivocal series of definite observations. Many exposures consist of the massive strata which form the pepinos, and in them irregular bedding and local slumping around the margins of sink-holes tend to obscure the true structure. The impressions obtained from distant views are probably more

reliable than detailed measurements of individual strata, and they indicate that the strata of the coastal plain dip uniformly toward the north at an angle which is not lower than three degrees, and which does not exceed six. In the railroad cut one mile west of the Canovanas Sugar Central, the thin-bedded marls and calcarenytes dip five degrees north, and this amount may be taken as the average for the formation in the Fajardo district. It checks almost exactly with the numerous measurements the writer has made in the Arecibo district and in portions of the San Juan and Lares districts. The dip of the strata is discordant with the slope of the surface, whether the latter be measured across the present surface or across the relatively accordant tops of the clustered pepinos, which rise to the elevation of an old erosional level that may be traced far inland in the hills of the Cretaceous oldland immediately to the south. Obviously the five degree dip is an acquired deformational characteristic, that has been completely disregarded in the recent erosional history of the coastal region.

The discordance between the one degree slope of the erosional surfaces and the five degree angle of dip affords a means of estimating the thickness of the Quebradillas formation. The angle of discordance is not more than four, nor less than three degrees. Between Bayamon and Canovanas the limestone belt maintains an average width of four miles, making the estimated thickness of the formation not less than 1100 feet and not more than 1450 feet. In the Lares district Hubbard gives the thickness as 700 feet at Quebradillas and 875 feet at Camuy.[87] At Arecibo it approximates 1000 feet, and in the vicinity of Manati it is somewhat in excess of 1200 feet. From this point eastward the limestone maintains a relatively constant thickness, and the computations for the Fajardo district appear to be normal. The rapid decrease toward the northwestern corner of the island is probably due to the more extensive erosion which the beds have undergone since their exposure, and it need not be attributed to local or regional differences in the rate of subsidence during Quebradillas time. In fact, several lines of evidence show that the period of its accumulation was characterized by more marked crustal stability than obtained during any other Tertiary age. It may be questioned, however, whether the 1500 feet maximum thickness which the formation now possesses represents its total thickness at the end of the period of deposition; for its tilted strata have already passed through one cycle of erosion and have entered upon a

[87] Hubbard, Bela: Geology of the Lares district, op. cit., Plate I.

second. In each cycle some of the upper beds have been removed, yet projection of the dipping strata and the erosional planes to the edge of the Porto Rican platform indicates that the loss through erosion may not have been great, and that the formation probably did not exceed 1800 to 2000 feet when deposition ceased. In view of the number of uncertain factors, however, it would be unwise to place too much confidence in this rough estimate of original thickness.

In the Fajardo district the Quebradillas formation rests directly and unconformably upon the underlying Cretaceous volcanics and sediments. The contact is not exposed within the boundaries of the district, because the erosional surface above which the pepinos rise is buried beneath a veneer of lagoonal and alluvial deposits of variable thickness. The Tertiary hills between Bayamon and Cataño, however, are locally separated from outcrops of Cretaceous rocks by as short a distance as 200 yards, in which the residual soils of the "Older Series" have been modified by surface wash to an extremely limited extent. The Cretaceous materials of this area consist of tuff and ash, both of which have been deeply lateritized. In places the weathered surface appears to have undergone so little gullying that it undoubtedly represents the unmodified erosional plane upon which the Tertiary coastal plain was originally deposited. It is impossible to gauge how much lateritization the rocks underlying this surface have undergone since stripping re-exposed it, but the depth and extent of alteration are greater than in the Cretaceous rocks of any other portion of the district. This fact appears of especial significance, because it implies that the greater part of the weathering must have taken place before the coastal plain was laid down, rather than in the brief lapse of time since its removal, else the older erosional surfaces would exhibit far more profound effects of residual decay. The assumption that marine strata were deposited upon a subaërially eroded land surface which escaped completely the usual planation by wave action appears absurd, yet this conclusion is inescapable. And fortunately it can be proved by direct evidence from other parts of northern Porto Rico. In several stream gorges in the San Juan, Arecibo, and Lares districts, the basal beds of the coastal plain may be seen in direct contact with the underlying Cretaceous volcanics. In every case which the writer has had opportunity to study, the Cretaceous rocks had been deeply lateritized before the Tertiary strata were deposited on them, and in several places, notably in the canyon of Rio Arecibo and in the valley of Rio Yunes, lateritic soil zones, ten to forty

feet in thickness, are present immediately beneath the unweathered Tertiary limestones. The profound weathering which has taken place in the Cretaceous rocks at the margin of the coastal plain in the Fajardo district indicates that here, too, the subaërially eroded oldland underwent little or no marine planation when Middle Tertiary submergence occurred. The basal strata of the coastal plain were laid upon a practically unmodified surface of deeply weathered volcanic rocks.

Further proof of this interpretation is furnished by the nature of the contact between the Tertiary and Cretaceous rocks. Broadly considered the line of contact is relatively straight, but in detail it is exceedingly irregular. It is composed of moderately strong salients and re-entrants that show the undulating character of the pre-Miocene surface, for they are unrelated to the features of Quaternary stream dissection. All of the re-entrants contain outcrops of the Quebradillas formation, some of which may be seen in the pepino hills south of San Juan harbor, south of Lago San José, and between Carolina and Canovanas. Between the first two of these three localities a salient protrudes about a mile northward in the vicinity of Rio Piedras; between the second and third, at the town of Carolina, another extends nearly two miles north of the adjacent re-entrants. As shown on the geologic map of the district, outcrops of Quebradillas limestone occur within the recesses in locations that are considerably south of the northernmost points reached by the Cretaceous spurs. The significance of the irregularities is more noteworthy if it be recalled that the surface on which the coastal plain strata rest has been tilted five degrees north, and it seems probable that the fluvially eroded surface on which the Quebradillas limestone was accumulated had a relief of several hundred feet, in spite of the deep weathering which had affected every part of it. An examination of the Cretaceous rocks and rock structures in the spurs shows that their elevation was in no small measure due to the resistance given them by their compressed synclinal structure.

### THE FAUNA OF THE QUEBRADILLAS LIMESTONE

The Quebradillas limestone is the most fossiliferous of the Tertiary formations in Porto Rico, and from its outcrops in western Porto Rico Maury [88] and Hubbard [89] have described 104 different molluscan forms. A comparatively small number of corals has been listed from this horizon

[88] Maury, C. J.: Tertiary Mollusca from Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, 1920, Vol. III, Pt. 1.

[89] Hubbard, Bela: The Tertiary molluscs of the Lares district, ibid, 1921, Vol. III, Pt. 2.

in the recent work of Coryell and Ohlsen.[90] Their study was based upon the specimens in the Reeds and Hubbard collections, both of which contain material taken only from the northwestern districts, where this phylum is but meagerly represented. Eastward, as has been pointed out, the lithologic characteristics of the Quebradillas limestone change from a preponderance of clastic layers to an abundance of reef beds; and with the change in the character of the strata, the complexion of the fauna changes accordingly. Corals increase in number and variety, and within the limits of the Fajardo district they equal the Mollusca in importance. Other groups of organisms are present in fewer numbers. Reeds, Hubbard, and the writer have found foraminiferal beds, but the microfauna is somewhat more prolific in the Lares and Arecibo districts than in the northeastern part of the island, where the remains are poorly preserved and appear to have suffered considerably from the effects of wave action prior to their burial. Echinoids are not uncommon despite the fact that only a single specimen was found in the Fajardo district, in the limestone hills south of Cataño. Sharks' teeth, also, have been taken from the strata of the formation, but none were discovered in the course of the present survey.

There are not many exposures of the Quebradillas limestone in the Fajardo district, and the opportunities for fossil-collecting are correspondingly limited. Nearly all of the outcrops are fossiliferous, it is true, but many of the massive strata composing the scattered pepinos contain coral heads which are so firmly crystallized in the rock, or are so large in size, that their recovery with the equipment which the author had at his disposal was not feasible. Other types of organic remains are rare in the coralline beds, many of which are so heavily encrusted with travertine that it is impossible to detect the small fossils within them; but in the semi-crystalline beds, the calcarenytes, and the coarser-grained marls Foraminifera are common, and Mollusca are unfailingly present. Their state of preservation is uniformly poor, and in the majority of exposures only the internal molds of the Mollusca can be recovered. In five localities, however, comparatively good fossils were obtained, and all but a few of the species identified were taken from them. Four of the localities are situated in the limestone belt between Canovanas and Rio Grande de Loiza; the fifth is located in the hills south of Cataño (Fig. 24).[91]

[90] Coryell, H. N., and Ohlsen. Violet: Fossil corals of Porto Rico, with descriptions also of a few Recent species, ibid, 1929, Vol. III, Pt. 3.

[91] Professor Horace Elmer Wood, II, has kindly supplemented the author's fossil collections with specimens, many of which were gathered in the Cataño locality.

The study of the fauna is incomplete. The many samples of marl which were collected have been examined for Foraminifera, and several faunules have been isolated and are awaiting study. The single fragment of an echinoid has not been identified, and some of the most poorly preserved corals and Mollusca remain unclassified. A small collection of corals was referred to Dr. H. N. Coryell, who has kindly made the following identifications:

*Antiguastrea cellulosa* (Duncan)
*Porites douvillei* Vaughan
*Cyathomorpha tenuis* (Duncan)
*Brachyphyllia* sp.
*Plocophyllia* sp.
*Antilloseris* sp. (?)

Thirty-eight molluscan forms have been differentiated, of which twenty-six are Pelecypoda, and twelve Gastropoda. Many specimens were referred provisionally to described species, because their identification has been based upon internal molds or upon none too diagnostic shell fragments. The faunal list follows:

Pelecypoda
**Leda peltella* Dall [92]
*Arca* n. sp.
***Arca (Scapharca) guajatica* Sheldon and Maury [92]
*Arca (Scapharca)* n. sp.
**Glycimeris portoricoensis* Hubbard, n. var.
*Ostrea cahobasensis* (?) Pilsbry and Brown
*Pecten (Plagioctenium) cercadica* Maury
*Pecten (Plagioctenium)* n. sp.
*Pecten* n. sp.
*Pecten (Chlamys)* cf. *waylandi* Cooke
*Venericardia scabricostata* (Guppy)
*Venericardia santodomingensis* Pilsbry and Johnson
**Phacoides (Miltha) hubbardi*, n. sp. (=P. sp. indet. Hubbard) [93]

[92] Reported in the Quebradillas formation of western Porto Rico by (*) Hubbard, (**) Maury, (***) Hubbard and Maury.

[93] Several specimens in the Fajardo collection indicate the need of recognizing as a distinct species the form which Hubbard described as *Phacoides (Miltha)* sp. indet. (The Tertiary molluscs of the Lares district, op. cit., p. 112, Pl. XVIII, fig. 5). The specific name *P. (Miltha) hubbardi* is herewith proposed.

*Phacoides (Lucinisca) cf. calhounensis Dall
***Divaricella prevaricata Guppy [92]
Codakia spinulosa (?) Dall
***Cardium (Laevicardium) serratum Linné
***Cardium (Trigonocardia) haitense cercadicum Maury
*Cytherea berkeyi Hubbard
***Chione woodwardi (?) (Guppy)
**Antigona tarquinia antillica Maury
Antigona tarquinia (?) Dall
***Metis trinitaria Dall
Tellina sp. undet.
Semele (?) sp. undet.
***Teredo incrassata (Gabb)

Gastropoda
Solarium sp. indet.
Turritella tornata Guppy, n. var.
*Strombus bifrons (?) Sowerby
Orthaulax aguadillensis Maury, n. var. (?)
*Orthaulax portoricoensis Hubbard
*Cypraea cf. spurcoides Gabb
*Columbella (Strombina) cf. portoricana Hubbard
*Alectrion gurabensis varicum Hubbard
***Cancellaria laevescens (?) Guppy
*Conus catenatus (?) Sowerby
*Conus marginatus Sowerby
Conus symmetricus semiobsoletus (?) Maury

Especial attention has been given the molluscan fauna in the paleontological work which has been done thus far because of its immediate utility in the problems of correlation. If allowance be made both for the varietal differences which the author has distinguished and for the poor state of preservation which has made some of the identifications uncertain, twenty-one of the thirty-eight forms differentiated have been reported in the Quebradillas limestone in the Lares district. The percentage is extraordinarily high when the lithologic changes that occur in the intervening distance are considered, and the exact stratigraphic equivalence of the beds at both ends of the island cannot be questioned. There are, it is true, six species in the fauna which are found in the Los Puertos

limestone, a comparatively high percentage, considering the small fauna described from the Los Puertos strata. Five of the six species, however, are known to be common to both horizons, three of them being relatively long-ranged types which are widely distributed in the Middle Tertiary rocks of the Caribbean region. Only one species which has not been reported above the Los Puertos limestone in Porto Rico occurs in the Quebradillas formation of the Fajardo district; namely, *Orthaulax aguadillensis* Maury.[94] This species has been listed from the Tertiary limestones of Vieques and Saint Croix, however, and its occurrence in the Quebradillas fauna was to be expected. There is no reason, therefore, to postulate the presence of Los Puerto strata in the district, and Hubbard's opinion that they end by overlap near the eastern border of the San Juan district appears to be fully substantiated.

The correlation of the Quebradillas limestone with stratigraphic units in other parts of the West Indies was seemingly well established, but the recent studies of Woodring have raised several points which re-open the question. The partial equivalence of the Quebradillas with the Ponce limestone along the south coast of Porto Rico was demonstrated by Hubbard, and Woodring regards it as a correlate of the Tertiary strata on Vieques and Saint Croix. The affinities of the Quebradillas and Bowden faunas were announced by Hubbard as early as 1917, although the first published correlation is Maury's, which appeared in 1919.[95] Woodring, however, considers the Quebradillas to be older than the Bowden, but the basis for his opinion is not very fully presented.[96] The writer is not qualified to discuss the change of status proposed by Woodring, but he is convinced that the faunal facts require more careful scrutiny before its correlation with the Bowden is to be dismissed. A little more than twenty percent. of the Quebradillas fauna occurs in the Jamaican Miocene, a remarkably high figure when the distance separating the two islands is considered. A study of a small molluscan fauna from Long Point, Saint Croix, completed recently by Miss Ella-Kate Wemple, has yielded a list in which fifty percent. are Bowden species, although a study of the fossils

[94] The writer does not agree with Woodring that *O. aguadillensis* Maury and *O. portoricoensis* Hubbard are the same species. Both are represented in the Fajardo collection as distinct and easily differentiated forms.

[95] Maury, C. J.: The correlation of Porto Rican Tertiary formations with other Antillean and mainland horizons. Amer. Jour. Sci., 4th Ser., 1919, Vol. XLVIII, pp. 209-215.

[96] Woodring, W. P.: Miocene Mollusks from Bowden, Jamaica. Contrib. to the Geol. and Pal. of the West Indies, Pt. 2, Carn. Inst. of Wash., 1928, No. 385, pp. 62-63 and table facing p. 41.

from other Saint Croix localities may be expected to lower the proportion of common forms. A hasty classification of a collection from southern Vieques has revealed more Bowden than Quebradillas species. There is good reason to believe, as Woodring does, that the Saint Croix and Vieques Tertiary and the Ponce and Quebradillas limestones are essentially contemporaneous deposits, but the cumulative evidence seems also to favor their correlation with the Bowden, rather than with some older horizon.

The geologic age of the Quebradillas is even less firmly fixed than its correlation, for it has been variously assigned to the Upper Oligocene and to the Lower and Middle Miocene. The problem involved is too vast in scope to be given consideration in the present report, and it need merely be stated that the concensus of current opinion places this formation and its correlates in the Lower Miocene. This point of view appears to have grown out of the not fully explained tendency to rob the Oligocene to pay the Miocene, and among recent authors only Hubbard has argued strongly for the Oligocene age of these transformed horizons. The question involves fundamentally the settling of the position of the boundary between the Oligocene and the Miocene, on the one hand, and correlation with European Tertiary horizons, on the other. On these moot points opinions are undergoing too rapid evolution for dogmatism, and toward their solution the present report has nothing to contribute.

## Quaternary Sedimentation

During the latter part of Tertiary time the whole of Porto Rico was above sea-level. Gentle arching seems to have put an end to coastal plain accumulation; and, after the ensuing erosion cycle had reached an advanced stage of development, vertical uplift raised the island about 800 feet and erosion started anew. At no time was the elevation quite high enough for differential erosion to carve the mountain and coastal elements into forms with high relief, such as have in recent time led to extensive fluvial aggradation in parts of the interior. The edge of the island and of its submarine platform coincided, and marginal deposition must have been restricted to the steep slopes that are found on every side except the east, where the late Tertiary landmass extended to the farthest limits of the Virgin Islands. In consequence of this emergent condition, no permanent deposits either of fluvial or of marine origin were formed until the Quaternary, when, in spite of renewed uplift, fluctuations in the position of the strandline and rapid heightening of the relief during the early stages of dissection have been followed by the formation of the continental

and marine materials which occupy large areas within the limits of the Fajardo district (cf. geologic map). The variety of the Quaternary deposits is surprising, for they include littoral, estuarine, lagoonal, eolian, delta, floodplain, and alluvial fan types. The local problems of their genesis are too numerous to receive extended treatment, and their more important features must be briefly summarized under the following headings:

(1) The San Juan formation
(2) Recent deposition in the coastal section
(3) Fluvial aggradation in the interior.

## THE SAN JUAN FORMATION

The name "San Juan" was proposed by C. P. Berkey to include the scattered outcrops of consolidated calcareous sands which occur along the northern coastline of Porto Rico.[97] As used by Berkey and later by Semmes,[98] the formational name was applied strictly to these calcarenytes, in which conspicuous and persistent cross-bedding provides ample evidence of their eolian origin. At a somewhat later date the differentiation of deposits comparable either in age or in origin to the San Juan formation induced Lobeck[99] and Hubbard [100] to expand the term "San Juan", until it embraced not merely the partly cemented eolian sands, but also contemporary and younger materials of both wind-blown and hydroclastic derivation. Far from being useful, the hybrid concept which has been thus created makes it impossible even to discuss the individual varieties included in the sedimentary miscellany without constant danger of confusion, and it is here proposed to restrict the term to its original meaning, for the following reasons:

(1) Formational names are applicable only to single lithologic units. The eolian and marine deposits embraced in the expanded San Juan formation are lithologically and genetically distinct, and they do not intergrade; hence the use of the same name for all is erroneous.

(2) All lines of evidence support the opinion advanced by Berkey [101] that the San Juan formation may be as old as Pleistocene, whereas most of the deposits which it is proposed to add are of Recent origin. The employment of a single formational name for all of these sediments in-

[97] Berkey, C. P.: Geologic reconnoissance of Porto Rico, op. cit., pp. 11-12.
[98] Semmes, D. R.: Geology of the San Juan district, op. cit., pp. 53-55.
[99] Lobeck, A. K.: Physiography of Porto Rico, op. cit., pp. 361-366.
[100] Hubbard, Bela: Geology of the Lares district, op. cit., pp. 98-103.
[101] Berkey, C. P.: Geologic reconnoissance of Porto Rico, op. cit., p. 12.

volves the creation of a terrain, and this policy is not sanctioned by current practice.

(3) The San Juan formation was deposited, perhaps continuously, along 125 miles of coastline under conditions that were similar throughout the entire distance. The other Quaternary sediments of the coastal areas are the products of factors which operated locally and discontinuously, and they are, without exception, disconformably related to the San Juan beds.

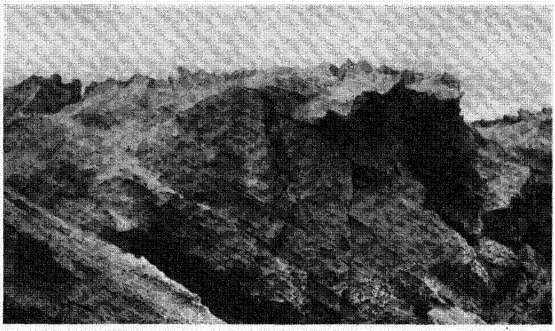


FIG. 25.—*The San Juan formation*

Typical cross-bedding and solution effects along the exposed cliffs at Punta Vacia Talega.

The San Juan formation, *sensu restrictu,* may therefore be defined as the poorly consolidated cross-bedded calcarenyte of eolian origin, outcropping in isolated and often widely scattered bluffs and cays situated chiefly along the northern coast of Porto Rico. There are four outcrops in the Fajardo district; namely, (1) in the northern part of the city of San Juan, the type locality; (2) along the Condado section of the shoreline immediately east of San Juan and in other parts of Santurce; (3) at puntas Cangrejos and Maldonado, two adjacent peninsulas north of Lago Torrecilla; and (4) at Punta Vacia Telega.

In all these localities except one the characteristics of the formation are the same. It consists of massive beds, in which the only visible structure is the regular cross-bedding (Fig. 25). The latter has a con-

stant direction of dip slightly south of west, and the angle of dip varies within the narrow limits of 22° and 30°. The constituent grains are well cemented, although the degree of consolidation differs somewhat according to the exposure of the rock. Where it fronts the sea and is drenched continually by the spray from breakers, it is firmly indurated for an inch or more beneath the weather-beaten surface. Where not so exposed, the degree of consolidation is decidedly less, although sufficient to render the formation a consistent ridge- or cliff-maker. Berkey, Semmes, and Lobeck have described secondary horizontal structures in some of its outcrops west of San Juan, notably in the vicinity of Arecibo, but in the Fajardo district secondary structures of this type were not observed. As in other parts of Porto Rico, the rock is composed primarily of rounded fragments of corals and shells, but microscopic examination reveals other constituents, including worn and polished foraminiferal tests, angular quartz grains, and, less commonly, subangular feldspar fragments and pieces of other igneous minerals. The calcareous fragments have been rounded, but the other particles stand out prominently in thin-section because of their angularity. Calcium carbonate forms the cementing material, binding the contiguous surfaces of adjacent fragments, but only rarely entering the interstices.

The lithologic features of the rock indicate that the materials composing it were not blown far. Wind-blown sands that have been transported even for moderate distances show more homogeneity in grain size and in mineral composition, as well as more perfect rounding, than is exhibited in the San Juan calcarenyte. In the latter, although the calcareous fragments are rounded, the degree of rounding is not great, whereas the quartz particles and the other mineral fragments display practically no effects of rounding, for many of them still possess sharp edges and corners. The very presence of the non-calcareous constituents, in fact, supplies additional evidence of the slight amount of transportation, for the wind, a perfect sorting agent, separates materials that have different specific gravities, while abrasion disposes of the softer particles, before movement has gone on for any length of time. A study of the surfaces of the grains, moreover, reveals that only those of the calcareous fragments are typically pitted and frosted, whereas the surfaces of the quartz grains are clear and glassy. Even with moderate wind action frosting takes place in grains of all types. These physical characteristics in themselves are sufficiently suggestive, but, if considered in conjunction with the location and distribution of the sands, they permit no escape from the conclusion that the San Juan formation represents a line of

coastal dunes, the materials of which were gathered by the prevailing northeasterly trades from an immediately adjacent beach.

The peculiar distribution of the San Juan formation indicates its genetic association with a shoreline older than the one which now bounds the island of Porto Rico on the north. Not alone in the Fajardo district, but along the entire coastline to the west, its occurrences are restricted to the prominent salients and headlands and to small detached islands which lie short distances offshore. The all but perfect alignment of the San Juan outcrops offers the temptation of projecting them into a continuous series of dunes formed originally on the landward side of an offshore bar, which occupied a position now retained by the headlands and by the islands of Cordilleras Reefs. Lobeck suggested this explanation of the formation's origin in a figurative way, but left the hypothesis without support.[102] There is, however, adequate reason to believe that the explanation holds; for the linearity of the outcrops, contrasting with the haphazard and local occurrence of the modern dunes; the uniform structural and physical characteristics of the deposits, betokening identical conditions of genesis along 125 miles of coastline; the recurrent lowering of sea-level during the cycles of Pleistocene glaciation, a feature favoring the development of offshore bars along the emergent coast of the island; and the invariable association of the San Juan dunes with the Tertiary coastal plain, are facts which provide unanimous support for the theory, and which at the same time are incompatible with any other mode of origin. Certainly the modern dunes, which are absent from long stretches of the coastline, even where conditions seem to favor their development, and which fit into the irregularities of the present shoreline without a suggestion of alignment, afford an instructive contrast.

The constant association of the San Juan formation with the Tertiary coastal plain, mentioned in the preceding paragraph, merits additional comment. The outcrops of the dune sands are co-extensive with the Quebradillas formation, and eastward in the Fajardo district the occurrences of the calcarenyte cease where the Quebradillas limestone disappears from the mainland a short distance east of Loiza. Even on such prominent points as Miquillo, Picua, and Embarcaderos, not to mention Cape San Juan, the San Juan deposits are absent, as is the Quebradillas formation along this portion of the coast. Two miles or more offshore, however, a prominent ridge makes its appearance on the submarine platform, and on the United States Coast and Geodetic Sur-

[102] Lobeck, A. K.: Physiography of Porto Rico, op. cit., p. 362.

vey charts it may be traced east-southeastward along Cordilleras and Hermanos reefs to Culebra. It rises more than 100 feet above the floor of the submarine platform, and in Cordilleras Reefs it attains the surface in a number of small islands, such as Icacos, Ratones, Lobos, and Diablo cays. The rock composing these islands consists of strongly cross-bedded, pure white calcareous sand, the characteristics of which indicate an origin similar to, and contemporaneous with, the San Juan formation on the mainland. The nature and significance of the islands have been previously discussed by the writer,[103] and the conclusion was reached that the rocks of which they consist must be referred to the San Juan formation. In acquiring expression above the surface of the sea the consolidated dunes rise some 50 or 60 feet above a much broader base of older material, which physiographic evidence indicates is an extension of the Quebradillas formation from the mainland. The persistence of the high calcium carbonate content of the calcarenyte shows that it was formed at a time when the Cretaceous volcanics did not constitute a part of the shoreline, as they do at present in Culebra and in the northeastern corner of Porto Rico.

The age of the San Juan formation has only been tentatively fixed. From its relationship to the Tertiary coastal plain and to Recent formations, and from its degree of lithification Berkey concluded that its development must be referred to the Pleistocene. The writer believes that it can be dated somewhat more closely by using the physiographic evidence available.

In the first place, the major physiographic features in Porto Rico and the Virgin Islands show that the island elements have been relatively stable since Middle Miocene time save for two short periods of positive movement, the latter of which was accompanied by slight eastward downwarping. The short emergence which initiated the construction of a barrier beach and associated dunes can best be explained by postulating a change in sea-level rather than a change in land-level, and the world-wide changes in the strandline which accompanied the advance and retreat of the Pleistocene ice-caps furnish an entirely adequate explanation for the temporary emergence of San Juan time.

In the second place, the formation has been tilted. Near Arecibo its base is approximately fifteen feet above sea-level, and it declines eastward to sea-level at San Juan, and to a position not less than 30 feet below sea-level in the islands of Cordilleras Reefs. The amount of

[103] Meyerhoff, H. A.: Physiography of the Virgin Islands, Culebra, and Vieques, op. cit., pp. 198-207.

tilting is much smaller than that which has taken place in the same direction in the older, erosional landforms, but it is enough to show that the formation was deposited before the cessation of the tilting movement. The latter occurred wholly within Pleistocene time.

In the third place, the minor modifications which the San Juan deposits have undergone since slight tilting partly submerged them are all referable to Recent time. They are so definite in character that, taken in conjunction with the tilting, they furnish an adequate basis for dating the formation of the calcarenyte as relatively late Pleistocene.

In the southern and western part of Santurce the partly consolidated and deeply weathered sands which are exposed in some of the street cuts and along the American Railroad are only tentatively referred to the San Juan formation, because they exhibit departures from the diagnostic features of the latter that entitle them to a more analytical study than could be given them. They are situated south of the line of San Juan outcrops, and they fail to reveal the characteristic cross-bedding, even in the many fresh excavations which the author found and examined. Although a careful microscopic analysis has not been made of the samples taken, they appear to contain a much higher percentage of quartz than the San Juan calcarenyte. Toward the west they merge with the marly deposits which are now being formed along the shores of San Juan harbor, but whether they constitute a source for the latter, or are themselves similar deposits exposed by the slight emergence of recent geological date, is not known. Sediments of like nature were not found in any other part of the district, and the extent to which they have been modified and buried in the rapidly growing settlement of Santurce made their relationship to the San Juan formation obscure. Until a more definitive field and laboratory study of them is undertaken, judgment concerning their age, origin, and stratigraphic affiliations may wisely be suspended.

### RECENT DEPOSITION IN THE COASTAL SECTION

In the Fajardo district the other sediments of the coastal region are unconsolidated materials of recent origin. Their accumulation was so intimately related to the physiographic development of northeastern Porto Rico that their distribution and characteristics can best be understood if they are considered in connection with the factors which governed their deposition, and for this mode of treatment they may be grouped genetically into (1) the playas, (2) the lagoonal sediments, and (3) the littoral deposits.

(1) *The playas*—The term "playa," which in literal translation means "beach" or "shore," has been applied also to the flat triangular areas that extend like wedges from the shoreline into the interior. Their distribution is so obviously dependent on the features of fluvial dissection that the essential elements involved in their origin require little exposition. They are best developed along those portions of the district's coastline where the Tertiary coastal plain is absent, and the extent which each attains is roughly related to the size of the stream that drains it. The materials composing the playa deposits are almost wholly alluvial in character, and their relatively flat surfaces, which slope seaward at a very low angle, consist of a veneer of floodplain and fan materials covering slightly older delta deposits that were built outward into estuaries. The delta sediments are occasionally exposed in the marshy tracts at the seaward margins of a few of the playas, where recent emergence has carried them several feet above sea-level. The dark massive clays of which they are composed contrast sharply with the bedded sands or fine gravels that form the playa surfaces farther inland, and the delta muds appear to have settled in the salt or brackish water of the bays beyond the reach of the stream currents that deposited the coarser and higher strata. In other parts of Porto Rico marine shells have been discovered in some of the playa beds, but none were found in the Fajardo district, although the combined fluvial-estuarine conditions of sedimentation were undoubtedly alike in every portion of the island.

The playas associated with Rio Fajardo and Rio Blanco are the largest within the region studied, but neither is entirely typical, because their playas are inseparable from their extensive floodplains. The other streams in eastern and northeastern Porto Rico are small and many are intermittent, and as a result of their small volumes some have failed to fill completely the estuaries into which they discharge. Several have steep gradients, and the deposits they have formed near their mouths are more like alluvial fans than deltas or floodplains. In spite of the variety the individual playas exhibit, their formation represents the outcome of a simple sequence, involving normal fluvial dissection, marginal submergence of 30 to 40 feet, delta and floodplain construction in the estuaries, with concomitant upstream aggradation, and, finally, slight emergence. The form, size, and sedimentary materials of each playa are dependent largely upon the stage of development the local stream associated with it had reached prior to submergence.

(2) *The lagoonal sediments*—From San Juan Harbor eastward to the mouth of Rio Grande the coastal section is low and flat (Fig. 2), and

near the shoreline marshes and swamps are common. Associated with the latter in the western part of the coastal belt are a few enclosed bodies of open water, such as Lago Torrecillo and Lago San José. Shut off from the Atlantic by low barrier bars, they are being rapidly filled by mud and vegetation. Like them in all other respects, San Juan Harbor differs chiefly in maintaining an open connection with the ocean. The enclosed water bodies lie practically at sea-level, and the water within them is kept brackish by the inflow of the tide through the tortuous and narrow channels that connect them with the sea. The unconsolidated sediments surrounding them form a relatively broad plain, which rises in elevation almost imperceptibly inland, and above which the few remnants of the Quebradillas limestone protrude with sharp discordance. The material composing the plain varies from place to place, but its variation is systematic. Muds, some of them black from their high organic content, are most characteristic. In interstream localities they are not infrequently calcareous, but near the streams they are usually argillaceous and contain admixtures of river silt and sand. Along the northeastern margin of San Juan Harbor where the water of the bay laps exposures of the San Juan calcarenyte or an associated deposit of poorly consolidated sand, marls are in the process of formation. And in several localities pockets of white quartz sand, surrounded on all sides by the normal deposits of clay, endow the formation with its one baffling mystery.

There can be little question regarding the origin of the muds. The absence of stratification, their association with partly filled lagoons, and their position between the hills of the interior and the bars which now form the coast, show beyond dispute that they are lagoonal deposits which have been exposed as a result of the recent slight emergence which eastern Porto Rico has undergone. The sources of the sediments, except the quartz sands, are equally clear. The lateral gradation from clays to silts and sands, both in the direction of the streams and in the direction of the interior hills, as well as the slight rise in elevation in the same directions, indicates that the materials were brought into the lagoons by streams and rain-wash, and except for the organic matter, were initially alluvial in character. It must be assumed that Lobeck was considering only the agent of transportation which carried them to their present resting place when he dismissed the possibility of their marine origin and classified them as alluvium;[104] but this principle of classification cannot be accepted, for the deposits along the north coast of Porto Rico must be deemed lagoonal in origin. It is true that allu-

[104] Lobeck, A. K.: Physiography of Porto Rico, op. cit., p. 349.

vium is associated with them, overlapping them in places; especially on their landward margin. Locally, as in the area east of Rio Herrera, an alluvial cover may completely mask the lagoonal muds beneath, and in mapping the deposits it is quite impossible to effect a clear separation of the two types, as the geologic map attempts to show.

At the present time no explanation is available for the pockets of quartz sand.[105] Their isolated position makes it extremely difficult to regard them as mechanical deposits, and there is no tangible proof of organic precipitation. They increase in size and number in the coastal sections to the west, and it is hoped that the studies in the Arecibo district will provide some solution of their mystery.

(3) *The littoral deposits*—The remaining sedimentary deposits which occur in the coastal region are directly associated with the coastline, the evolution of which will be discussed as a phase of the physiographic history. In addition to the bars, spits, and tombolos, there are a few older marine deposits which were formed before the recent uplift of a few feet, and which occur as peninsulas along some stretches of the shoreline. Among them may be mentioned Miquillo and Picua points, in the marine sands of which, three to six feet above sea-level, Recent Mollusca are embedded. They both have spit-like forms, although the precise reason for the formation of two such prominences along this part of the coast is not clear. Punta Embarcaderos near Luquillo appears to be a cuspate bar which developed contemporaneously. Coral reefs are forming marginal limestones off several portions of the coast, but their development cannot be discussed within the limits of the present report.

### FLUVIAL AGGRADATION IN THE INTERIOR

There is no line of demarcation between the playa deposits and the floodplains of several of the large streams, like Rio Fajardo, nor can a sharp boundary be drawn to separate the lagoonal and normal river deposits in the northern part of the district. The extent of the floodplains and their relation to the playas and lagoons show that their deposition has been markedly accelerated as a result of submergence, which necessitated aggradation for long distances upstream. The rivers are slightly entrenched in their floodplains in consequence of very recent uplift, but the amount of entrenchment is rarely adequate to keep them from overflowing their banks in times of abnormal rains.

[105] Cf. Britton, N. L.: Botanical investigations in Porto Rico. Jour., N. Y. Botanical Garden, 1922, Vol. XXIII, pp. 56-57.

The depositional features found near the mouths of the streams, however, present few problems, but inland several drainage systems have undergone local aggradation which is more difficult to explain. Terraces are haphazardly distributed along a few of the stream courses (Fig. 27). Their formation was undoubtedly due to changes in water volume and load, but why the changes should have occurred in each case is by no means obvious. The terraces are not associated with all the drainage systems, hence local factors must be sought to account for them. One of the most obvious is stream capture, but whether piracy can be held responsible for every example which the Fajardo district contains the author does not know. The terraces along Rio Grande de Loiza may well have been developed when it captured the headwaters of Rio Canovanas. The steep gradient of the latter and the coarse materials it transported from the dioritic outcrops of the Caguas lowland were undoubtedly more than the mainstream could carry over its lower gradient, even with the additional volume of water. Aggradation to the point of balance would have followed, to be succeeded by degradation and terrace development after equilibrium was achieved. This hypothesis has the advantage of plausibility, although close scrutiny brings to light objections which have not been disposed of. In any event its application is limited, and the terraces along other streams remain unexplained. Regional factors, such as change of level, tilting, and climatic cycles cannot account for them, and it was not possible to determine whether piracy and temporary overload as headward erosion tapped easily reduced rocks furnish a satisfactory set of causes for every case.

Of greater areal importance are the alluvial deposits of the Caguas basin, which bury the floor of the lowland to moderate depths.[106] The alluvium is of a two-fold character, consisting in part of local floodplains deposited by Rio Grande de Loiza and the several large tributaries which join it within the areal limits of the basin, and in part of marginal alluvial fans which coalesce with each other and interfinger with and partly overlap the floodplain deposits toward the center of the basin (Fig. 10). Three interrelated factors appear to have been responsible for the extensive aggradation which has occurred: (1) the abnormally rapid excavation of the underlying dioritic stock, causing an unbalanced relation between the slopes and stream gradients in the lowland areas, on the one hand, and in the surrounding uplands, on the other; (2) the stream piracy which occurred as the limits of the lowland were extended;

[106] Ante, pp. 208-209, 241.

(3) the ultimate confluence of many large and somewhat discordant streams in the topographic depression. Given the non-resistant diorites and the line of structural weakness which localized the development of the Caguas lowland, and the operation of the three factors enumerated was inevitable. Perfect adjustment has not yet been achieved, and, where so many diverse fluvial elements are concerned, it is natural to find that the various portions of the basin are in different stages of adjustment. Near its eastern and western ends degradation is already in progress

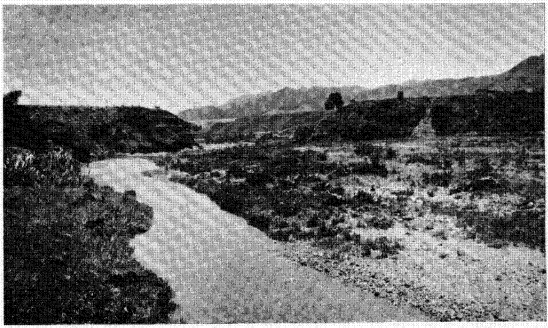


FIG. 26.—*Dissected alluvial fans in the Caguas lowland*

Rio Gurabo has cut its channel about thirty feet into the unconsolidated gravels east of Juncos. The scarp from which the clastic materials were washed forms the background.

(Fig. 26, cf. also Fig. 3), and locally the alluvium has been dissected to depths of 30 or 40 feet. Elsewhere the fans are still being built up, and in the center of the basin some floodplain construction continues. An unestimated amount of the local aggradation now occurring can be traced to the intensive cultivation of the region during recent years, but the natural processes at work have not been greatly modified or disguised.

## PHYSIOGRAPHIC DEVELOPMENT OF THE FAJARDO DISTRICT

### TERTIARY EROSION

The Fajardo district has undergone the same physiographic evolution as the rest of Porto Rico; but, because of the unusual opportunities which the rocks and structures have provided for differential erosion, the older

landforms have not retained the prominence which they exhibit in other parts of the island. In several portions of the district the flat crests of structural ridges, the accordance of detached remnants of upland surfaces in interstream localities, and the horizontal spurs radiating outward from the higher slopes of the Luquillo Mountains, all approximating elevations of 1400 to 1600 feet (Figs. 3 and 4), provide unmistakable evidence of an old erosional level that has all but succumbed to more recent dissection. In northeastern Porto Rico scarcely enough of it remains to constitute a clearly defined peneplane, but if its remnants be projected from the flanks of the Luquillo Mountains along the ridge that forms the northern boundary of the Caguas lowland, to the upland areas north and south of Aguas Buenas, or across the Caguas lowland to the northern slopes of the Sierra de Cayey, it is seen to occupy a place of greater importance; and in the highland west of Caguas it forms the highest element in every panorama. Toward the west its height increases, and if its gently tilted surface be reconstructed and extended eastward over Vieques Sound, it is found to coincide with the Saint John peneplane of the northern Virgin Islands.[107] Above its undulating surface the Luquillo Mountains rise as monadnock ranges that resisted reduction because of their structure, and to the south the Sierra de Cayey forms a lower monadnock group. This high erosional level was called the "Upper Peneplane" by Lobeck,[108] and the name "Saint John" has been applied to it by the writer.[109]

The date of origin of the Saint John peneplane has not been settled. Lobeck advanced the opinion that its formation antedated the development of the surface on which the coastal plain was deposited in Middle Tertiary time, whereas Semmes considered the two surfaces to be the same. The former hypothesis cannot be entertained in view of the fact that the erosional surface which lies beneath the coastal plain rises southward at a five degree angle, and, if projected, it would intersect the Saint John level and rapidly pass above it.[110] Semmes's interpretation, on the other hand, seems possible if it be also postulated that the declivity of the erosional plane beneath the Tertiary strata decreases inland; but it does not account for the equally significant relationship that exists between the Saint John and the sub-coastal plain surfaces from the eastern

[107] Meyerhoff, H. A.: Physiography of the Virgin Islands, Culebra, and Vieques, op. cit., pp. 100-103.

[108] Lobeck, A. K.: Physiography of Porto Rico, op. cit., pp. 312-314.

[109] Meyerhoff, H. A.: Tertiary physiographic development of Porto Rico and the Virgin Islands, op. cit., pp. 560-567.

[110] Ibid., fig. 3, p. 564.

to the western end of the island. The Saint John peneplane rises at a uniform rate from 1400 feet in the Fajardo district to 3000 feet in the highlands between Yauco and Lares. Discounting the five degree slope to the north, the plane of Tertiary deposition sank, perhaps as much as 3000 feet, in the same distance at the time the coastal plain was formed—a sag which is now reflected in the increasing thickness and width of outcrop of the Tertiary strata toward the west, but which is not reflected in any way by the position and relationships of the Saint John level. The

FIG. 27.—*The Caguana peneplane*

The Caguana erosional level is prominent in the western hill section. At this locality, 26.4 kilometers south of San Juan on the road to Caguas, alluvial terraces occupy a conspicuous place in the Quaternary valleys.

latter, on the contrary, maintains a position that is exactly parallel to a younger and lower peneplane, which indiscriminately bevels the Cretaceous and Tertiary rocks. In view of its structural accordance with the younger, late Tertiary peneplane and its definite discordance with the erosional surface beneath the Tertiary strata, the development of the Saint John level must have started after the coastal plain was formed and arched in Miocene time.

In every part of the district except the Luquillo Mountains, the lower and younger erosional level mentioned in the preceding paragraph forms a conspicuous, though not always a dominant, physiographic element (Fig. 27). In the coastal section it is found in the crests of the dissected Cretaceous hills, and even the pepinos in the larger Tertiary clusters show

a tendency to seek its elevation. In the Caguas lowland the isolated hills of harder rock invariably rise to its position, which is clearly indicated by the accordant levels bordering the basin, especially on the south (Fig. 3). In other parts of the interior, on the other hand, it forms the floors of high interior valleys, as the anticlinal valley in which Aguas Buenas is located well illustrates. Like the Saint John peneplane it rises westward from an elevation of 500-600 feet along the coast fronting Vieques Sound and Fajardo Roads to a height in excess of 800 feet at Aguas Buenas. Beyond the limits of the district, where it is farther removed from the coastline, and where its preservation has not been impaired by the rapid excavation of non-resistant rocks, its areal extent increases, attaining maximum expression in the north-central and northwestern interior.[111] It has been named from Barrio Caguana in the Arecibo district, where it planes the folded Cretaceous rocks and the gently dipping Tertiary strata without regard for structure or lithology. In the Fajardo district its imperfection is due not alone to features of differential erosion, which initially limited its development and ultimately facilitated its destruction, but also to the small amount of uplift which it underwent at the end of Tertiary time. Quaternary erosion has progressed far at its expense, yet, in the many inland localities where remnants of it still remain, the well defined topographic unconformities that separate it from the Saint John peneplane on the one hand, and the Quaternary levels on the other, provide the Fajardo region with some of its major relief features. The scarp between the Caguana and Saint John erosional planes is uniformly 800 feet high; that between the Caguana and Recent levels varies from 300 feet along the north coast and 500 feet along the east coast, to 600 feet in the southwestern corner of the district. The Caguana cycle appears to have been inaugurated by 800 feet of vertical uplift at the beginning of Pliocene time. In parts of the island its development continues, for Quaternary dissection has not yet reached its headward limits; but in the region under consideration large sectors of its surface have been entirely destroyed, and all of it is undergoing rapid reduction.

The preceding sketch does not pretend to solve the many local problems connected with the two cycles of Tertiary erosion, for space does not permit exhaustive treatment. The extension of north-flowing streams, their superposition across the ridge that bounds the Caguas lowland, the expansion of the Rio Grande de Loiza system, the inception of

[111] Ibid., Fig. 4, p. 569.

the series of captures which led to the slow consolidation of all of its headwater tributaries within the Caguas basin—a process which continued into Quaternary time—are but a few of the special features connected with the Saint John and Caguana cycles that deserve more thorough analysis than has been accorded them in the present study.[112]

## THE QUATERNARY CYCLE

In every other part of Porto Rico the elevation which ended the Tertiary was so great that Quaternary erosion is still in a youthful stage of development. The movement, however, was differential and slow, lasting perhaps through all of Pleistocene time, and even when it ended, the Caguana peneplane was but 300 to 600 feet above sea-level along different sections of the Fajardo coast, and only 800 feet in the southwestern corner of the district. To the east the flat synclinal structure and the non-resistant rocks facilitated the speedy excavation of the Vieques Sound and Naguabo lowlands; on the south, erosion proceeded quickly in the Caguas basin, abetted by the size of Rio Grande de Loiza, which flows close to the western boundary. Thus carved into relief, the highlands within the district have undergone vigorous headward attack from every side, though partial protection was afforded on the south by the character of the structure. The Quaternary cycle, favored by so many factors, has therefore reached a much more advanced stage of development than elsewhere in Porto Rico.

No single adjective is adequate to describe the stage of dissection which has been reached. Most of the district has been maturely dissected (Fig. 4); yet, as is usual in a region of comparable size, the upland areas remote from major drainage lines are still struggling through the vicissitudes of youth, while the coastal belt exhibits the features of old age. Locally special factors have retarded progress, as in the Luquillo Mountains; or again they have accelerated it, as in the coastal plain, where the early stages were carried on entirely by subsurface solution. Here a third cycle peneplane has been formed, with only the few isolated clusters of limestone monadnocks to mar its perfection. Inland nonresistant lithologic elements, like the diorite of the Caguas lowland, have been carved into old forms, while the country upstream and down, drained by the same streams, is in a less advanced stage of development. In places erosion has produced over-steepened slopes, has caused discordant stream junctions, or has led to stream capture. In such situations aggradation has temporarily stayed the destructional processes until the nor-

[112] Ante, pp. 239-252, 346-347.

mal balance between stream gradients, valley slopes, and water volume was restored. Gradation is rapidly being achieved, but maladjustments are still numerous.

In the interior of the Fajardo district Quaternary erosion and deposition are wholly fluvial in character, and they represent the usual results of stream processes acting on a region that has undergone differential and rather protracted uplift during the earlier part of the cycle, and minor vertical oscillations during the latter part. Along the coast, however, the diastrophic movements have yielded extremely complex results, some of which have been described by Lobeck.[113] A brief chronology of the events is needed for an understanding of the physiographic forms which are present.

The deposition of the San Juan formation was the first of the events which can still be deciphered. The deposits formed a line of dunes, perhaps unbroken at the time of origin, except opposite the mouths of the larger rivers, extending from the northwestern corner of Porto Rico at least as far as Culebra. The position which the formation occupies with respect to the present shoreline, as well as the alignment of its scattered outcrops, provides reason to believe that it was formed on the lee side of an offshore bar along an emergent coast. During the period of its origin and for a short time thereafter, however, the island was being tilted downward toward the east and upward toward the west, and it is unlikely that a simultaneous vertical movement caused the emergence that started bar and dune development along the entire coastline. On the other hand, the variations in the strandline during the advances and retreats of the Pleistocene ice-caps are entirely adequate to explain a temporary condition of general emergence, which could occur in the midst of tilting.

The appearance of an offshore bar and the growth of dunes upon it required but little of Pleistocene time, and with the return of the waters to the ocean as the glaciers melted, these normally transient deposits acquired a measure of permanence when the resulting submergence effected their partial consolidation. Tilting continued, meanwhile, and as it progressed, the broad fluvially degraded flats east of the Fajardo district subsided beneath sea-level, and with them went the Virgin Islands platform, all but the extreme Atlantic margin of which had, until this time, occupied a position above the sea.[114] The conversion of the eastern low-

[113] Lobeck, A. K.: The Physiography of Porto Rico, op. cit., pp. 343-371.

[114] The inapplicability of Daly's and Vaughan's hypothesis of low level abrasion during maximum glaciation to the Virgin Islands-Culebra-Vieques platform is discussed at length in Volume IV, pp. 107-119, 198-207 of this series.

lands into shallow inter-island channels gave the Fajardo district its natural boundary fronting Fajardo Roads and Vieques Sound, although the present shoreline differs in many minor details from the one which formed at the close of the Pleistocene.

The Holocene record is comparatively clear. Tilting ceased, and the streams in every part of the island began the task of adjusting themselves to the new level. Degradation was the dominant type of activity, except in the newly drowned areas east of Porto Rico. Before fluvial processes had made much headway, however, a general submergence of thirty to forty feet occurred, and in the estuaries that were formed, the development of the playas was inaugurated, while in the old Pleistocene lagoons between the San Juan dunes and the coastal hills sedimentation started once again. It was during this cycle of development that the features of the present shoreline took definite shape. Bars were hastily constructed across the open mouths of the embayments; islands detached from the mainland by the subsidence were tied to it again by tombolos (Fig. 28); Cretaceous headlands were cut back by waves wherever they fronted the sea (Fig. 19), while elsewhere the line of Pleistocene dunes was vigorously attacked and reduced to smaller and more widely spaced remnants connected by slender bars, like beads strung upon a delicate thread.

Scarcely had marine gradation fully entered upon a youthful stage of development when its work was interrupted by slight uplift of regional extent. The amount was not great—perhaps only five or six feet; but it was enough to nullify the work already done. On the eastern side of the Cape San Juan peninsula and along other rocky sections of the coast the old wave-cut terrace, only a few yards wide, now supports a growth of vegetation and sometimes a camino, which could not otherwise obtain access to the rugged shoreline. Steep wave-cut cliffs, their slopes scarcely modified, are succumbing to the processes of subaërial decay. The narrow bars which tied the headlands have been appreciably broadened and heightened, and their surfaces are furrowed by beach ridges which may possibly mark the progressive stages of uplift. Vegetation has taken root on nearly all the bars in the Fajardo district, but in places the wind shows some inclination to heap the sands into dunes.

The physiographic record ends appropriately with an emergence which has been of inestimable service to man. Not only did it elevate the shoreforms, but it raised the estuarine deposits which now make the playas, and the lagoonal muds which make the fringing lowlands of the northern coast. In the lagoons and playas streams have entrenched their

FIG. 28.—*The*

A view from the lighthouse on Cape San Juan, showing the double tombolo which slender coral reef, now dead and slightly emerged, forms the irregular chain of cays. in the center rise to the level of the Caguana peneplane, and remnants of the Saint

channels, providing either natural drainage or the possibility of artificial drainage, and as a result the young plains have been converted into fertile agricultural lands, upon which a large part of the sugar crop is grown. Partly in consequence of their agricultural development, these plains have become a nucleus for human settlement and industry. At the beginning of this report the distribution of population within the Fajardo district was briefly outlined. A sketch of its dependence upon the physiographic features, which, in turn, constitute but the visible expression of the underlying geology, will serve as a suitable conclusion.

Settlement and progress in northeastern Porto Rico have been dominated by Quaternary landforms, and, almost symbolically, the inhabitants of the interior uplands seem as remote from the modern world as the older landforms on which they live. Rarely does a carretera reach them. An energetic government is extending roads into many parts of the inaccessible interior, but much of it has so little prospect of development that improvement of many of the routes of travel would be without economic justification. The steep slopes preclude most profitable agricultural pursuits, and the few occupations which can be followed, such as coffee and banana raising and charcoal burning, support a severely limited number of families. The meager livelihood available is mirrored in every phase of the life of the people. In physiographic terms they are isolated by Quaternary uplift and dissection, and the influence of these factors becomes more striking when the density of population is seen to increase in the areas of lower relief. So perfect is the gradation that one is

*northeastern shoreline*

ties the cape to the mainland. Two lagoons have been formed, and in the larger a Punta San Diego (center right) has been similarly joined to the mainland. The hills John peneplane stand out dimly against the Luquillo Mountains in the background.

tempted to see if the ratios between relief and density of settlement do not maintain a constant value.

Where Quaternary erosion has produced open valleys and broad lowlands, settlement is thick, as the Caguas basin and the lower valleys of Rio Grande de Loiza, Rio Fajardo, and Rio Blanco show. And where processes of aggradation have yielded not only flat plains but fertile soils, as in the coastal section, the density of the population far exceeds the high average for the entire district. Concentration has been still further encouraged in those few localities in the coastal region where, as in the neighborhood of San Juan, the estuaries and lagoons, deepened by Quaternary submergence, have not been wholly obliterated by subsequent sedimentation. Shipping facilities, agricultural development, settlement, and communication are so completely dominated by the Quaternary landforms and are so profoundly modified where older physiographic elements persist, that a map showing in detail the culture and agriculture of the Fajardo district can be used as accurately and as reliably to interpret the physiography, as a physiographic map can be employed to interpret even local aspects of settlement and occupation. Human adjustment to environment is extraordinarily perfect.

## BIBLIOGRAPHY

The following bibliography is not intended to be exhaustive. Full lists of the early studies dealing with the natural history of Porto Rico appear in some of the previous reports of the Scientific Survey, and

greater emphasis has therefore been placed upon works published since the Survey was inaugurated. Of the older contributions only those which have been utilized in the preparation of the present report are included. A survey of the literature, old and new, shows impressively the steadily growing interest in West Indian geology, and no bibliography can hope to remain long up-to-date.

The writer wishes to acknowledge his debt to the authors of the titles listed, for, without the background they have provided, the Fajardo studies would have been impossible.

BERKEY, CHARLES P.

1915. Geological reconnoissance of Porto Rico. Ann. N. Y. Acad. Sci., Vol. XXVI, pp. 1-70.

1919. Introduction to the geology of Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. I, Pt. 1, pp. 11-28.

BLACKWELDER, ELIOT

1925. Exfoliation as a phase of rock weathering. Jour. Geol., Vol. XXXIII, pp. 793-806.

BRITTON, N. L.

1919. History of the Survey. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. I, pp. 1-10.

1923. Botanical investigations in Porto Rico. Journal, N. Y. Botanical Garden, 1922, Vol. XXIII, pp. 49-59.

CLEVE, P. T.

1871. On the geology of the northeastern West India islands. Kongl. Svenska Vetenskaps Akademicus, Handlingar, Bandet IX, No. 12, pp. 1-48. Stockholm.

1883. Outline of the geology of the northeastern West India islands. Ann. N. Y. Acad. Sci., Vol. II, pp. 185-192.

COLONY, R. J., AND MEYERHOFF, H. A.

1928. The Copper deposit at Barrio Pasto, Porto Rico. Econ. Geol., Vol. XXIII, pp. 515-527.

CORYELL, H. N., AND OHLSEN, VIOLET

1929. Fossil corals of Porto Rico, with descriptions also of a few Recent species. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. III, Pt. 3, pp. 167-236.

DINWIDDIE, W.

1899. The great caves of Puerto Rico. Harper's Weekly, March, Vol. XLIII, p. 293.

EARLE, K. W.

1924. The geology of the British Virgin Islands. Geol. Mag., Vol. LXI, pp. 339-351.

FETTKE, CHARLES R.

1924. Magnetite deposits of eastern Porto Rico. Amer. Inst. Min. and Met. Eng., Trans., Vol. LXX, pp. 1024-1042.

The geology of the Humacao District, Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. II, Pt. 2, pp. 117-197.

GANNETT, HENRY

1901. A gazetteer of Porto Rico. U. S. Geol. Surv., Bull. 183.

HILL, R. T.

1898. Cuba and Porto Rico with the other islands of the West Indies, Chapters XV-XIX, pp. 145-184. Century Co., N. Y.

1899. Mineral resources of Porto Rico. U. S. Geol. Surv., Annual Report, Vol. XX, Pt. 6, pp. 771-778.

Porto Rico. Nat. Geog. Mag., Vol. X, pp. 93-112.

HODGE, E. T.

1920. Geology of the Coamo-Guayama District, Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. I, Pt. 2, pp. 111-228.

HUBBARD, BELA

1920. The Tertiary formations of Porto Rico. Science, Vol. LI, pp. 395-396.

1921. The Tertiary molluscs of the Lares District, Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. III, Pt. 2, pp. 79-164.

1923. The geology of the Lares District, Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Vir- Islands, Vol. II, Pt. 1, pp. 1-115.

LOBECK, A. K.

1922. The physiography of Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. I, Pt. 4, pp. 301-379.

LOW, BELA

1929. The mineral deposits of Porto Rico. Eng. and Min. Jour.

MATLEY, C. A., AND HIGHAM, F.

1929. The Basal Complex of Jamaica, with special reference to the Kingston District. Quart. Jour. Geol. Soc., Vol. LXXXV, pp. 440-492.

MAURY, CARLOTTA J.

1919. The correlation of Porto Rican Tertiary formations with other Antillean and mainland horizons. Amer. Jour. Sci., 4th Ser., Vol. XLVIII, pp. 209-215.

1920. Tertiary Mollusca from Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. III, Pt. 1, pp. 1-77.

1929. Porto Rican and Dominican stratigraphy. Science, N. S., Vol. LXX, No. 1825, p. 609.

1930. Correlation of Antillean fossil floras. Science, N. S., Vol. LXXII, No. 1862, pp. 253-254.

MEYERHOFF, H. A.
1926-1927. The physiography of the Virgin Islands, Culebra, and Vieques. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. IV, pp. 71-219.
1927. Tertiary physiographic development of Porto Rico and the Virgin Islands. Bull. Geol. Soc. Amer., Vol. XXXVIII, pp. 557-576.
1930. The pre-Oligocene stratigraphy of Porto Rico. Science, N. S., Vol. LXXI, No. 1838, pp. 322-323.

MITCHELL, G. J.
1922. The geology of the Ponce District, Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. I, Pt. 3, pp. 231-300.

NITZE, H. C. B.
1898. Investigations of some of the mineral deposits of Porto Rico. U. S. Geol. Surv., Annual Report, Vol. XX, Pt. 6, pp. 779-788.

SCHUCHERT, CHARLES
1929. Geological history of the Antillean region. Bull. Geol. Soc. Amer., Vol. XL, pp. 337-360.

SEMMES, D. R.
1919. The geology of the San Juan District, Porto Rico. New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. I, Pt. 1, pp. 33-110.

VAUGHAN, T. WAYLAND
1916. Some littoral and sublittoral physiographic features of the Virgin and northern Leeward Islands and their bearing on the coral reef problem. Jour. Wash. Acad. Sci., Vol. VI, pp. 53-66.
1919. Some features of the Virgin Islands of the United States. Ann. Assoc. Amer. Geog., Vol. IX, pp. 78-82.
1923. Stratigraphy of the Virgin Islands of the United States and of Culebra and Vieques islands and notes on eastern Porto Rico. Jour. Wash. Acad. Sci., Vol. XIII, pp. 303-317.

WILLIS, BAILEY
1912. Index to the stratigraphy of North America. U. S. Geol. Surv., Prof. Paper 71.

WILSON, HERBERT M.
1899. Water resources in Porto Rico. U. S. Geol. Surv., Water Supply Paper 32.

WOODRING, W. P.
1928. Miocene mollusks from Bowden, Jamaica. Contrib. to the Geol. and Pal. of the West Indies, Pt. II, Carn. Inst. of Wash., No. 385.

WOODRING, W. P., BROWN, J. S., AND BURBANK, W. S.
1924. Geology of the Republic of Haiti. Port-au-Prince, Haiti.

New York Academy of Sciences

Porto Rico and the Virgen Islands