ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Vol. XXVI, pp. 1–70, pll. I–III

Editor, Edmund Otis Hovey

GEOLOGICAL RECONNOISSANCE OF PORTO RICO

BY

Charles P. Berkey

NEW YORK
PUBLISHED BY THE ACADEMY
3 March, 1915

THE NEW YORK ACADEMY OF SCIENCES

(Lyceum of Natural History, 1817-1876)

Officers, 1915

President—George Frederick Kunz, 601 West 110th Street
Vice-Presidents—Charles P. Berkey, Raymond C. Osburn, Charles Baskerville, Clark Wissler
Corresponding Secretary—Henry E. Crampton, American Museum
Recording Secretary—Edmund Otis Hovey, American Museum
Treasurer—Henry J. Cochran, 389 Fifth Avenue
Librarian—Ralph W. Tower, American Museum
Editor—Edmund Otis Hovey, American Museum

SECTION OF GEOLOGY AND MINERALOGY

Chairman—Charles P. Berkey, Columbia University
Secretary—A. B. Pacini, 2704 Bedford Ave., Brooklyn

SECTION OF BIOLOGY

Chairman—Raymond C. Osburn, 557 West 124th Street
Secretary—William K. Gregory, American Museum

SECTION OF ASTRONOMY, PHYSICS AND CHEMISTRY

Chairman—Charles Baskerville, College of the City of New York
Secretary—Ernest E. Smith, 50 East 41st Street

SECTION OF ANTHROPOLOGY AND PSYCHOLOGY

Chairman—Clark Wissler, American Museum
Secretary—Robert H. Lowie, American Museum

The sessions of the Academy are held on Monday evenings at 8:15 o'clock from October to May, inclusive, at the American Museum of Natural History, 77th Street and Central Park, West.

[Annals N. Y. Acad. Sci., Vol. XXVI, pp. 1–70, Pll. I–III, 3 March, 1915]

GEOLOGICAL RECONNOISSANCE OF PORTO RICO[1]

By Charles P. Berkey

(Presented in abstract before the Academy, 7 December, 1914)

CONTENTS

[1] Based on the observations and studies of an expedition organized under the joint support of the New York Academy of Sciences and the Insular Government of Porto Rico.

Manuscript received by the Editor 1 February, 1915.

Introduction

The Island of Porto Rico has never had a thorough or detailed geological study. There have been, however, a number of papers written that have described special features or general conditions in a very ac-

ceptable manner. Most of the writings[2] of this kind are widely scattered in volumes of periodicals or proceedings of learned societies or pamphlets which in most cases are not readily obtained or consulted.

From a perusal of these articles, one learns that Porto Rico belongs structurally and genetically to the mountain chain now represented by the isolated islands forming the principal West Indian group. Enough work has been done, especially by R. T. Hill,[3] to outline roughly the geological history of the Island of Porto Rico and indicate on a map the distribution of some of the formations. An especially good general description of physical features, also, is given by H. M. Wilson.[4] An introductory general description, in large part along the same lines as these, will probably serve the present purpose.

General Description

The Island of Porto Rico is situated in the Torrid Zone between latitude 17° 54″ and 18° 30″ north and longitude 65° 13″ and 67° 15″ west. It is the easternmost and southernmost of the Greater Antilles. It lies within the trade-wind belt, and the constancy of these winds gives the island a remarkably mild and uniform climate. There is an abundance of rainfall on the windward side, which in this case is the east end and the north side as far west as Camuy. The effect of the mountains across which these winds blow is to make the south side of the island and most of the western portion comparatively arid. Some districts are said to have no rainfall for a whole year at a stretch.

The Atlantic Ocean lies to the north and east, the Caribbean Sea lies to the south, while Mona Channel on the west separates the Island of Porto Rico from Hayti. Brownson Deep, reaching the profound depth of twenty-four thousand feet below sea level, one of the deepest spots known, lies immediately to the north. Tanner Deep lies to the south, reaching a depth of fifteen thousand feet. Although the relief of the island above sea level is less than four thousand feet, this represents only the extreme top of a great mountain mass which rises above the submerged platform, from which its real height should be measured. The extreme relief difference represented by the summit of El Yunque on the one hand and Brown-

[2] The writings referred to, together with others that have some description of physical conditions in Porto Rico, are listed at the end of this paper. Those of most usefulness in the present investigation are certain papers by R. T. Hill and H. M. Wilson, besides a very few others of less extended character.

[3] R. T. Hill: "Porto Rico." National Geographic Magazine, volume 10, pages 93 to 112 (1889).

[4] H. M. Wilson: "Water Resources of Porto Rico." Water Supply Paper No. 39, U. S. Geological Survey.

son Deep on the other is approximately twenty-eight thousand feet. Regarded in this way, the Island of Porto Rico belongs to one of the higher relief features of the earth.

It is in reality a badly eroded summit of a great mountain belonging to an east-west chain or range including the Greater Antilles. The general structural features of the islands are consistent with this east-west axial trend which is expressed in the topography of the central Cordillera extending from the west end near Rincon, where it starts abruptly from the water's edge, to Fajardo, where it terminates in El Yunque, the highest point on the island. The mountain range, however, is not so simple as this statement would lead one to believe, for there are in reality two ranges or branches toward the east, one of which is known as the Sierra de Luquillo, culminating in El Yunque, and the other, which is best developed in the divide between Cayey and Guayama, is called the Sierra de Cayey. The military road crosses this latter branch near Aibonito over a pass that reaches above 2,000 feet. To the westward, the double character of the mountain ranges is not so pronounced, but there is a semblance of it in the spurs that reach the sea rather abruptly, one near Rincon and the other near Mayaguez. The exact elevations of the higher mountains have not been accurately determined, the values given on the older maps being evidently too great. The revised approximate elevations are: for El Yunque, at the eastern end of the island, 3,750 feet; for El Guilarte, which stands to the west of the Arecibo road, 3,610 feet. The highest point in the Sierra de Cayey is about 3,000 feet. Many points are nearly as high as those given, and all of the roads that cross the island reach elevations on the divide that are in excess of 2,000 feet. Many of the roadways in the interior districts reach elevations over 2,225 feet.

Although the island as a whole has a mountainous aspect, and although much of the interior is very rugged and picturesque, there is usually a comparatively gentle or smooth topography along the coast, and some of the marginal areas are almost perfectly flat. These are uniformly at the mouths of the larger rivers and represent river alluvium or delta-like deposits,—they are known in the island as playas.

The aspect of the island as a whole is moderately rugged. Although the major portion of the rock makeup is igneous, and although there is considerable complexity of structure represented in all parts of the range, all of the surface forms are of erosional origin. The relief is that of early maturity in the interior and perhaps late maturity in portions of the coastal districts. Exceedingly steep slopes are the rule in all parts of the island where there is any considerable relief, and one of the most surprising things is the way the soil clings to these slopes. One often

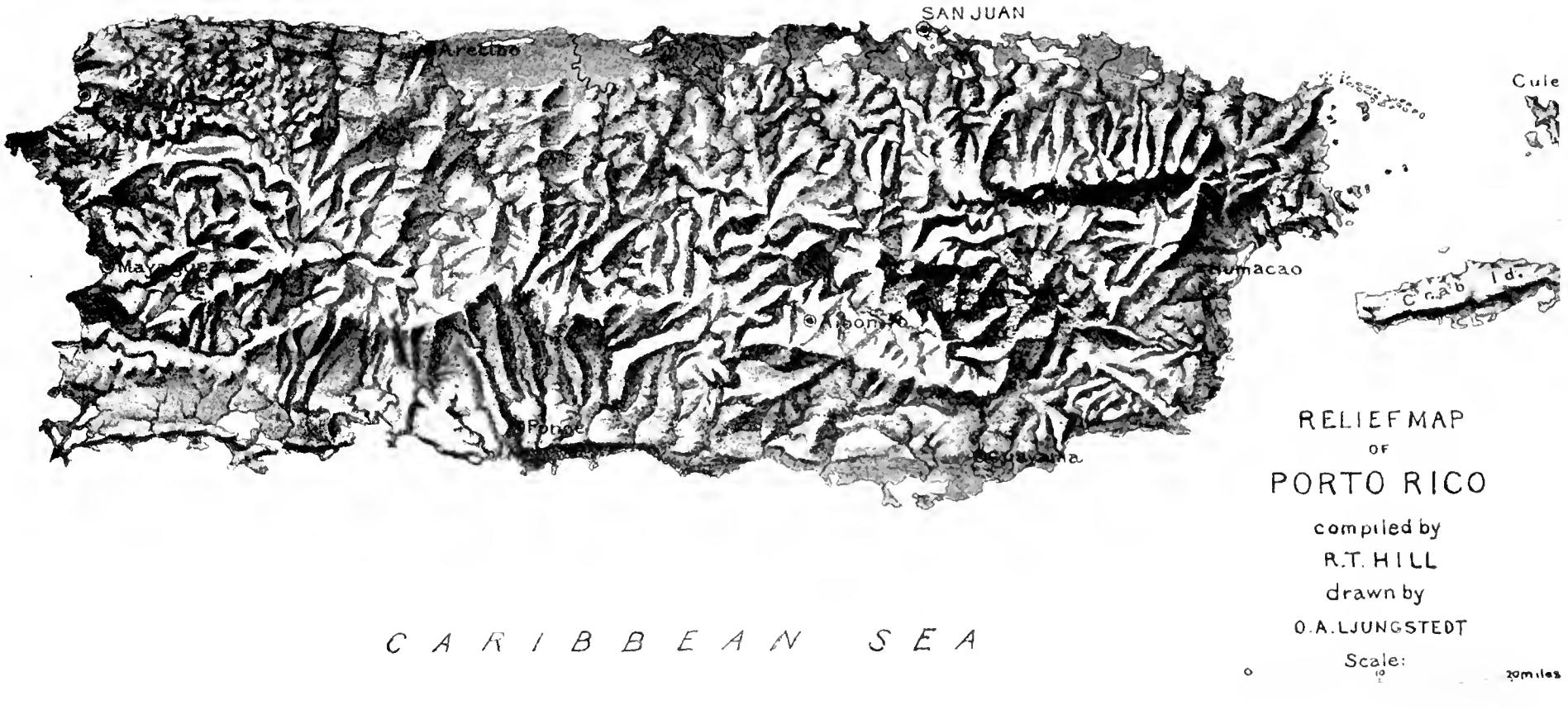


PLATE I. RELIEF MAP OF PORTO RICO

Reproduced by permission from Bulletin 25 of the Forestry Division, U. S. Department of Agriculture.

sees slopes of this kind with angles of thirty to forty degrees from the horizontal under cultivation.

The islands of Culebra and Vieques lie to the east of Porto Rico and are said to be similar in structure and makeup, but neither of them was visited on this expedition.

The streams of the island are numerous and surprisingly large for the size of the areas drained. According to Mr. Wilson's description[5] of the water supply there are twelve large streams flowing north, four flowing west, seventeen flowing south and six flowing east. Besides these there are said to be 1,300 small streams, and on account of the heavy rainfall on portions of the island many of them are of larger size than such an area would usually afford. The main divide runs near the southerly margin of the island, so that about one-third of the drainage is tributary to the Caribbean Sea on the south, and about two-thirds to the Atlantic Ocean on the north. This unsymmetrical position of the dividing range is an abnormal feature, the cause of which is the subject of discussion in another portion of the report. Because of the prevailing trade winds, the rainfall is very unevenly distributed. The east end and the north side are comparatively humid and plentifully watered: in contrast, the west end and especially the south side are comparatively arid. In order to overcome partly the shortage of water, a large system of irrigation is now being developed on the south side of the island. At the east end, northeast of El Yunque, there is an annual rainfall of 123 inches. On the other hand, at Cabo Rojo, at the other extreme on the southwest side of the island, it is exceedingly dry, and in occasional years there is said to be not a single drop of rainfall. Other parts of the island vary between these extremes. The wettest months are September and November.

In most districts, the underlying rock is compact enough to discourage much deep water circulation and the stream run-off is correspondingly responsive to the rainfall. In the northwest corner of the island, on the broad limestone belt extending from Aguadilla to Camuy, there is a prevailing tendency for the surface waters to sink into underground channels, leaving the surface very much more poorly watered than even the somewhat scanty rainfall would lead one to expect. In some cases, streams developed on the more compact rocks of the interior districts completely lose themselves in underground channels upon entering the limestone belt, and in some cases do not again come to the surface for several miles. Elaborate caves and channel-like caverns are common and, in the northern belt of limestone country, there are thousands of such occurrences

[5] H. M. Wilson: "Porto Rico; its Topography and Aspects." Jour. Am. Geog. Soc., Vol. 32, p. 220. 1900.

still preserved that are now wholly abandoned by the waters that formerly occupied and helped to form them. There are no inland lakes, but there are a few coastal lakes and they appear to be related to the development of alluvial plains or playas and recent elevation and subsidence changes.

The climate is strictly tropical, but it is so tempered by reason of the constant trade wind breezes from the ocean and the elevated character of much of the ground that it is usually agreeable and mild. The lack of great changes of temperature and the prevailingly moist conditions on most of the island have direct influence on the character of the rock decay and disintegration and also on the quality of the soil produced as well as its behavior as a residuary product. Other matters of climatic conditions have little or no bearing on geological problems and may well be avoided. The average daily temperature is eighty degrees; it rarely goes above ninety degrees or below seventy. The maximum temperature is ninety-nine degrees. Extremes recorded for the year indicate a range of forty degrees.

The area of Porto Rico is given as 3,670 square miles, which is about three-fourths the size of the State of Connecticut. It is roughly rectangular in outline and in actual dimensions is about thirty-five miles in average width, and one hundred and five miles long from east to west. It is the fourth in size of the West India Islands and is one of the most productive and densely populated districts in America.

Because of the greater interest recently taken in studying the natural resources and natural history of Porto Rico, it was judged to be a suitable time to make a more elaborate and detailed study of the island's geological framework and history. In accord with this view the New York Academy of Sciences organized an expedition which spent a part of the summer of 1914 on the island. The accompanying descriptions are based on the work accomplished by this expedition.

New York Academy of Sciences Expedition

The geologists sent to make a preliminary study or reconnoissance of the Island of Porto Rico left New York on the 15th of August, 1914. Four weeks were spent in Porto Rico, the expedition returning to New York City on the 21st of September. The party consisted of Dr. Charles P. Berkey of Columbia University, New York, and Dr. Clarence N. Fenner of the Geophysical Laboratory, Washington. Arrangements were made with the bureau of transportation of the Insular government in San Juan for conveyances, so that as much ground as possible could be seen in the time available. More than 2,000 kilometers were covered by

the aid of this transportation service and observations were made in sufficient detail to judge the general character and structural relations of the formations crossed. In addition to this kind of travel on the roads, short trips were made on foot to examine features or outcrops of rock which appeared to deserve investigation, and an occasional more extended trip on horseback was taken to points in the interior. With these facilities for travel, it was possible for both members of the party to give undivided attention to geological observations. It was possible to stop and make

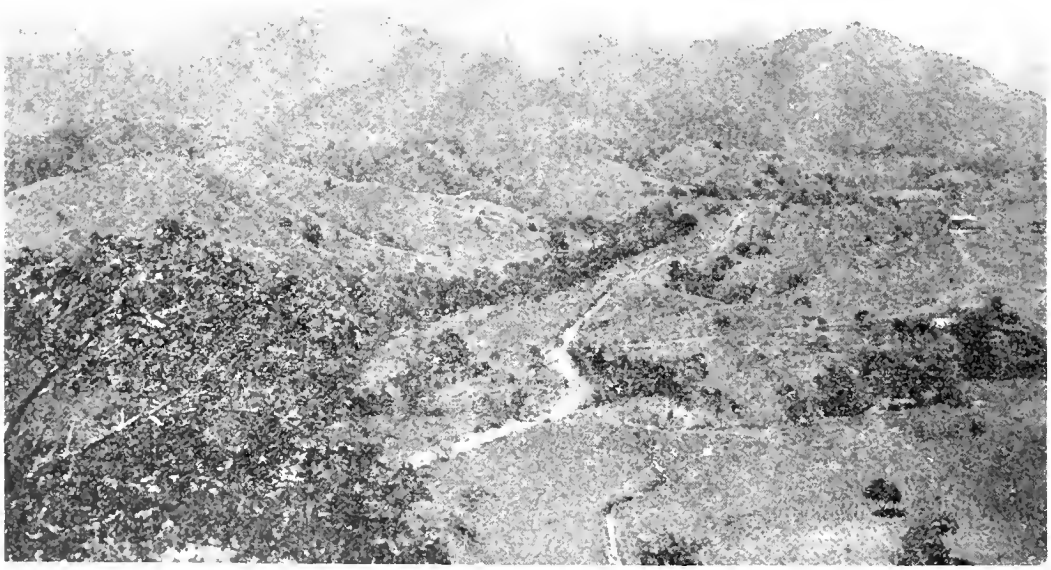


FIG. 1.—*Relief features characteristic of the interior ranges of Porto Rico*

Photograph taken from the Ponce-Penuelas road at K-10, looking northward across eroded formations of the older series to the main drainage divide.

brief examinations along all the roads at hundreds of places, and, on several of the roads crossing the island, sufficiently elaborate data were secured to furnish a basis for geological cross-sections showing both relief and structural features. A complete circuit of the island was made and in addition it was crossed from north to south on three principal roads. This, together with numerous side trips into the interior, permitted observations to be made on practically every formation of any considerable consequence in the island. No point in the whole area is situated more than seven miles from some road or other point of observation covered by the party, and, even in those cases, except in the extreme southwest

corner of the island, observations were made on all sides or completely around the unexplored areas. Because of the extent of the reconnoissance, it is the opinion of the writer that all of the essential, large, fundamental geological formational units have been found and their general structural relations have been determined.

OBJECT OF THE EXPEDITION

The purpose of this expedition was, first of all, to determine the nature and origin of the rock formations of Porto Rico, and to group them into series suitable for use in subsequent geological work. In the second place, it was the object of the party to determine as many of the larger structural relations as could be seen and to unravel as much of the geologic history as such a hasty examination would warrant. In the third place, the physiographic features were studied for the purpose of determining their origin and relation to the formational structure and their bearing on the more recent history of the island. Lastly, it was appreciated that the island was complex enough to have many problems that could not be solved without very much more extended investigation, and it was the purpose of this expedition to point out the problems that should receive special study and that seemed to give promise of important results. Considerable attention has been given to the economic resources of the island by private individuals and considerable money has been spent on various enterprises connected with their development. These problems were also kept in mind, and wherever convenient, special observations were made on them. Although it is possible to make suggestions concerning these economic resources, they are for the most part matters that should receive very much more extended special study. A matter that concerns the welfare of the island more directly than any of these is the question of quality and variety and origin of the native soils. These of course are in large part geologic matters also, and although this reconnoissance is not sufficiently detailed to form the basis of a discussion of this matter, it is one of the lines of investigation connected with further work that will have direct value.

Investigations and Discussion

ROCK FORMATIONS

The most fundamental thing to be determined at the outset of an investigation of this kind is to discover and differentiate the different rock types and the structural units to which they belong. All of the prelimi-

nary work of this expedition was devoted, primarily to this question and collections were made for comparison throughout the island. In the beginning, observations were made chiefly along the coastal margins because of the greater amount of ground that could be covered and because of the apparent simplicity of the outermost and younger or more recent formations. The chief formations with their representative rock variety will be discussed in order from the younger to the older series.

In the first place, such a reconnoissance shows that there are two great series of formations separated by a marked unconformity. Both are somewhat complex, but in that respect the older series is very much more complex, both in range of composition and number of units involved and in variety of structural relation, than the younger one. In spite of this discrepancy, it is still the most convenient and useful division to make, and, because of the strikingly different characteristics of the two series and the great prominence of the structural break between them, there is no possible chance for mistaking this fundamental feature.

The whole lot of formational units are therefore grouped under the following two heads:

1) Younger Series.
   Including the Tertiary shales, reef limestones and recent deposits.
2) Older Series.
   Including a complex group of formational units,—tuffs, ashes, shales, conglomerates, limestones and a great variety of intrusives, all of which are probably of pre-Tertiary age.

There are several possible subdivisions of the younger series, but in this discussion only those exhibiting enough physical constancy and character to be useful in field correlation are taken into account. These are especially (1) the San Juan Formation, a Pleistocene sand-dune deposit, and (2) the Arecibo Formation, a series of reef limestones and associated shales and marls. Besides these, there are more local developments that deserve special discussion, such as the San Sebastian shales, the Juana Diaz marls and sandy shales, and the Ponce chalk beds; but in a broad grouping these are all phases of the larger Arecibo Formation and it will take detailed paleontologic study to make the proper subdivisions.

The older series has many formational members and their general relations are reasonably well understood, but a systematic subdivision is not yet attempted. Correlation in this series is still more difficult than in the other, because of the great variation in character laterally and the influence of igneous activities that prevailed throughout its whole development. Some of the most characteristic of these types will be described.

Younger Series

San Juan Formation.—On approaching the island by the usual route entering San Juan harbor, the first rock whose structural detail can be seen is that on which the city of San Juan itself is built. One can see that the formation is made up of strongly bedded material that has all of the structural characteristics of a cross-bedded sandstone and is resistant enough so that it forms, at this point, a promontory extending far beyond the supporting mainland and presenting a cliff face of at least 75 feet in height. A closer inspection supports all of these observations as to structure and adds the important observation that the granular material

FIG. 2.—*Partially destroyed dune sand deposits of the San Juan formation*

These deposits are a short distance west of Arecibo and are nearly covered with fresh dune sands of the same material.

is, in large part, calcareous in composition and organic in primary origin. The same type of material, with all of its characteristic structures, was seen at several other points along the north coast. Special studies were also made on sea cliffs of this formation in the vicinity of Arecibo, where the exposures were so well developed that good photographs of the structure could be taken. One of these is reproduced as an illustration of the characteristics of this formation. It shows exceedingly steep cross-bedding structure that measures up to thirty-three degrees dip, and there are also occasional structural lines that are almost horizontal. The rock is exceedingly porous, the grains are unusually uniform in size, and the

binding material is calcareous, attaching one grain to another merely at the point of contact. The extension of ledges of this kind of rock far beyond the possible reach of swift-flowing streams, together with the fact that the distribution is limited to certain sections of the north coast, and, in addition, the evidence furnished by the internal structure of the rock itself, lead to the conclusion that the formation is essentially an old dune-sand deposit. Sand dunes are developed on the present coast line from very similar material, but none of the very recent dunes are solidified. On the other hand, the San Juan formation seems to have been developed before certain of the later elevations and subsidences that affected the island in its recent history, so that its material is fairly well cemented and its base extends below the present water level. Its outcrops also extend to greater elevation above sea level than any of the modern dunes. It is judged, therefore, that this particular formation is the most recent of all in the island to act as a ledge former, and it is judged by its situation and content to be of Pleistocene age. See additional description under heading "Structural Features."

This is the most unusual formation in the island. It is a type seldom seen or seldom recognized, and it is one of the smallest in Porto Rico, in spite of the fact that it makes such an important showing at San Juan harbor.

Because of the prominence of the formation in the city of San Juan it is suggested by the writer that the name *San Juan formation* be used for it and that this name be confined to the Pleistocene beds representing solidified sand-dune deposits.

Arecibo Formation.—Next below and older than the San Juan formation is a great series of reef limestones and shell limestones preceded by shales that form a belt of considerable width along the north coast and a portion of the south coast of the island. In a large way this series forms a structural unit. Above it in all cases lie the recent alluvial deposits and the San Juan formation and below it lie the older and more complicated igneous and sedimentary rocks. The break between these two represents the chief unconformity in the whole geological column. The heaviest development of this formation is along the north coast between Tao Alto and Aguidilla. In this belt, the massive limestones of the Arecibo formation attain the greatest thickness observed anywhere on the island, but no opportunity was found for determining the amount accurately. There is in sight, however, certainly as much as 500 or 600 feet in the bluffs along the Arecibo River. In this belt also, especially farther toward the west, in the vicinity of Lares and San Sebastian, there are underlying shales of considerable thickness which in places carry lignitic

material and which have been the object of some exploratory work for coal. It is evident, from observations made, that the shale beds of the Arecibo formation vary greatly and in some places are entirely wanting. At the Arecibo River, for example, where the beds of the formation can be seen well exposed in the river bluffs, there is no shale development at all. The limestones lie abruptly on the eroded and somewhat weathered surface of the older formations which at this point are represented by coarse and obscurely bedded or even massive volcanic tuffs. At the best place seen, which was on the east side of the river about opposite K-66 on the Arecibo road, there were a few feet of transition material between the limestone beds proper and the unmodified tuff. It had not the structural appearance and makeup of the shale as seen at other points, however, and this part of the formation is regarded as entirely absent on the Arecibo River. Shaly beds, however, are seen again on the south side of the island and their best development is in the vicinity of Juana Diaz, where some of the beds are distinctly sandy and rather fossiliferous and carry petrified wood. Lignite is also reported from this vicinity, but no material of that kind was found by the writer. It is more than likely that the shale beds on opposite sides of the island do not correspond in horizon at all, but that structurally they are both basal beds.

The most striking development of the shale beds and overlying marls and softer layers of thin-bedded character, instead of the massive reef structure, is on the Jacaguas River south of Juana Diaz. The dips also of the formation in this particular locality are much greater than those observed at any other point. For considerable distances an average dip of 30 to 36 degrees was estimated and the total thickness represented, based upon the width of the belt, must be at least 3,000 feet. At no other point on the south side, however, was there an opportunity to see whether the beds of this character are constant or of large lateral extent. As one goes eastward, a comparatively short distance, they are almost entirely lacking. On the Descalabrado River, which is only ten kilometers to the east, the underlying older series of tuffs and intruded shales and limestones were followed to a distance of two miles south of the military road, whereas at Juana Diaz the basal shales of the Arecibo formation begin a half mile above the military road. It appears, therefore, that the formational margin is swinging rapidly southward, and it is judged, from other observations made, that there is almost nothing of it represented at a distance of twenty kilometers to the east, or, in other words, that the formation does not extend farther east than the vicinity of Salinas. At one other point on the south margin of the island, there is an unusually good opportunity to follow the successions of formations, and

that is in the vicinity of Guanica. Limestones belonging to the older series occur immediately south of Yauco and are very strongly developed there. The hills in which these beds outcrop extend southward almost continuously to Guanica, but at that point observations showed that the formation had changed and is actually part of the reef limestone of the Arecibo formation, although it is possible that the large fault observed west of Ponce may pass through this area and obscure the other structural relations. It looks, from the rapid survey, as though it would be favorable for some of these additional studies of the character of the lower beds of the Arecibo formation. Between Guanica and Juana Diaz, wherever the inner margin of the Arecibo formation was seen, it was bounded by a fault which brings the upper beds abruptly against the older tuffs and shales of the pre-Tertiary.

The formation furnishes an abundance of fossils. The lower portion or the lower beds on the south side of the island, as seen at Juana Diaz, seem to be the most promising for a determination of the age of the beds of the formation. Higher beds, forming a chalky white limestone to the west of Ponce, are also very fossiliferous, but in this area they are separated from the older rock series by a fault, so that it is quite impossible to tell how far above the base of the formation these beds may lie. It is judged that the portion of the formation seen at Guanica is a still higher horizon, but the exact age values have not been worked out. The total thickness of the whole Tertiary series on the south side of the island is very great. It was estimated that the shales and marls and limestones in the vicinity of Juana Diaz must certainly amount to three or four thousand feet. For a long distance along the Jacaguas River south of Juana Diaz, the beds stand with a dip of approximately thirty-five degrees toward the south and throughout the greater portion the character is notably different from the beds occurring farther to the west which are judged to overly them.

To the east of San Juan, along the north coast, there is much less prominence of the Arecibo formation and after passing Rio Piedras it in no place crosses the main road. There are occasional hills somewhat similar to those characteristic of the landscape of Bayamon and vicinity, but they do not reach to so great a height and are separated by very much larger stretches of low ground. The strongest development of this formation seen to the east of San Juan is that along the Grande de Loiza River between the railway and the coast. In going still farther east to the vicinity of Luquillo, the inner margin of the formation passes out to sea and the older formation reaches the shore. From this point around the whole eastern end of the island no more outcrops of the Arecibo for-

mation were seen, and this is true also of the southerly side coming from the east end through Naguabo and Yabucoa and Guayama, and still farther west to some undetermined point between Guayama and Santa Isabel. There may be, however, occurrences of this formation underlying the alluvial material along the coast at points considerably nearer Guayama than the outcrop map indicates.

The formation as a whole is essentially a structural unit. Although it is quite easy to distinguish the underlying shale member, especially well developed between San Sebastian and Lares, and although there are other structural changes, there is nowhere any appearance of unconformity or marked break in the succession. Besides, the shale member is not everywhere developed and, as a matter of fact, is seldom seen in tracing the formational boundaries. In some places, it is definitely shown to be absent, so that it seems unwarranted to represent this member as an important part of the formation, so far as areal distribution is concerned. Judging from field observations already made, the shale and marl beds are more extensively developed on the south side than elsewhere. But this is based on observations in one particular area and the member cannot be traced very far in either direction because of other difficulties. The beds lying above the shales and representing the part referred to as a more massive limestone portion are probably susceptible to considerable differentiation on the basis of fossil content, and it is entirely possible that a rather complete range of Tertiary horizons may be determined after complete paleontologic study. In the field, however, and on the basis of structural factors, there is no apparent ground for subdivision. In this discussion, therefore, the whole series of beds, from the unconformity at the base to the alluvium and San Juan formation overlying it, is referred to as a single formation and, on account of its extensive development in the region about Arecibo, it is suggested that a suitable name would be the *Arecibo formation*.

Some parts of the formation show the peculiarities and content of a coral reef, and these portions have the most irregular and most massive structures. Other parts show bedding structure more or less perfectly developed, and throughout the whole formation here and there, at irregular intervals, and usually of only very limited extent, there are more shaly facies. It is the opinion of the writer that this irregular distribution of shaly beds is responsible for one of the peculiar topographic features developed in the belt underlain by the Arecibo formation. This is the occurrence of almost perfectly flat soil-covered areas of no very great lateral extent at different levels, above which the numerous small knobs or hillocks of limestone rise, giving the peculiar haystack-like topography.

This type of topography is represented by the small level tract surrounded or dotted over with small hills, called "pepino hills" locally, standing like haystacks above the plain at many different elevations above the sea. This leads to the belief that the fundamental control in its development is the presence of a shaly bed in the series, which forms at each point the basis of the local plain. The hillocks standing above it or surrounding it represent remnants of the more massive and probably more porous and more easily destroyed limestone which has been attacked and largely removed by weathering, and especially by solution, down to the more

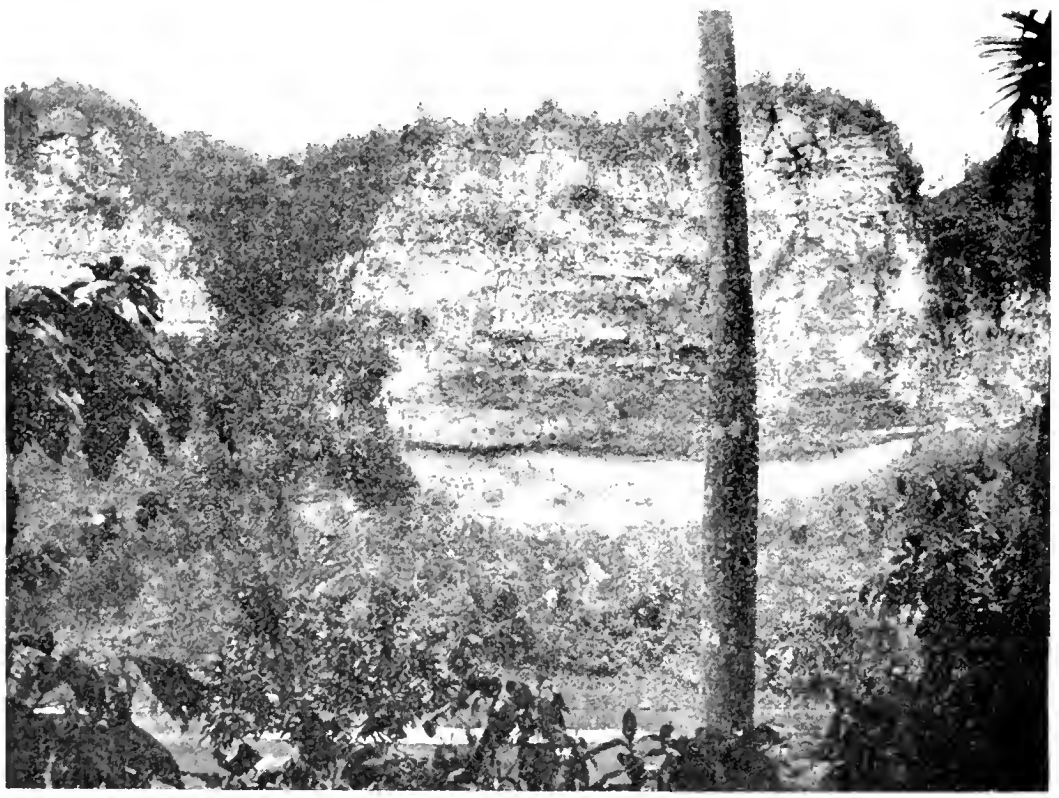


FIG. 3. *Unconformity below the Arecibo formation*

This view shows the older tilted and eroded tuffs and shales below, as seen on the Arecibo River. The contact is immediately beneath the horizontally bedded limestones at about the center of the view where the chief weathering is noted.

resistant shaly soil-forming member. If this is the principal cause of the peculiar topographic form just described, it is quite easy to see that the distribution of such features should be expected to be rather irregular both in lateral extent and in actual elevation above sea level or in relation to the different horizons in the formation itself. In regarding this as the principal factor, there is no tendency to overlook the fact that the island has stood at different elevations with respect to sea level in former times, and that a corresponding difference in ground water levels would be felt throughout the border region. But there is no evidence whatever

that the numerous different levels represented by many of the small plains referred to above were necessarily connected with any of these subsidence changes. Additional comment on the hillock topography, so strongly developed in some parts of the area, is made in connection with discussion of drainage in another part of this paper.

The Arecibo formation is of Tertiary age. So far as identifications of the fossils have gone, they appear to confirm the opinion that the larger part of the formation belongs to the Oligocene epoch. These determinations were based largely on collections made in the heavy limestone beds and reefs in the vicinity of the Quebradillas River. The shale beds lying at the base of the series, and exposed farther to the south in the vicinity of Lares, are certainly somewhat older and probably belong to the Eocene epoch. There are higher beds developed rather irregularly that doubtless represent still later time, referred by Hill to the Miocene epoch, but these determinations must be left to future detailed study of the formation as a whole.

It is considered eminently fitting to refer to some of the chief variations which have especially strong development in certain localities, by special locality designations, such as,—San Sebastian shales, Ponce chalky limestones and marls, Juana Diaz shales and marls, Guanica coral reefs, Quebradillas reef limestones, etc.

The correlating of all these and other local representatives of the Arecibo formation is a work that can be done only by extensive and detailed stratigraphic study and paleontologic comparison. This is one of the larger pure-science problems awaiting future investigation.

Older Series

Below the Arecibo formation and forming the surface in the interior, beyond the Arecibo margin, the island is made up of an exceedingly complex series of many different kinds of rocks. They include chiefly varieties of igneous rocks, both extrusive and intrusive, both fragmental and massive, ranging from small stringers or dikes or flows to large boss-like masses that cover many square miles in area. In addition to the igneous rocks of these types, there are numerous shale beds and conglomerates of rather massive habit aggregating a very great thickness, and with them are associated limestones and foraminiferal beds of considerable variety. A study of the rocks of this series for the purpose of determining their character and origin indicates that practically everything in the older series except the limy portions of the shales or the limestones proper are more or less directly of igneous origin. The coarser materials and those least affected by any secondary processes are the tuffs which are of direct

volcanic origin and are exceedingly abundant and extensive. They are found at intervals in all parts of the series, and it is impossible to say that they are either more or less abundant in those portions which appear to be older, rather than in those which appear to be younger or higher in the series. The closest associate of these materials is the bedded tuff, made up of volcanic fragments which have been somewhat assorted by surface agencies so that they exhibit some sedimentary structural characteristics. These are also exceedingly abundant and widely distributed and they pass by insensible gradations of finer and finer materials into those

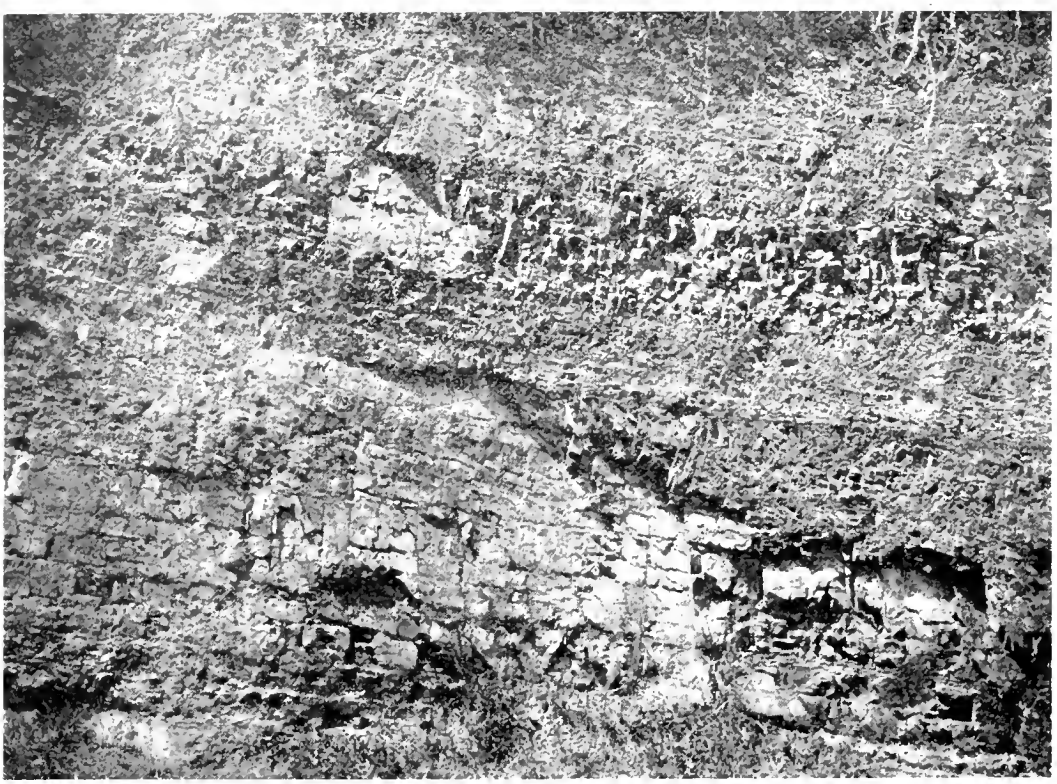


FIG. 4.—*Typical shale occurrence*

This is seen along the road between Ponce and Penuelas at K-10. The beds at this point lie in a less disturbed attitude than is usual in members of the older series.

that are recognized as true ash beds. Most of these have become so thoroughly cemented, or so much modified by secondary attack, that they now present a perfectly sound and compact appearance. In thin section, however, it is easy to see that the material is wholly volcanic and that the bedding is the only secondary modification except that having to do with the binding, induration or alteration of the rock. The ash beds are probably close relatives of the so-called shales.

Shales.—Rocks of this type are developed characteristically at Fajardo, at Mayaguez near Barranquitas and at numerous other points, espe-

cially along the divides toward the west. At the two points first mentioned, in particular, they are light yellowish or reddish in color, rather porous in structure, strongly bedded and have a prominent blocky fracture habit. The exact character of these rocks is a question under study at the present time, but enough has been done to show that, in their present condition, they have been oxidized to the yellow or red color, and have been leached so that they have a porous structure and light weight due to the removal of at least a part of some constituent that is more readily soluble than the rest of the rock. Microscopic comparison with beds of the same structural relation, but of very dark color and very dense habit, leads to the opinion that the two types are not essentially different in origin, but that the lighter colored and lighter weight shales, such as are found at Fajardo and at Mayaguez, are simply the weathered equivalents of darker ones. It appears from this comparison that the shales are normally highly calcareous and that the lime content is supplied by the presence of a very large amount of organic matter in the form of foraminifera. In some cases this organic matter makes up fully one half of the rock and in all cases weathering produces a very porous effect that should be expected to be identical with the red and yellow shales occurring typically at Fajardo and Mayaguez. The siliceous content of all of the shales examined proves to be exceedingly fine and wholly lacking in granular or quartzose material such as characterizes most sedimentary shales. It is the judgment of the writer that this material in the shales of Porto Rico, instead of being the ordinary disintegration products derived from the weathering of ordinary land masses, is in reality largely ashy material of volcanic origin. With this conception of them, it would appear that even the limy shales are therefore close relatives of the ash beds, and it is entirely possible that they do not represent any great difference in history, but rather somewhat different surroundings during accumulation.

Limestones.—Besides the shales, there are massive limestone beds of several different types.

In most cases the occurrences are separated by structural complexities that make it uncertain about field correlation, but undoubtedly later field study will connect some of these and additional paleontologic study will arrange their succession. The most prominent occurrences seen are described below.

Coamo Tuff-Limestone.—The limestone with the closest genetic resemblance to the types already described is represented in a broad belt passing from south to northwest across the upper end of Coamo Reservoir near Coamo Springs, and which can be traced in prominent development

westward across the Descalabrado River to the Jacaguas Reservoir. Similar limestones are found at other points on the south side of the island and are judged to belong to the same member of the older series. Because of the strong development in the vicinity of Coamo Springs, and because of the fact that it represents a type so striking as to be recognizable as a field unit, the limestone has been called by us in the field the *Coamo Tuff-Limestone*. It is developed in the vicinity of the Coamo Reservoir to a thickness of several hundred feet and its most characteristic appearance is the brownish mottled color effect produced by the

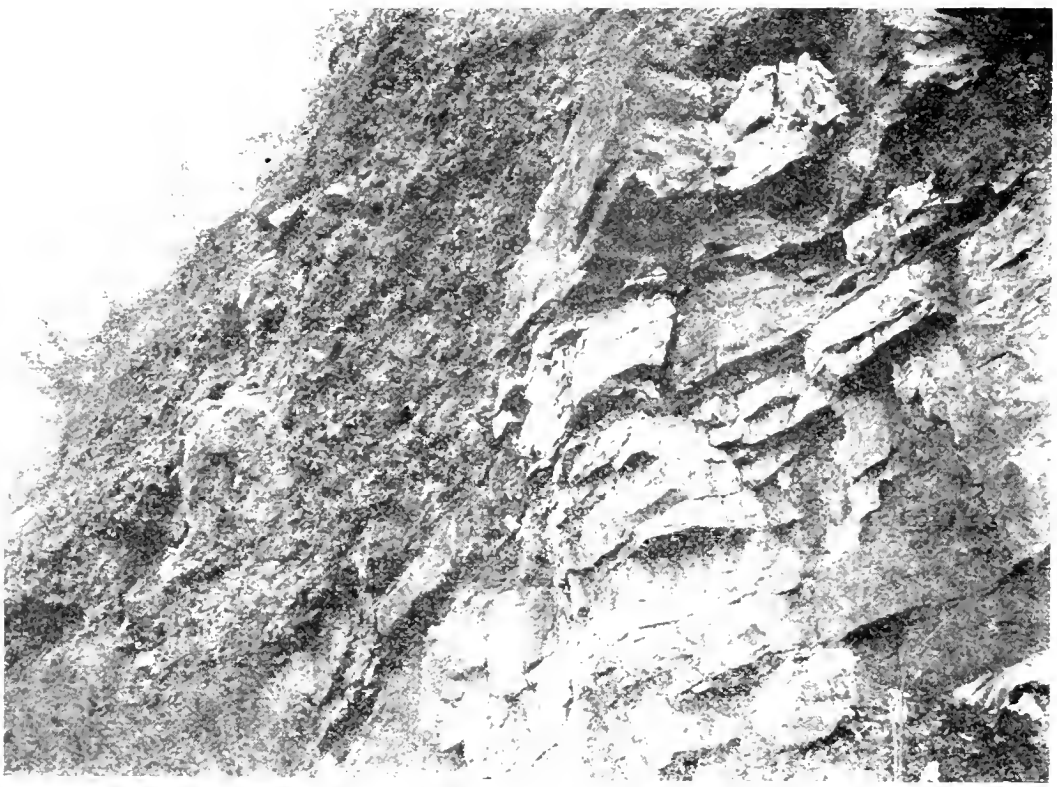


FIG. 5.—*Interbedded coamo limestone layers with massive tuffs*

This formation is seen at the military road crossing of the Descalabrado River.

presence of fragments of tuff and accumulations of ash. In some beds this material is so abundant as to make up almost the whole rock and it becomes an interbedded tuff layer. Occasionally the limestone beds are very pure and almost entirely free from volcanic materials, and there are also numerous beds of real volcanic tuff, but typically there is an intermixture of tuff materials with the lime in great enough abundance to give a brownish spotted or mottled effect. An equally characteristic feature of the rock is its concretionary or nodular appearance due to algous growths to which the lime accumulation is chiefly due. The finest development to be seen anywhere in the island is on the Descalabrado

River at the point where the military road crosses it. A photograph of the interbedded relation of tuff and limestone at this point accompanies this discussion. This is probably, in part at least, the rock referred to by Hill in some of his discussions as "mountain limestone." It seems to us that the several occurrences of limestone beds which have clearly different relations in the series, and the probability of being able to place them in different horizons, based on this content, makes it desirable to use more characteristic local designations for them. Such usage cannot be confusing even if it should be proven, as it may very well be, that some of them are identical. In this discussion, therefore, wherever possible, the chief occurrences that are not clearly identical with formations already described are characterized by adding the name of the locality where there is especially good development of the formation. A limestone seen at Coqui, considerably farther east, and several occurrences near Yaneo, and others still farther toward the west, have many points of resemblance to the Coamo limestone. In some cases even the brown volcanic spots are also present, but this is not true of all places. The most constant index as seen in the field is a fine meshed coralline fossil form, strikingly resembling a piece of loosely woven cloth.

The limestone beds developed at Coamo reservoir, however, rarely show this type, but instead have a remarkable development of algæ of the form known as Lithothamnia.

Trujillo Alto Limestone.—There are several other limestone members in the older series. One has been observed only on the north side of the island in the vicinity north of Trujillo Alto and in the vicinity of Loiza. This is a very dense fine bluish limestone made up wholly of fine microscopic organic growths. In some places it has a rough fragmental structure, but for the most part the rock is massive and the abundant organic content, largely algæ, is its most striking characteristic. Whether it is younger or older than the Coamo limestone has not been determined, but that it belongs essentially to the same general series is quite certain. On account of its distribution it is conveniently referred to as the *Trujillo Alto limestone reef.* This member probably has a very moderate thickness and no great areal distribution. It is affected by solution developing caves at the Trujillo Alto locality in much the same manner as is the Arecibo formation, but this rock is a much more compact type and its content and structural relations are quite distinct. It was probably of reef origin also, but is associated intimately with the upper shale members of the older series rather than with the Tertiary series.

"Shred" Limestone.—Another limestone may be seen at several places on the Arecibo-Ponce road on the south side of the divide from K-13 to

K-19. It has no great thickness, but there are several independent beds. Its most striking character is the presence of patches of dark color distributed in a shred-like way through the grayish mass. The rock as a whole is massive, exceedingly compact, of a bluish gray color, and, except for these dark-colored shreds, shows no recognizable structure whatever. They contain algæ, however, which are expected to determine something more definite about their position in the series, but they are obscure forms, and doubtless considerable work will have to be put on these beds to determine their exact horizon. They are intimately associated with a series of igneous fragmental beds and a considerable thickness of very red shale or ash beds. Together these alternating limestone and red fragmental beds make a striking structural succession which was not seen anywhere else. They lie in a position which is not far from the point where the Coamo limestone belt should be expected to cross the Ponce-Arecibo road, but no such structural development has been noted at any other place. It is, of course, possible that the fine red ash represents the tuffs of the regular Coamo formation and the "shred" limestone represents a phase of the Coamo not developed elsewhere, but the striking physical difference encourages the making of a distinction, at least for the present.

La Muda Limestone.—A rather heavy development of limestone in the vicinity of La Muda between Rio Piedras and Caguas has some superficial resemblance to the beds just described from the Arecibo road, but their relationship is not fully determined. The rock is not prominently tufaceous and is not marked in the same way. It has in places a coarse fragmental structure almost completely obscured by healing and it is, as usual, attacked by cave development. Some of the caves have collapsed, leaving a complex aggregate partly made up of igneous material filling the former chambers. A conglomerate bed lies below the limestone and shale at this point and both are cut off abruptly by a large intrusive mass. How these are related to other typical members of the older series is not known, but it will be possible to trace the beds to more definite relations. This is probably one of the oldest limestone members in the pre-Tertiary series. It is conveniently referred to as the *La Muda Limestone.*

In addition to this there are very numerous small or thin local developments of limestone layers distributed through the shale beds at various points. These are taken to be, in most cases, simply somewhat more heavily developed limy layers of the same origin as the rest of the foraminiferal and ashy shales; but the nature of their origin shows that it is reasonable to expect a development of calcareous content sufficient to make them more of a limestone than a shale.

"Mountain Limestone."—In some localities, such as that near Barranquitas, and probably at other points along the same divide, the shaly beds become very calcareous, as has been pointed out by Mr. Hill. These were referred to by him as limestones and are probably included in his "mountain limestone" and estimated that the thickness of such beds amounted to fully a thousand feet. The prominence of the shaly structure in these beds and their apparently close genetic relation to the type described in this discussion as shales, leads us to regard this occurrence as essentially the calcareous extreme of the shale series. As already noted, the shales are characteristically calcareous and some of them are predominantly so.

Corozal Limestone.—At Corozal, a fragmental limestone was seen just south of the village. Its relations were not worked out and its meaning is therefore not well understood, but its structural peculiarities lead to the suspicion that it may be associated with volcanic fragmental accumulation. It was found that in at least one place in another part of the island there had been volcanic outbreaks through heavy limestone beds, and it is evident that fragmental material from such activity might therefore include a good deal of simple limestone fragments. It is hardly conceivable that they would in most places accumulate in enough abundance to make a limestone bed a second time, but such a thing is doubtless possible.

Conglomerates.—There is a very extensive development of conglomerate occurring in a belt whose general trend seems to be from southeast toward the northwest, crossing the military road between Aibonito and Coamo. There must be a total thickness of strata, including shales and interbedded tuffs with occasional small limestone, of perhaps several thousand feet. In all parts of the formation where conglomerate is developed, the pebbles represent the same kinds of rocks as were encountered in the tuffs and intrusive masses. Actual representatives of previously solidified bedded material or indurated ash or shales are very rare, but in one case at least a pebble was observed that was judged to represent a fragment from an older silicified tuff. As a matter of fact, the materials are practically all of simple igneous character and the matrix in most parts of the formation is very abundant, or even predominant, the particles of which are of the same igneous material. The distribution of material and the range of composition leads one to believe that this conglomerate represents a special state or condition whereby materials of essentially tufaceous origin were, immediately after their volcanic eruption, worn, rounded, somewhat assorted and bedded and mixed with related material. At the point examined, there was no satisfactory

evidence of marked unconformity between the conglomerate above and the underlying series of formations. But the fact that the conglomerate beds, which follow to great thickness, are prevailingly of simpler structural habit, as compared with the calcareous shales, ash and tuff series immediately below, suggests that there may be a break here of larger consequence than is observed in other parts of the pre-Tertiary or older series.

The development of so extensive a series of conglomerates doubtless does represent a considerable change in physical conditions, compared to those controlling simpler deposits which preceded and followed them, and it is possible that it may be found useful in separating the complex series of older mixed bedded rocks and tuffs into an older and a younger division by using this conglomerate as a dividing member. This is supported to some extent by the occurrence of a conglomerate of similar character but of very much less extent on the north side of the island, several miles south of Bayamon, and also one of apparently less prominence near La Muda. If additional field work should show that the conglomerate belt could be traced from one side of the island to the other, it seems to me that it would be entirely practicable to make this division.

The conglomerate is invaded by igneous intrusive material in much the same manner as is observed in the other rock formations, but the massive habit of the rock as a whole leads to a predominance of transverse dike-like masses rather than the simpler looking sills. At one point in particular, however, near K-86 on the military road between Aibonito and Coamo, the conglomerate has been invaded by a magma that must have been fluid enough to penetrate the porous matrix surrounding the conglomerate pebbles where it now exhibits a crystalline habit. This injected matrix is essentially a coarse diorite porphyry in composition, through which the pebbles are distributed in the manner that they seem to have had in the original rock, so that there are still obscure traces of bedding structure. There are additional petrographic peculiarities in this rock that will be described under a different heading. This tendency of the dioritic magma to penetrate and incorporate fragmental matters was noted in several other places. It was most strikingly exhibited in certain intrusive members cutting through tuffs and shales. In some of these cases there is so great a quantity of fragmental matter as to wholly obscure the true nature of the rock unless one can see the structural relations. In the case of the conglomerate, however, the crystalline habit of the matrix is a striking feature and it is very evident that it is wholly different from the regular conglomerate habit.

Tuffs.—The most abundant of all of the rock types is represented by a great variety of volcanic tuffs. These accumulations seem to be the fundamental basis of the whole island. Whatever has been formed in the way of shales, sandy beds or conglomerates or any other of the ordinary sedimentary types seem to be directly derived from the same material that makes up the tuffs and the rocks directly associated with them, related in an interbedded succession. In most cases, the tuffs are essentially massive in their structural habit and are made up of a complex accumulation of large and small fragments of volcanic materials which prove to be chiefly andesitic and closely related porphyritic types. There is great variety in texture and minor structure and present condition, but on the whole there is enough uniformity of actual composition to justify classing them all as andesitic tuffs.

In very many places there is obscure bedding structure indicating a tendency to assort and work over this material at the time of its deposition. This is especially noticeable in the finer materials and some of these beds are made up essentially of ash. These ash beds resemble the type referred to as shales so closely, in some places, that it is impossible to distinguish between them in their field appearance. I judge also that there is practically a gradation from one rock to the other, the ash beds showing transitions to shales, especially where they have developed under conditions encouraging much weathering and working over of the fragmental materials and promoting the growth of organisms in sufficient amount to make the accumulating beds somewhat calcareous in composition.

Tuffs and ashes are well known to be especially liable to attack by alteration and to the ordinary changes that modify rocks. It so happens, therefore, that many of these representatives are completely modified and have become so dense that they exhibit none of their ashy or fragmental structure without microscopic examination. In this condition they are usually also exceedingly hard and as resistent to destruction as the hardest crystalline rock. The largest development of massive almost structureless tuffs which were seen occupy the Sierra de Cayey between Guayama and Cayey and also the range along the military road toward Aibonito; but there are extensive occurrences in many other sections. Some of the most prominently developed bedded tuffs and ash beds were seen on the north flank of El Yunque along the Sabana River and on the north side of the divide below Comerio, and also along the Ponce-Arecibo Road both near the summit of the range and farther to the north midway between Arecibo and Utuado.

From what was seen of this type of rock, it was not possible to form a

definite conclusion concerning the age represented except by their relation to certain interbedded shales and limestones. It appears that the underlying older portions of the series of tuffs and ash beds have comparatively little of such interbedded calcareous material and have everywhere been modified or altered or metamorphosed to a greater degree than beds that lie higher in the series. But beyond this there is little to judge of the actual age. As one goes higher in the series, however, there are occasional prominent limestone members with which tuffs are intimately associated or interbedded, and it may be possible, by reason of these relations, to form a more accurate estimate of the geologic age of this later portion of the series.

Volcanic Flows.—In addition to the sedimentary beds of various sorts and the related tuffs, there are at occasional places evidences of volcanic lava flows. These were seen at several places on the road between Bayamon and Barranquitas. They are amygdaloidal in present habit and represent vesicular basalt and andesites. On the whole, evidences 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. A more prominent thing as a structural feature is the occurrence of very numerous intrusive bodies.

Intrusives.—The intrusive masses in Porto Rico occur in all parts of the island and in all of the formations except the Arecibo and the overlying alluvial deposits. No such evidence was seen in any part of the Tertiary of younger series; but the complex series of rocks representing the pre-Tertiary, here referred to as the older series, are cut in all sorts of ways by both large and small intrusive masses. The smaller intrusives are chiefly andesite porphyry in composition and have everywhere penetrated the shales 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 is 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. But occurrences of the same kind are exceedingly numerous in nearly every district and in total amount form a very great additional thickness

to the bedded rocks, shales, ash beds, etc., with which they are associated. In some cases, these invading magmas have incorporated great quantities of fragmental matter, giving the rock in its present condition a very strikingly fragmental appearance. This habit associated with its perfectly apparent intrusive relation makes a very unusual combination in the field. In many places there are included blocks of immediately adjacent rock such as one sees in the occurrence at the quarry at Fajardo Playa, but, in extreme cases, the mass is chiefly fragmental in its make-up and one could not readily interpret its history without complete field

FIG. 6.—*Diorite porphyry sills*

These sills are intruded between layers of calcareous shales and ash beds on the road near Comerio. The streaked or banded layers are shales, the massive portions, seen best at the left side of the print, are sills. A transgressive relation can be seen between the two layers at the extreme left.

determination of its relations. Such occurrences may be seen in the vicinity of Guayama on the road about a mile east of that place, and also a short distance south of Rio Piedras.

Few of these intrusive masses show anything but a rather uniform medium grain texture and larger ones have the average appearance of a rather fine or medium grain diorite. The granular appearance, however, is probably deceptive, due to the way the rock disintegrates, for thin sections made from many typical intrusive representatives are nearly all plainly porphyritic in texture.

In addition to these intrusive masses, which are of small size or at least of not very great areal dimensions, there are in a few districts large boss-like occurrences of massive coarse-grained igneous rock. The boundaries of none of these have been traced out, but it is certain from the distribution now known that in each case the area occupied is several square miles in extent. The most prominent one of this type of intrusive mass is that seen in the southeast portion of the island, including the district about Huamacao and Yabucoa and Las Piedras and Juncos. Whether or not this is all one mass belonging to a single intrusion has not been determined. The variety of composition seen in the different samples taken at different points is consistent with the presence of more than one intrusive unit; but it is also possible and quite as likely that the variety observed is wholly due to magmatic differentiation. The southerly portion of this mass, especially that near Yabucoa, is represented by a very coarse, very quartzose and almost pegmatitic granite. Farther to the north, in the vicinity of Las Piedras and Juncos, the rock has the appearance of a syenite. Although a part of the rock does show the composition of a true syenite, by far the greater number of specimens collected on this expedition show the presence of quartz in sufficient amount to make the rock a granite. It would appear, therefore, that this occurrence in the southeast portion of the island is essentially a granite mass and that it is of unusually large size, reaching practically from the coast at Maunabo to Caguas. The distance across this mass is, therefore, not less than about 12 miles north and south. In all probability it is not of quite so great an extent east and west, but these boundaries are unknown.

One other large intrusive mass was observed in the west central part of the island, in the vicinity of Jayuya and Utuado. In general appearance and texture this rock, in the average outcrop, does not differ much from that seen at the east end of the island which is commonly referred to as syenite. In this occurrence, however, such specimens as have been examined with the aid of the microscope, show the presence of quartz in most cases in sufficient amount to make the rock of granite composition. In this case, as in that referred above, there are considerable differences of composition shown by the rocks which seem to be a part of the same mass. Specimens found, for example, near Adjuntas have the compositional characteristics of diorite, whereas a specimen taken near the margin of the boss on its northerly side, near K-53 on the road toward Arecibo, is a syenite. At certain other points near Utuado, the rock is a granite porphyry.

The best idea of the variety of composition and textural quality represented by all kinds of intrusives in the island can be gathered from an

examination of the water-washed pebbles in the stream beds that have come down the steeper mountain sides. An examination of such material shows an extremely large varietal range, and, although by all means the greater number are some variety of diorite or andesite porphyry, there are occasional more basaltic and more acid types represented.

Summary.—From this description of the variety of rock types represented by the leading field units, it may be readily seen that a subdivision into members of mapable constancy is no easy matter.

It is the opinion of the writer that, for the present work and for investigations immediately to follow, local designations or names will be of most direct usefulness, and that a correlation should be expected to be the final outcome of a series of such studies. For the present, therefore, it is judged best to use the terms Fajardo shales, Mayaguez shales, Jayuya road shales, Barranquitas shales, etc., as suitable names in these respective districts for the shale member of the older series, without any intention of suggesting their equivalence. In spite of the physical similarity in these cases, it is not at all likely that they belong to the same horizon.

Similar argument will hold for most of the other members,—the ash beds, the tuffs, the limestones and the conglomerates,—and it is recommended in these cases, also, that locality designations be used in the field investigations. Those described in this report are not necessarily all that deserve special designation, but the same rule may be applied to additional occurrences without in any way obscuring the ultimate solutions of the problem of correlation. On account, therefore, of the complexity of the structure and the limited amount of work yet done in connecting the separated occurrences into continuous field units, it is advisable to retain such terms as Coqui limestone, Coamo limestone, Corozal limestone, La Muda limestone, Trujillo Alto limestone, Cayey tuffs, etc., for the earlier descriptions and special studies.

PETROGRAPHIC RANGE

There is an exceedingly great variety of certain classes of rocks in the Island of Porto Rico. Those most prominently developed and showing the greatest variation in minor character, structure and relationship are the volcanics, especially the volcanic fragmentals. All sorts of tuffs, cinder beds, ashes, mud flows and bombs are represented in great quantity, in very wide distribution and in all stages of alteration and induration.

Observations made on thousands of occurrences of this character of materials leads to the conclusion that most of it is essentially of andesitic composition. Although there is an occasional fragment of either more basic or more acid composition, the predominant types are always of

andesitic makeup. The present condition of these rocks, representing as they do nearly all stages between fresh material and either a thoroughly weathered or considerably metamorphosed condition, is a more interesting study than their primary composition. Some of the most dense and resistant rocks in the whole island are these older metamorphosed tuffs and ashes.

Next in point of abundance is the group of crystalline igneous rocks. In this case there is somewhat greater prominence of varieties represent-

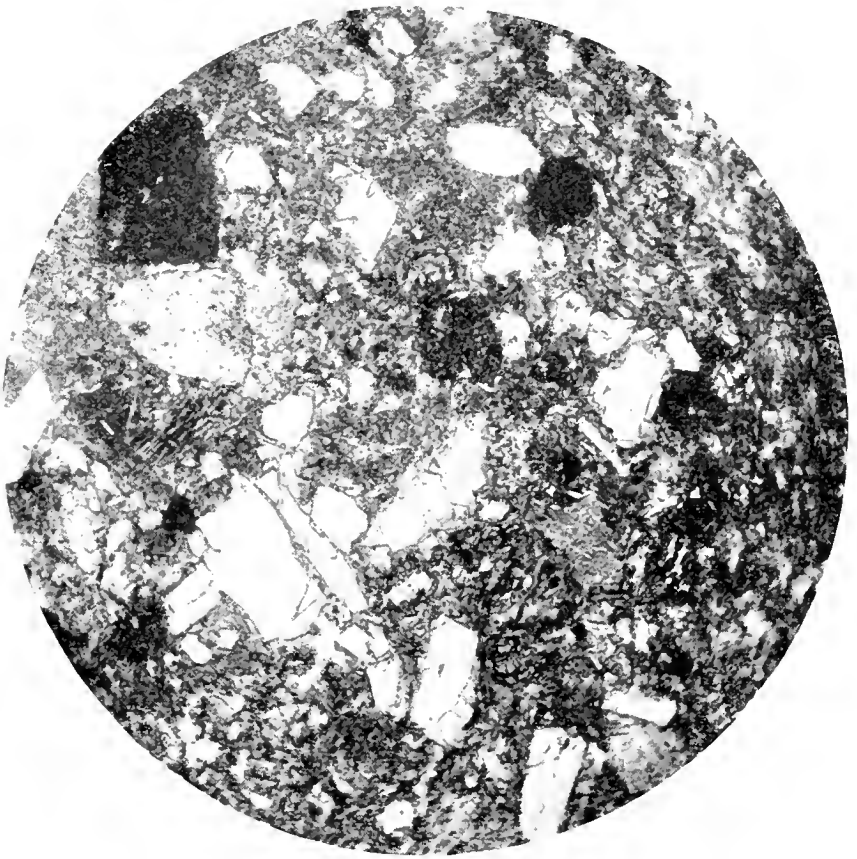


FIG. 7.—*Photomicrograph of a typical thoroughly indurated andesitic ash, magnification 28 diameters*

A rock of this type appears in the field as a dark-greenish hard resistant obscurely bedded layer, usually closely associated with more massive tuffs on the one hand or more strongly bedded shales on the other. The clear grains are mineral fragments; the more complex grains are fragments of lava, cinders, glass, etc., all thoroughly bound into a complex aggregate.

ing the acid and basic ends of the classification scheme, but here also the rocks of the andesite-diorite family are by all means the most numerous and most widely distributed. The greater number of occurrences are represented by members of this family belonging to intrusives that would be classed normally as andesite porphyries, porphyrites of various kinds and diorite porphyries. The minor variations represented by these rocks

would probably include all of the habits known to this family. In addition to the porphyries of this family composition, there are less common occurrences of felsite, quartz porphyry, granite porphyry and basalt porphyry. In surface flows there is, besides the andesites, an occasional amygdaloidal basalt, but so far as observed there was no rhyolite or other very acid surface type. Among the massive larger intrusives, the commonest and most abundant type is a granite porphyry or granite varying in some parts to the composition of syenite. A massive rock of the na-

FIG. 8.—*Photomicrograph of a typical weathered shale from Fajardo Playa, magnification 28 diameters*

The dark field is made up of an extremely fine aggregate of earthy materials. The white circular and irregular spots are entirely empty and constitute the porosity of the rock. The circular forms of these voids suggest that they represent former calcareous content in the form of foraminifera, now completely removed by weathering.

ture of a diorite is also represented, as is a very coarse rock of the nature of a giant granite. How these are related, how many intermediate varieties there may be and whether this variation represents magmatic differentiation within a single mass or instead different units of intrusion, has not yet been determined in enough detail to make a positive statement. But in at least two cases where these large masses were seen,

the hasty examination given to them leads to the belief that differentiation effects can be traced.

The closest relatives of the igneous rocks are the sediments, and because of the fact that the material constituting these sediments has been furnished by the volcanic fragmental supply in large part, their character and makeup is in many cases not strikingly different from the ashes and finer tuffs. They do, however, represent an additional assorting, an additional weathering and an additional opportunity for intermixture of

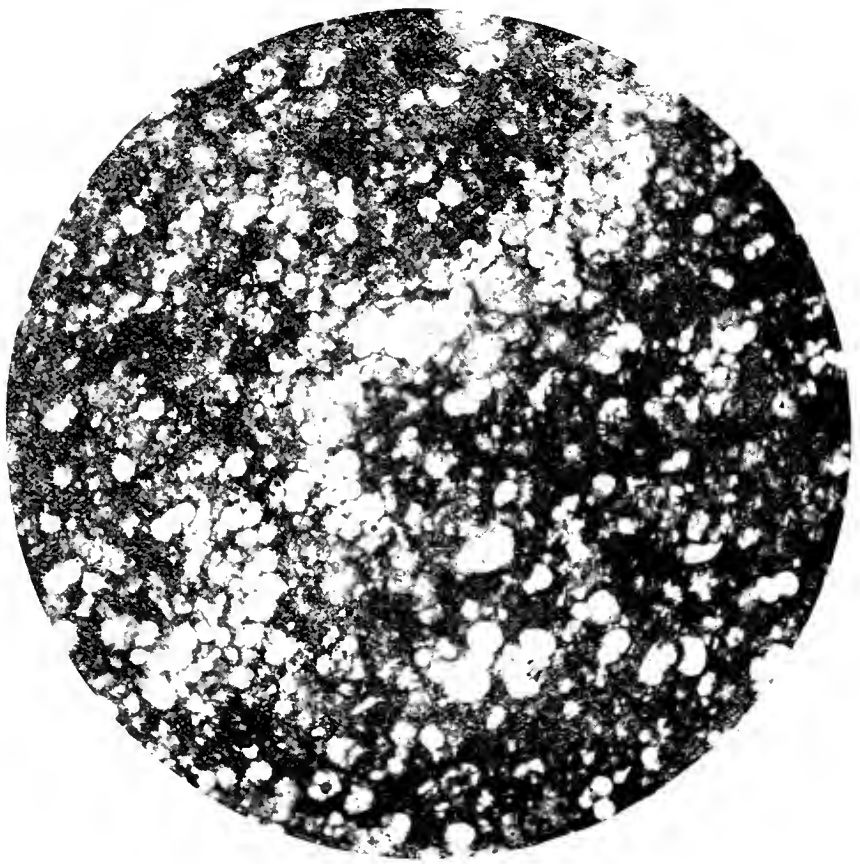


FIG. 9.—*Photomicrograph of a foraminiferal shale from the Bayamon-Comerio road, magnification 28 diameters*

The dark areas are chiefly earthy aggregates of very fine texture; the whitish areas are calcareous spots which in many cases still preserve the forms of foraminifera. It is the removal of such materials from the shales that is believed to account for their porosity as seen in weathered outcrops.

materials from different sources and of organic material developing at the same time. These conditions give a great range of composition and mineral makeup to the shales and sandstones and they merge by imperceptible gradations from simple tufaceous or arkosic sediments to calcareous rocks or even to fairly pure limestones. The common source of the calcareous element in these rocks is from an intermixture of fora-

miniferal matters representing organic growths accompanying the accumulation of the deposit.

The limestone members on the one side representing almost pure organic accumulations, and the conglomerates on the other representing the simpler destructive volcanic fragmental matters, give the range between which an exceedingly great variety of sediments are represented.

The shales of the younger series, represented by the Lares and the Juana Diaz shales, are more strictly detrital and of true erosional and

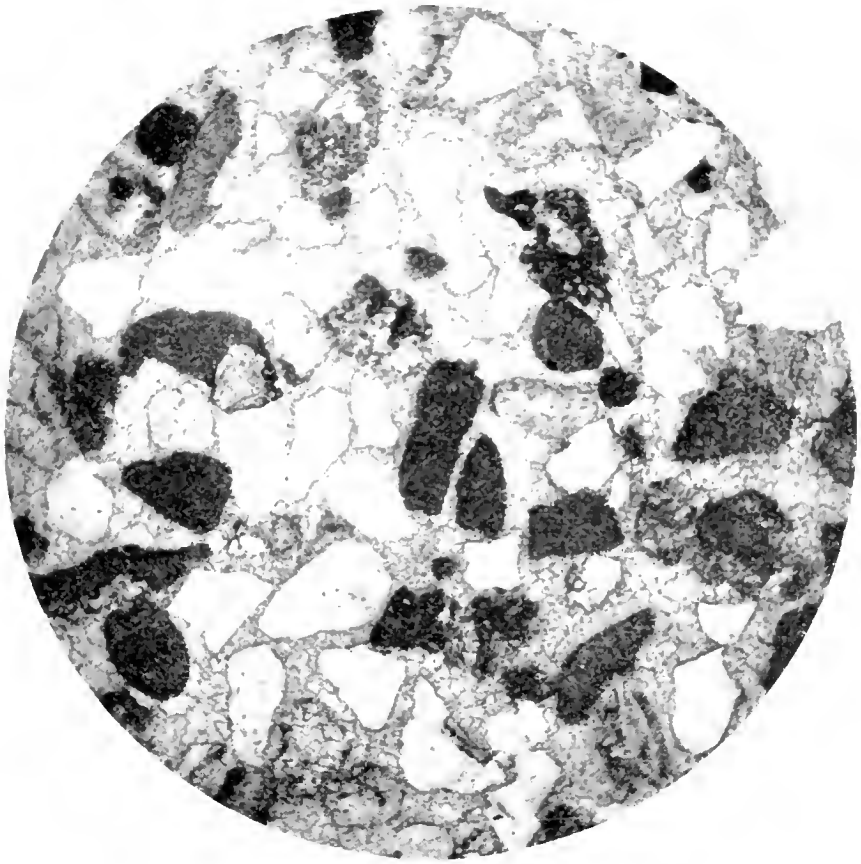


FIG. 10.—*Photomicrograph of the San Juan formation indurated dune sand, magnification 28 diameters*

The clearest grains are simple mineral fragments; the dark ones and the grayish ones with internal structure are fragments of calcareous organic growths. The grayish matrix is a secondary binding material of calcitic composition, in this case practically filling the interstitial spaces.

destructive origin, and in places they contain lignitic material which suggests different physical conditions. This shows, however, in their upper layers an increasing amount of organic content also, and finally are succeeded by limestones of wholly organic makeup. The failure of volcanic activity during and subsequent to that time gave no opportunity for the amount of intermixture that is seen in the shales of the older series, so that as a result the younger series of rocks is petrographically

more simple and less modified. The organic content is of greater variety, however, and because of the reef-building tendency the primary structure is more varied than is seen in the limestones and shales of the pre-Tertiary representatives.

The most striking petrographic type is, probably, the solidified dune sand making up the San Juan formation. Its uniformity of grain, strong cross-bedded character, porous habit, together with its rather surprising stability, make it an object of some considerable interest. Several of these classes of rocks, therefore, represent petrographic series of unusual range and variety, and because of their perfection of development would seem to warrant detailed study.

There are no foliated metamorphic rocks so far as yet seen in Porto Rico. One specimen of such rock, a mica schist, was shown to the writer as having come from the Portuguese river not far from Ponce, but a hurried reconnoissance in the vicinity failed to uncover anything even resembling it. The specimen probably does not belong to the rocks of Porto Rico. No evidence whatever has been seen of conditions that would be expected where such rocks occur.

The most profoundly modified rock observed is a massive serpentine. Such material was seen at two places by this party, one near Yauco and another on the road to Comerio, and the same type is reported by Professor Crampton on a much larger scale near Maricao. But they are all simple petrographic cases after all, being ordinary intrusive units of heavier ferro-magnesian content than the average which have been heavily altered, especially by hydration processes, to the present condition. Genetically and historically, the serpentines are not materially different from the other intrusive bodies.

Depth of Decay

Alteration has affected the rocks at most points to considerable depth, but in spite of this there are plenty of outcrops, and along the roads there are many cuts exposing fresh rock. The stream beds are strewn with fresh pebbles and boulders. Although decay obscures the character of the rock in most of the outcrops, the structure is usually fairly well preserved, and in most cases enough can be seen to enable one to determine the formational habit.

The most striking thing about many of these badly decayed outcrops and cuts is the remarkable way they stand against destruction or removal by ordinary weathering and erosion agents. At many points, road cuts are made, with side walls absolutely vertical, through wholly decayed rock material, that stand for years without crumbling down. Embank-

ments made of earth along roads and trails behave in the same way and one is continually surprised at the steepness of such slopes and their apparent stability. Slopes of 40° are not rare on hillsides that are cultivated, and one occasionally crosses divides that are mere knife edges with slopes of this kind on both sides. Such stability of the soil is a great factor in preserving the agricultural productivity of Porto Rico and in the distribution of its agricultural industries over so much of the interior area.

There seem to be three factors of large consequence in this stability of the soil mantle. One is the clinging character of some of the vegetation which tends to bind the soil together; another is the small range of temperature variation which reduces disintegration or disruption tendencies to a minimum; and still another is the low content of inert or refractory materials, such as quartz, in the rocks whose destruction has furnished the soils; all of which factors favor the making of especially tenacious soil. Most of the soils are for the same reason exceedingly difficult to cultivate. As a direct consequence of this soil behavior and climatic control, there is comparatively little dust formed in Porto Rico. This is especially noticeable on the roads, where one is almost never in the least troubled by it.

In two districts, one on the north fringe of El Yunque along the Sabana River and the other on the north side of the divide near Adjuntas, deposits were seen which suggest glacial action. Very large boulders are stranded in positions where it is difficult to account for them by ordinary erosion means, but too little study was given and too little evidence is at hand to warrant a more definite statement.

STRUCTURAL FEATURES

Most of the structural features represented in the geology are mentioned in connection with descriptions in other sections of this report. This is especially true of such structures as may be regarded as essentially primary, including the interbedded and intrusive forms of various kinds. There is no doubt but that the most prominent structural combination in Porto Rican geology is represented by the succession of interbedded sedimentary beds and tuffs, cut by or interleaved with intrusives in the form of sills, dikes or irregular stringers. The combination occurs in great variety as to succession, relative amounts or proportions, quality of material, present condition and relations to other members, but in spite of these variables the structural feature is essentially the same and has the same meaning everywhere.

Igneous Structures

The most striking thing in connection with the structure is the remarkable uniformity of the sills and their close resemblance on that account, after weathering, to the fragmental beds with which they are associated. The small amount of metamorphosing influence that they seem to have had, also adds to the difficulty. In some cases, however, a transgressive intrusion has disturbed the adjacent beds a great deal in a mechanical way.

In the average case, it is judged that the intruded magma has neither penetrated the materials of the adjacent beds to a noticeable amount, nor

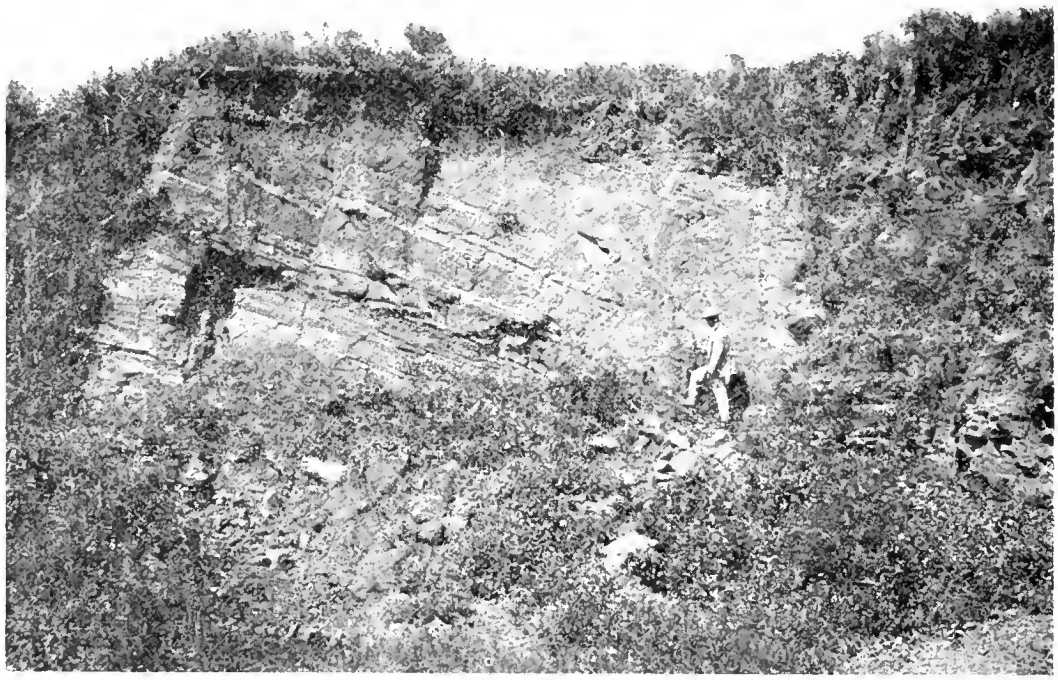


FIG. 11. *Shales and ash beds cut by a large irregular dike and sill*

The dike is shown at the location of the standing figure and the sill extends upward to the left between the plainly bedded layers. Both the dike and the sill are crowded with fragmental material to an extent that makes the intrusive have more the appearance of a volcanic fragmental than a true intrusive.

has it absorbed or incorporated a great deal of such material. But in a few cases where structural relations were indisputable it was equally clear that the intrusives, both transgressive and concordant, were literally choked with foreign fragmental matter, making them resemble the real tuffs so closely that it is doubtful whether the difference would have been detected except for the clearness of the intrusive relation. Such occurrences suggest that there may well be many other apparently fragmental interbeds that are in reality fragment-clogged intrusives. On ac-

count of the great abundance of the fragmental matter, it does not seem possible that these intrusive masses could penetrate in that condition to some of the positions where we now find them. It is more likely that a rather fluid magma has penetrated some unusually porous fragmental bed forming a matrix for it, perhaps also spreading it somewhat, and then in breaking across to another bed, in some cases it was still mobile enough to drag the mixture along into the larger transgressive structures. This idea is somewhat supported by the finding of a conglomerate bed, near K-86 on the military road west of Aibonito, impregnated with an igneous matrix in essentially this same manner. In addition to these forms, there are numerous larger intrusive masses, the largest of which deserve a special name. I see no objection to calling them bosses. The two largest occur, one between Caguas and the Caribbean sea toward the south and southeast, and the other between Jayuya and Utuado on the north side of the divide.

Volcanic Vent Complexes

A special igneous structure that has not been referred to except incidentally is that composite of disturbed structures which represents the location of old volcanic vents. They are essentially a complex of irregular intrusive units cutting and including masses and aggregates of various fragmental and sedimentary types in a mixed relation. In the clearest cases, such a complex suddenly takes the place of a formation of apparent promise of continuity such as a series of sedimentary beds, and after an interval these beds are again found continuing as before. For example, the Coamo limestone formation is abruptly cut off and its place is taken for a mile or more by one of these igneous complexes, the limestone continuing on the other side again. The Jacaguas reservoir, just above Juana Diaz, lies in one of these old volcanic-vent complexes, occupying, however, only a portion of the area. Another such case is represented by the complex cutting the great conglomerate beds on the military road at about K-87–88 west of Aibonito. Another is believed to be represented by the very striking basin-like area crossed by the road between San German and Hormigueros. This one is now represented by a very smooth plain five or six miles across surrounded on all sides by more hilly country. The same conditions are undoubtedly indicated by the extremely complex structures seen on the Descalabrado river two miles below, south of the military road. Some of these mark the sites of ancient craters, clogged or choked with fragmental and intruding materials.

Folding

Most of the rock formations representing original bedded types have been more or less tilted or otherwise do not now have their original attitude. Those belonging to the younger series, the Tertiary limestones and shales on the north side of the island, are comparatively little disturbed, and in some cases do not have a very different dip in spite of the fact that they have changed very much in position with respect to sea level. On the south side of the island, however, even these later beds are in many places tilted at a higher angle than they had in the beginning

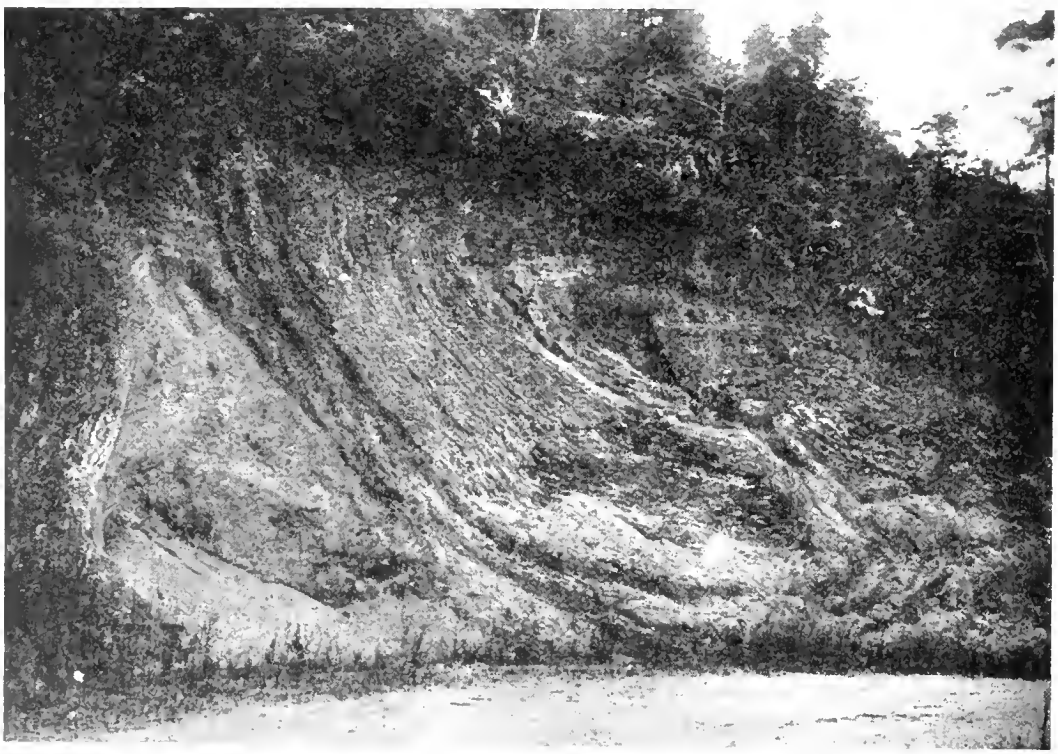


FIG. 12.—*Overturned fold and crush zone in finely bedded shales on the Jayuya road near the summit of the range*

and occasionally show high angles and even gentle folds. This condition may be seen on the Jacaguas River, near Juana Diaz, better than at most places, but similar conditions are indicated by the relations at certain points farther west. This condition on the south side of the island indicates more extensive and more violent dynamic disturbance on this side, which is further supported by the presence of faults cutting and affecting the Tertiary series on its present inner margin.

The older series, the pre-Tertiary, is still more profoundly affected and, in almost all districts, shale and ash beds may be found standing at high angles, in many cases practically vertical, and in occasional instances

crumpled and overturned in a most complicated manner. Minor fold structures of this kind are especially prominent in the higher ranges, for example, along the Jayuya road along the divide opposite station K-24 of the Ponce-Arecibo road. At such a place may be found as complicated structural features of this kind as is usually present in any folded mountain region. The high angle at which such beds stand at many other points leads to the belief that similar complexities characterize a great many of the districts occupying the higher mountain portion of the island as well as some of the marginal areas, but the great amount of erosion and the very limited exposures at most points tend to obscure some of these details. The complex way in which the igneous intrusive masses cut all of these formations also tends to obscure and modify and further complicate the simpler fold structures so that it is not always possible to properly credit the disturbed attitude. On account also of the fact that the total quantity of injected or intruded materials, including dikes, sills and bosses, is exceedingly large and must have caused extensive disturbances by reason of the displacement produced by the occupation by these intrusive masses, it is likely that much of the observed abnormal attitude of the bedded rocks may be due to this cause rather than to regional folding of a simpler sort. It is fair to say, however, that a sufficient amount of data is not yet available to draw general conclusions as to the meaning of the fold structures in Porto Rico. The striking thing is that all of the older formations are disturbed and that their position and attitude, even along the margins of the island, indicate that the region affected by these movements was more extensive than the present land area.

Faulting

There are many evidences of faulting on a small scale, in some of which the displacements can be measured. But in most cases the direct evidence lies chiefly in the existence of crush zones, slickensided walls and abrupt changes of rock type; there is no opportunity, on account of the general rock complexity, to secure quantitative data. Judging from the difficulty in tracing certain formations between districts where they have been identified, it is probable that there are occasional faults of large displacement. Numerous crush zones were seen on the Comerio road especially, but in this case also no system was discernible from the few measurements available.

The most prominent fault, in its effect upon present features, is the one now marking the inner margin of the younger series of chalky limestones and shales constituting the coastal belt along the south side of the

island from Juana Diaz past Ponce at a short distance to the north, crossing the Ponce-Arecibo road at K-4.8, and thence westward, crossing the Ponce-Penuelas road at K-10. This is the only large fault actually observed that is necessarily of recent age, although a few others are inferred. It must be of very late Tertiary age, because the chalky Ponce beds are abruptly cut off by it. The older rocks of the pre-Tertiary are lifted with respect to the younger series forming the present coastal margin wherever this fault has been seen. It has been traced by us from Juana Diaz to the vicinity of Penelas, a distance of about 12 miles. What becomes of

FIG. 13.—*Crumpled shales as seen along the Jayuya road near the summit of the range*

it at either end is not yet determined, but it is believed to extend much farther in both directions.

The physiographic habit of the island as a whole tends to support the view that the fundamental structural form is that of a large fault block, with the principal fault displacement and uplift along or near the southerly margin, tilting the whole mass gently northward. If this disturbance took place, as seems to be indicated by the fault described, in very late Tertiary time, accompanying the emergence from the sea, it would account for the abnormalities of Tertiary rock distribution as well as the unsymmetrical position of the main drainage divide. In any case, however, the fault block structure is a very late development and is superimposed on the other more complex and older structures of the mass.

The island is comparatively abruptly terminated at both the east and west ends. The younger limestone margin, which is fairly continuous along the north coast and extends along about half of the south coast, is wholly wanting at the east end and is also absent at the west end except at the corners. At Fajardo, at the east end and at Rincon, at the west end, for example, the older complex bedded rocks continue to the shore line. In the uplifting of the present island mass, it would therefore appear that breaks occurred at both ends. The included mass is therefore probably bounded roughly on three sides by faults, the east, west and south, and is as a block tilted gently to the north.

That there is, besides, considerable differential movement accompanying the uplift and disturbance, is indicated by the warping of the erosion plain lying beneath the younger series, the Eocene peneplain, which stands essentially at sea level in the vicinity of Loiza and more than a thousand feet above it at Lares. This difference is accompanied by a much wider belt of these later limestones also in the region about Lares than elsewhere. Such warping need not of course be confined to the last movement: it may have accompanied the depression in early Tertiary time, permitting, as is indicated by deposits, very marked differences in the development and encroachment of the organic accumulations.

Large Structural Groups

Where rock formations or field units are so numerous and so closely related and so complex in primary structure if taken in detail, it is advisable to combine them into fewer more generalized groups. A first step of a very general sort, but in all respects sound, has been taken in recognizing and using the terms "Younger Series" and "Older Series" in this paper. An additional step has been suggested in recognizing certain smaller associations under the terms San Juan Formation, Arecibo Formation, Coamo Limestone Formation, Juana Diaz shales and marls, Fajardo shales, Sierra de Cayey tuffs, Ponce chalky limestone, etc., but these are for the most part local designations, some of which may well be expected to become unnecessary after complete correlation is established. A good structural basis for sound subdivision of this sort is not yet worked out.

Unconformities

There is only one marked unconformity in the structure of the island. This is between the younger and the older series. It measures the break in the sedimentary succession represented by the erosion interval during which this mountain mass, now represented by Porto Rico, was reduced

to a comparatively monotonous surface for the most part at least near to the sea level. The time interval need not have been of very great geologic value, but it represents the time between the last violent outbursts of volcanic eruptive activity, occurring near the close of the Cretaceous, and the beginning of simple sedimentation and limestone reef development and other organic accumulations in the early Tertiary. This unconformity is very pronounced along the northern margin of the island wherever the two principal series of formations are well developed. This is not easily seen on the south side, but the relative complexities of attitude of the two series, together with their position, emphasizes the same fundamental relation. This break in sedimentation is not anywhere marked by a development of a basal conglomerate. In some places the new series is inaugurated by the development of shales, part of which are lignitic, indicating land conditions, but in other places such beds are entirely wanting and the upturned eroded members of the older series are followed abruptly by limestones of the reef type. The first type of succession is illustrated in the vicinity of San Sebastian and Lares and the latter type of abrupt limestone succession by the conditions seen on the Arecibo River. It is entirely likely that the time value of this break is not everywhere the same. Probably the districts in which shale beds are developed saw the beginning of sedimentary deposition at an earlier period than those in which the shales are entirely lacking. It will be possible to work out these historical and structural differences with further study of the content and distribution.

A very extensive development of conglomerates in the region immediately west of Aibonito and smaller occurrences at several other points, especially on the Comerio road south of Bayamon and also near the military road in the vicinity of La Muda, have a suggestion of the possibility of a rather important structural break, but there is thus far no conclusive evidence of the presence of any real unconformity.

Veins

Quartz veins are not prominently developed. There are occasional quartz stringers and in a few places they are abundant enough to make a sort of net work, but in no instance was a large persistent fissure vein seen. In some cases the stringers of quartz carry values in gold, and in all probability they are the source of the placer gold known to exist in certain districts. So far as observations have been made, there is no particular system represented in the vein occurrences. Questions connected with this subject together with mineralization and possible value as mineral resources should be made a special study.

Minor Structures

Although there is extensive development of sedimentary formations which have been subjected to much disturbance, there is comparatively little structure of a minor sort that seems to deserve such discussion in this description. Two, however, that seem to have special significance connected with the origin of the particular beds which have been found are (*a*) a peculiar crumpled, enterolithic structure seen in one of the ash beds near Guayama, and (*b*) the wind-assorted cross-bedding structure of the old dune sands of the San Juan formation at Arecibo.

Enterolithic Structure.—The enterolithic structure noted in the ash beds, on account of the thinness of the bed,—about eighteen inches,—and the simplicity of the associated structure,—simple tilted beds,—leads one to believe that the structure is essentially primary rather than of subsequent dynamic origin. Its appearance is perfectly consistent with the explanation that it is preserved from the time of deposition and its behavior at that time as a small mud flow. It is a structure such as might be formed by slumping movement of a soft layer. It should be expected that there would be frequent behavior of this kind in the accumulation of such extensive beds of ashy materials, which must in some cases have been deposited under conditions that would make slumping movements possible, but it is not to be expected that material of this kind would in most cases be capable of preserving any of these primary movements. In the case noted, the quality of the interior makeup of the bed seems to have been more favorable to such preservation. It is the only case where such an observation was made.

Double Cross-bedding.—The cross-bedding structure belonging to the San Juan formation is a prominent feature wherever these ancient dune sands are preserved. A great prevalence of steeply inclined minor structures is crossed by fewer nearly horizontal ones. Measurements made on sea-cliffs a short distance west of Arecibo, where this rock is very prominently developed, gave dips of 30 to 33 degrees repeatedly. A series of these is abruptly terminated by a more nearly horizontal bedding for a comparatively short distance and the whole structure is repeated. The layers with this kind of structure are prevailingly one-half to two feet thick and no ripple marks were seen on any of the beds examined. The cross-bedding structure in this case dips always to the west or southwest, and the average strike of the principal beds is about north 30 degrees west. This is consistent with a wind direction not very different from the present prevailing winds. Very strong structural development of this kind is also to be seen in the city of San Juan at the promontory on which the

Morro is built, but measurements of orientation were not taken there. An occurrence of this rock immediately to the east of Arecibo, a short distance south of the lighthouse, showed structures of this kind on a much larger scale than was seen elsewhere, and with an especially interesting combination structure. The principal or stronger divisions are widely separated and lie nearly horizontal. A comparatively small bed lying in this position was almost unconsolidated, but those strongly cross-bedded immediately above as well as those below were compact enough to stand in a vertical cliff 30 to 40 feet high. The chief interest attaches

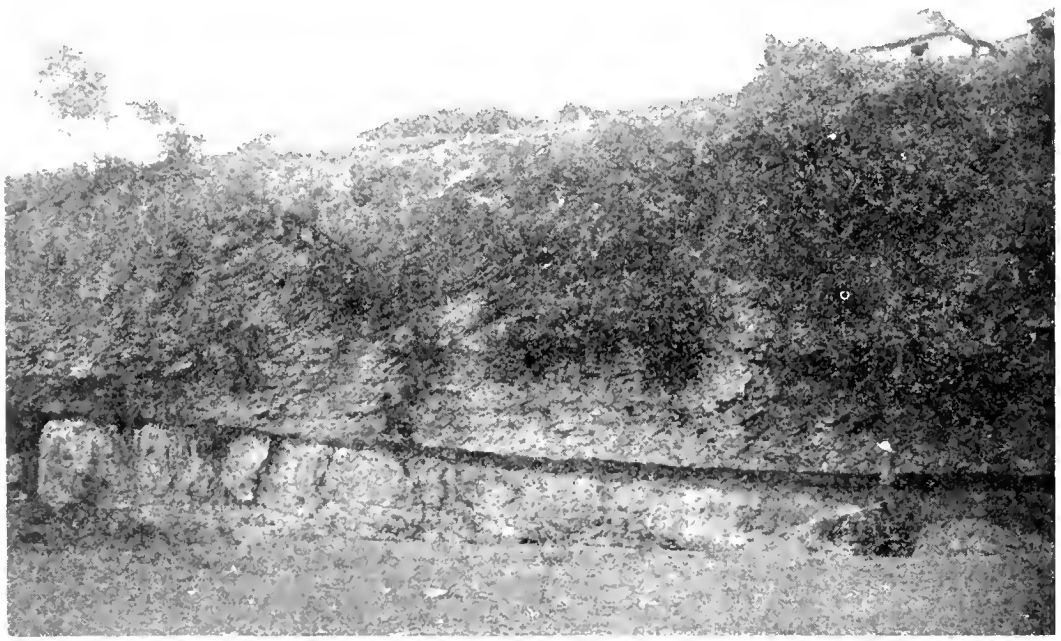


FIG. 14.—*Cliff of the San Juan formation south of the lighthouse at Arecibo*

The prominent cross-bedding, extending throughout the upper thirty feet of the cliff, is well shown, together with a less strongly marked horizontal structure crossing the same beds. The prominent break near the base is made by a layer of sand which is very poorly consolidated.

to the strongly cross-bedded portion forming the upper twenty feet or more of the exposed cliff. The cross-bedding structure itself extends without interruption through a much greater vertical range than in any other outcrop examined, but its attitude and dip were not markedly different; the feature that was strikingly different from the structure seen anywhere else was introduced by the presence of less pronounced but still very plainly marked horizontal structures, making an interpenetrating mesh-like arrangement in the face of the cliff. This can be seen strongly enough to show in a photograph even at a distance of 100 feet. It is evi-

dent that some peculiar condition has been in control in the development of this compound structure. There is no reason to assume any difference of source or origin for the steeply inclined structures, or cross-bedding structure, from that assumed for all of the other occurrences of the San Juan formation. It is apparently a perfectly normal product of the assorting action and deposition of material under the work of the wind. But under normal conditions it would not happen that a second structure in a horizontal position should be repeatedly developed crossing the well marked cross-beds so that the whole complex combination should be developed on such a scale as is seen in this case. From the nature of the deposit and the conditions in which it may well be assumed to have been formed—that is, at or near sea level in the vicinity of or bordering upon standing bodies of water—one would be inclined to favor the explanation that the accumulating cross-bedded sands fell into or rolled into a body of water which had a tendency to attack the newly deposited material and to bind the grains together. The difficulty with such an explanation is in the fact that the horizontal structure is repeated at small intervals practically throughout the deposit, and apparently without disturbing the primary depositional structure at all. It would seem quite unlikely that loose matters of this kind, falling into or rolling into a body of water of an open surface sort, should maintain or preserve the primary structure so well. Perhaps it is more logical, in view of all the features, to connect the development of this structure which seems, from its slight influence or modification of the cross-bedding, to be wholly secondary with the subsidence of the coast which is shown to have been one of the late events in the geological history. As subsidence progressed, perhaps somewhat irregularly, it would happen that the ground water level would rise correspondingly high in beds that were passing below sea level. At the surface of this ground water level the tendency would be to accomplish a binding of the granular materials together. Both above and below the ground water level there would probably not be so strong a tendency to develop this binding. With the next step in the progress of subsidence, another streak or indurated zone would be established and these have been repeated throughout the whole formation during the whole period of subsidence. An action of this kind would not tend to disturb the primary structure at all: it would on the contrary tend to preserve it or make it less destructible because of the improved induration. But it could, in addition, develop a succession of secondary structures throughout the whole mass which, if the binding is fairly substantial, might rival the primary structure in prominence when exposed to subsequent destructive attack. It is possible that such a succession of horizontal struc-

tures could be developed even under a perfectly continuous but very slow subsidence movement by reason of the natural seasonal ground-water fluctuation. From this point of view, the range between two succeeding

FIG. 15. *Detail of the double structure in the San Juan formation at Arecibo*

This photograph was taken at the same point as the one shown in Figure 14 to bring out the horizontal structure crossing the inclined layers. There is no doubt whatever that the dark layer of less consolidated sand in the lower third of the photograph is a primary bedding structure, but the horizontal marks crossing the inclined layers in the upper part of the view are believed to be of secondary origin.

horizontal markings would measure the fluctuation range of the ground water, the harder zones representing in that case the more persistent upper level for each succeeding depression position.

The cross-bedding structure shows as plainly as it does on exposed surfaces also because of the fact that certain streaks are more perfectly indurated than the intervening ones, and the objection might well be raised that a history of the kind suggested above would not be expected to develop such a difference of induration in layers inclined at such high angles to the horizontal. As a matter of fact, however, these sands are not simple in their makeup. They are in large part fragments of organic material and complete shells of small organisms of a calcareous nature and the primary cross-bedding structure represents an assorting action on this mixture of silicate and carbonate mineral material. It so happens, therefore, that the successive structural units are not necessarily of the same mineral proportions, and in the process of induration, or of binding the grains together, certain streaks yield more readily to this influence and develop greater solidity and resistance to destruction. It happens, furthermore, from a variety of rather unusual primary conditions and secondary influences that both a primary and secondary structure of unusual prominence and peculiar association are developed in the San Juan formation.

SPECIAL RELIEF FEATURES

Playas

The flat areas along the coastal margin which are known as playas are all developed at the mouths of rivers and are essentially alluvial deposits of floodplain and delta type. In most cases they seem to occupy areas that must formerly have been embayments in the coast. This development is most striking, for example, at the mouth of the Arecibo and of the La Plata and Loiza rivers. In some cases, however, there is no marked embayment and the deposit is more strictly marginal, such, for example, as the Fajardo Playa at the east end of the island and others on the south coast.

Promontories

In addition to the embayments and playas, there are, occasionally, in the intervening spaces, promontories where the rock formations extend into the sea and terminate in cliff forms. These are neither numerous nor are they confined to any particular portion of the island or to any rock formation. They are represented by the most recent of all of the

formations, essentially a silicified dune deposit such as that at San Juan, also by Tertiary limestone reefs, such as that at Quebradillas and at Guanica, or by the still older igneous and clastic series, such as that at Anasco, or by massive intrusives of a strictly igneous habit, such as that at Maunabo. It would appear from this that the former outline of the island must have been more irregular than it is at present and that the distribution of marginal formations is also not as regular as has been represented in earlier reports.

FIG. 16.—*Playa plain and marginal terrace*

View of the Playa plain (foreground), the marginal terrace (middle field) and the mountainous divide formed by the Sierra de Cayey as seen from the "Central Machete" near Guayama. This terrace bevels across the upturned edges of shales, ashes and intrusives of the older series and is probably due to marine cutting.

Terraces

At many places on both sides of the island there are comparatively smooth tracts having the appearance of bordering shelves which represent true terraces. Their location along the sea margin and the comparatively insignificant development of similar benches along the streams lead one to believe that they have an origin connected with the wave action and attack of the sea. This interpretation is supported by the presence of these terraces along the coastal margin where stream action would not seem to have been able to reach. In any case, the presence of such terraces, which stand from 100 to 200 feet above the present sea level, indicate a former more submerged condition, so that the sea or streams, or both combined, were able to attempt base-leveling at that ele-

vation. The presence of great quantities of roughly assorted gravels clogging some of the valleys of the southerly side of the island tends to support the same general conclusion. The bearing of these features on the geological history of Porto Rico will be taken up at another point.

Cuestas

Both on the north side, for nearly the whole length of the island, and on the south side, over the westerly half, there is a bordering belt of limestone and associated beds that have been developed on an eroded sur-

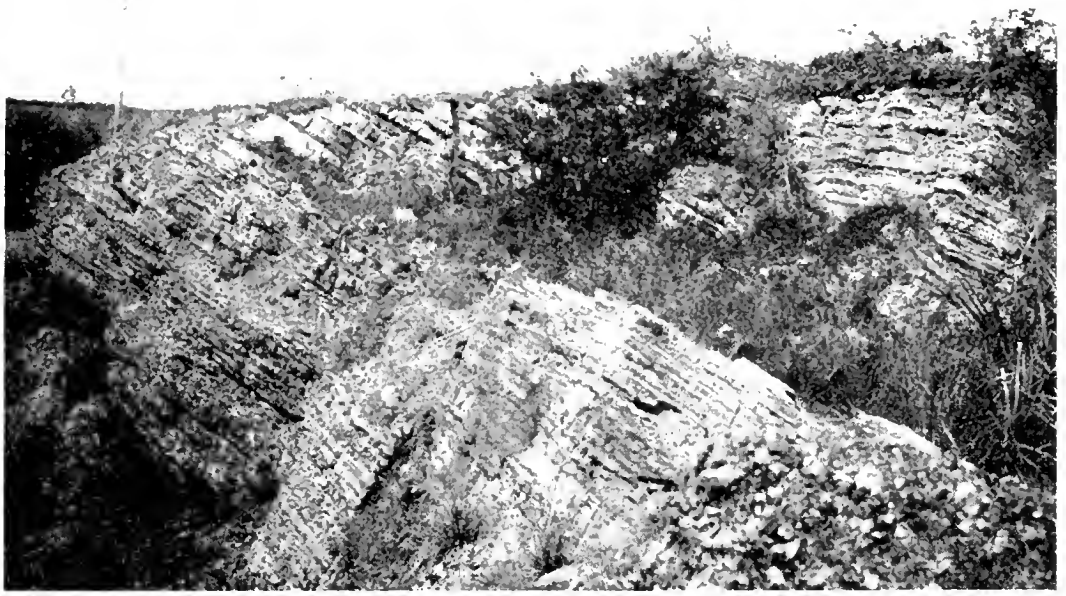


FIG. 17.—*Structure beneath the marginal terraces*

Strongly bedded ash together with associated shales cut by small dikes forming a part of the terrace near Guayama. These rocks belong to the older series and dip into or toward the mountains rather than toward the sea.

face which beveled across the more complex structures of the older series of formations that formerly made up the mass of the island. These limestone beds are several hundred feet in thickness and dip gently toward the sea. On the inner margin of their present extent toward the interior, especially along the north side of the island, they are abruptly terminated in a very irregular line of modified cliff forms facing toward the prevailingly smoother and lower ground for some distance toward the interior. For the most part, this limestone margin is exceedingly rugged and broken. The width of the belt with this rugged character

varies very much in different parts of the field. Its most striking development is in the district extending from Tao Alto to Aguadilla. In the district extending eastward from San Juan and also in some of the areas on the south side, this margin is very much broken and so obscure in some parts as to escape detection. In its best development, however, it is a typical cuesta, formed in the usual manner by the erosion of a formation representing a recently uplifted coastal series. The series of formations involved formerly extended inland very much farther than they do now. Only the outer margin remains from the erosional destruction of a series of beds and reefs that in former times covered a

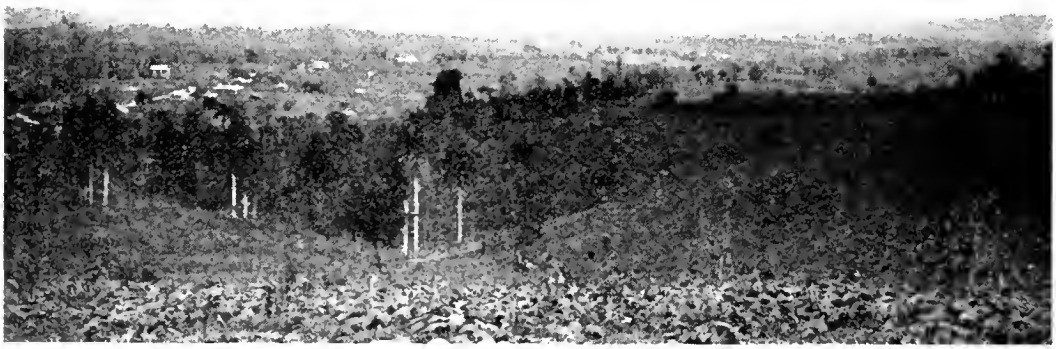


FIG. 18.—*Inner lowland near Bayamon*

View looking north from the Bayamon-Comerio road toward San Juan, showing the monotonous features of the lowland belt in the foreground and the comparatively prominent hill remnants of the Tertiary formation cuesta in the background.

large portion of the island. The road running from Aguadilla to Moca, San Sebastian and Lares extends for practically the whole distance, after leaving the coast, along the inner lowland at the foot of this cuesta or along the cliff forming the inface. The same features characterize the surface topography as far east as Corozal. This feature is much less pronounced on the south side of the island.

Peneplain

Beneath the limestones constituting the cuesta and representing the Tertiary series there are, in numerous places, traces of a former plain that represented the results of erosion on rocks that had a complex struc-

ture. Occasional profiles of more distant ridges also show a sky line that suggests the former existence of such a plain, and in favorable localities it can be traced directly to the foot of the limestone cuesta. Occasional traces are also seen on more mountainous tracts, especially at the west end of the island, near Rincon and in the vicinity of Mayaguez. At the latter place, these remnants of the old plain are called mesas. It is the judgment of the writer that these all belong to a single base-leveling surface or marine-cut platform formed in the period just preceding the development of the Tertiary limestone series. Judging from beds developed immediately upon this surface, it must have been completed in early

FIG. 19.—*Haystack (pepino) hills*

A characteristic view, showing the small soil-covered flats and associated haystack hills found in the region of the Arecibo formation. Photograph taken on the road between Arecibo and Barceloneta.

Eocene time, and perhaps was even largely developed in pre-Tertiary time. It may be referred to as the early Tertiary base level or peneplain.

There are many minor features giving variety to the surface relief which depend for their particular relations and character on underground structures which are as yet imperfectly understood.

Haystack Hills

The most striking topographic feature of the whole island is the remarkable development of small isolated or grouped rugged hills usually rising abruptly above adjacent smooth flat soil-covered areas at various levels throughout a broad marginal belt along the north coast, west of

San Juan. They constitute a feature so unusual that even the untrained casual visitor is impressed with them.

This feature has been referred to before in connection with the description of the "Younger series" of rocks, especially the Arecibo reef limestone formation. In spite of the unusual appearance presented by this distribution of "haystack" hills and intervening flats, their origin is judged to be comparatively simple. The active agents and processes have been the same as those at work on all other parts of the island, but the results differ because of the fundamental difference of material and

FIG. 20. *Cave structure in the haystack (pepino) hills*

Near view of the limestone hills forming the margins of the small cultivated flats in the typical haystack hills district. This view shows the cavernous nature of the limestone forming these hills, a structure that is regarded as the most significant feature and probably the largest factor in the development of these peculiar relief forms.

structure. Nowhere are these features developed except where the later reef limestones are the underlying bed-rock formation.

The essential steps in the development of these forms are the following:

The reef limestones are not uniform in composition or structure. They have more or less intermixture of earthy matters which are distributed irregularly, but chiefly at certain horizons, as more earthy or shaly beds of no very great lateral or vertical extent. Such conditions are re-

peated at occasional intervals in successive horizons. As such a series is lifted above sea level and subjected to ordinary erosion and weathering, the tendency is, (*a*) for the purer and more massive reef limestones to be attacked by the solvent action of percolating water with a development of underground channels, porous rock condition and actual caverns, (*b*) for the more earthy layers to resist and limit such action at the levels where this matter is present in sufficient abundance, with a development of residuary material. As this action progresses toward maturity, many of the larger caves collapse and sink holes are thus formed. With still further development, the sink holes merge into each other in local areas where solution has been most active, the earthy debris forms a soil in the bottom corresponding in level with the first important earthy layer, and adjacent remnants of the limestone reef stand out as sharp rugged hills separated by irregular notches that represent other smaller collapsed caves. The result of such action and conditions, finally, is the numerous "haystack" hills standing on flat soil-covered areas or surrounding such areas as if they were just set down as bunches on this surface. This relation is repeated at different levels throughout the belt from San Juan to Aguadilla, but the most striking developments are local, apparently where the structural relations are just right, and may be seen best between Tao Alto and Arecibo, especially in the vicinity of Manati and Vega Alta.

It was at first thought that former subsidence levels might have something to do with establishing the level tracts, but the observation that these tracts stand at very different levels in immediately adjacent districts together with recognition of the structural difference, lead us to give credit to the primary structural character of the formation itself as the controlling factor in the present distribution. According to this explanation, these hills are mere remnants left from solution attack on a reef limestone, the depressions between them representing collapsed caverns, the walls of which may still be seen on the sides of some of the more rugged hills, and the surrounding or intervening tracts are soil-covered and level, chiefly because of the accumulation of earthy material, left behind after removal of the overlying reef, now halted in its reduction at the first important less soluble beds.

MINERAL RESOURCES [6]

An examination of specimens of minerals and ores in the hands of local prospectors and residents interested in developing mineral resources,

[6] A good list or tabulation of the mineral occurrences of Porto Rico may be found in the article by H. C. B. Nitze listed at the close of this paper.

together with observations made personally, shows that there is considerable range of minerals and ores. It appears also that considerable attention has been given in a few cases to local development. There is large variety shown in a collection of this material and in some cases the specimens exhibited look very promising indeed. But there is almost no reliable information touching the quantity or the exact relations or estimates of possible profitable development. It can be said, without danger of contradiction, that none of the developments so far undertaken looking toward the systematic mining have proven profitable.

Gold

Only one enterprise of this kind seems to furnish any production, and this is the placer mining for gold. Gold washing has been practiced from the early Spanish occupancy to the present time, and it is not at all a rare thing to see several men digging in the stream gravels for the "pay dirt" and panning out the gold. This is done in all cases on a very small scale and with the aid of the simplest equipment, and the returns appear to be very moderate. It is claimed that in former times a much more elaborate system of working such deposits was in operation under the Spanish regime, and, according to historical statements, they were considered profitable. More recently, there has been at least one attempt near Corozal to develop this kind of ground by the use of modern appliances, but the plant has been allowed to go to entire ruin. The only places where actual placer washing was seen in progress was three miles south of Corozal and on the Sabana river near Luquillo. Near Corozal, also, some work has been done in an attempt to discover the veins or lode which may have furnished the placer gold. There are several pits, trenches and shafts, in some of which quartzose stringers were seen which appear to fulfill the requirements of a source of supply. Some free gold was found in panning a little of the weathered material at one of these spots. There is little doubt but that these veinlets or stringers, which were numerous at one of the cuts, are in part the sources of the placer gold of this locality. But at no place examined was there to be seen any "vein" of apparent consequence or any structure suggesting the course or extent of the mineralization. Of course the rather mixed state represented by the residuary matter, seen almost everywhere at the surface, does not lend itself readily to the tracing of veins, and it may therefore happen that conditions would prove, after thorough exploration, to be better than the first brief examination indicated. There are said to be some old abandoned workings dating back to Spanish conquest times at

the same locality, but such evidences are very obscure and would seem at best to have very little bearing on present prospects.

Copper

Some very good specimens of copper ores were seen in the possession of Mr. Henry D. Sayre, of Corozal, who assured us that there were several localities represented in the collection and that in no case had the real value of the occurrence been determined. It was understood that examinations have been made by engineers sent to Porto Rico in the interest of American mining companies, and that some exploratory work has been carried on by Porto Rican companies or groups of individuals, but so far as known there is at the present time no development work being conducted, and the possible value of these deposits has not been thoroughly proven.

Zinc, Lead and Silver

One prospect, on which several hundred feet of underground work has been done, was visited at Barrio del Carme in the Sierra de Cayey, on land owned by Pablo Vasques, several miles northwest of Guayama. The country rock is chiefly andesitic tuffs cut by porphyritic intrusives. A quartz vein carrying sulphides, pyrites, sphalerite, galenite and chalcopyrite has been followed and there is some ore on the dump. The vein varies from a mere streak to a width of two feet. The mineralization is irregular and the values are said to be chiefly in lead and silver. The second-class ore is essentially mineralized tuff. The exploratory work has been done in large part on side slips and streaks quite outside of the vein proper. In all of this side work, there was apparently no new mineral-bearing ground discovered. The first-grade ore is heavy and the distribution of values is not determined. There is no doubt of the existence of a real vein or of the ore in this case, but there is need of more intelligent exploratory development along the vein proper, together with a study of the possibilities of separating the chief values by some sort of milling operation, before a reliable conclusion could be reached as to possibility of working the deposit as a mine.

Iron

One magnetic iron prospect was visited. This occurrence is on the divide about ten kilometers west of Naguabo. It is reached by driving out on the road from Naguabo toward Torres to about this distance and then taking saddle horses to the divide, a distance of about two kilometers southward. On the expedition we were accompanied by Mr. Arturo Gallardo, Jr., Alcalde Municipal of Naguabo.

There are many surface bowlders of magnetic iron of fine quality in this vicinity. A little underground working is evident at one point but this is now caved in. Surface observations, together with a few magnetic observations, failed to show any very extensive deposit at that point, but the quality appears to be good in iron content. The ore carries a little copper and is associated with an igneous rock essentially andesitic in composition. It could be traced with a fair degree of certainty about fifty feet east and west just below the crest of the ridge. Considering the associations at this place, it seems necessary to conclude that the ore is igneous in origin and that it probably accompanies one of the porphyrite intrusives. Other occurrences of similar ores were mentioned to us in this same region, but none were visited.

Coal and Oil

There is no good ground for believing that valuable resources of these products exist in Porto Rico. Some prospecting for them is carried on, however, in a desultory way. The only basis for the hope of finding coal is the occurrence of lignite and lignitic material with the shales lying at the base of the younger series of rock formations, below the Arecibo limestone member. Lignitic material was seen in these shales near Lares, and similar or better material has been reported from near San Sebastian. From what has been seen, there seems to be no promise of very valuable deposits of this kind. The structure is simple and a very little exploratory work done in a systematic manner would determine the probable value of every occurrence known. There is no promise at all of such content in the older series.

No oil indications were observed. The only formation to be considered in investigating the prospect of oil is also the basal shales of the younger series.

Limerock

A particularly porous, granular and uniform limerock is obtained from the small island, Icacos, just off the northeast coast, and is used in sugar refining at the Central, owned by the Bird brothers, at Fajardo. The rock is organic, largely foraminiferal, and is probably structurally of the same origin as the San Juan dune sand deposits,—comparatively recent. Such materials are doubtless to be found in large amount, but not always so pure and so uniform in quality and structure. Limestone suitable for lime burning or for cement mixture is certainly not rare. Limestone of a quality that would permit its use in structural work is also found at some places, but apparently very little native stone is used.

Guano

Bat guano is found in some of the caves in sufficient amount to be a source of local fertilizer.

Road Metal

Several kinds of stone were seen used extensively in road improvements. The particular variety used depends largely on the local supply, but the most common are the Arecibo limestone and the massive syenite and granite porphyry. There is no lack of these as well as other types suitable for such use.

There are other mineral substances that will invite investigation, but no others came under the writer's personal observation and no facts regarding them are in hand.

HOT SPRINGS

Thermal springs are known in the vicinity of Coamo. Judging from their location and apparent relation to other physical features, they are believed to lie along a fault weakness. The district is also one of comparatively late igneous activity, and this, coupled with the other factors, leads to the suspicion that the springs are directly connected with the dying igneous activity and may actually represent juvenile waters.

At Coamo Springs Hotel, one of these springs has been developed and controlled for commercial purposes. The water is hot as it comes out of the side of a small ravine and runs down over the slope, which is covered to a moderate extent with deposit from these waters. The immediate bed rock is not well exposed, but it is judged to be either a tuff or an igneous complex and the field relations in the vicinity show that there is a thick series of beds both above and below. No doubt critical field study could determine the actual relations with considerable certainty.

An analysis of these waters, furnished by the proprietor of the springs and made at the agricultural experiment station at Mayaguez, is as follows:

Fixed elements per litre of water

Free carbonic acid	0.01296
Sulphate of lime	0.79902
Sulphate of soda	0.52531
Chloride of potassium	0.00031
Chloride of sodium	0.23054
Silicate of soda	0.08127
Carbonate of soda	0.03503
Carbonate of iron	0.01114
Total	1.68559

Gases in solution per litre of water at 0° of temperature and 760 mm. of pressure

Nitrogen	13 cc.	740
Oxygen	1	761
Sulphydric acid	1	967
Total	15	2468

Historical Statement

A complete or even a reasonably full account of the geological history of Porto Rico cannot be written at this stage of the investigations. Such a statement is necessarily the end product or climax of the whole series of studies that are proposed, but it may not be out of place to outline some of the leading and most clearly marked steps as a rough sketch or a preliminary attempt.

At the outset, it is well to appreciate that the Island of Porto Rico is geologically young. There are no traces, so far as known, of any of the so-called ancient rocks. It is quite true, of course, that the older series of formations is largely a volcanic complex whose exact age may never be accurately determined, but there is no occurrence of profoundly metamorphosed members or other evidences of great geologic age. Besides, the series, complex as it is and difficult to group into suitable divisions as it may be, undoubtedly forms a very closely related succession of minor formational units whose uppermost members are determinable as to age with reasonable accuracy. It would appear also from the nature of the deposits and their structural relations that the accumulation must have been, for the most part, a rapid process.

There is no good reason, so far as any of these facts are concerned, why the whole of the "Older series" could not have been accumulated in a single geologic period. The fossil content of the upper members of this series indicates that this period was the Cretaceous, as used in the broader sense in geology. 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.

This earlier period is characterized by volcanic and other igneous activity on a very large scale. Beds were accumulated both above and below sea level. There seem to have been oscillations of level accompanied by recurrences of similar beds, and apparently much shifting of the supply of material accompanied by great variation of character laterally. There is good evidence that succeeding volcanic outbursts broke through these beds at many places.

An occasional more prominent change of conditions, more or less clearly marked in the structural relations and character of material, may possibly be used as a basis for epochal subdivision. It is quite clear, however, that there was no profound change of geologic control throughout the whole of this earlier time,—it was strictly a volcanic period. The succession of disturbances by which it was affected is represented in part by dynamic modifications of the nature of folding, crushing and faulting, but this is probably an accompaniment of the more profound igneous activities also, and need not be regarded as evidence of any strikingly different causal process. If there were contributory causes of a regional sort controlling the folding, they are essentially simply superimposed upon or introduced into the larger, more profound and longer continued igneous activities which prevailed both before and after that time.

This long period, characterized by great complexity of formational development, including tuffs, agglomerates, conglomerates, shales, limestones and immense numbers of intrusives of great variation in size, form and composition, finally came to an end by the dying out of the volcanic energy, and greater stability of the whole with respect to elevation and subsidence was established. Erosion cut down the exposed formations, the sea attacked the margins and in time most of the projecting mountain mass was reduced near to base level, the sea encroached far onto the former land areas and a new historical chapter was begun.

It is not possible to say, with the data in hand, that the entire island was reduced to a peneplain, or perhaps a conoplain, but there is good evidence, from the traces still left of former planation and from the disposition of the remnants of overlying formations still preserved, that the greater part of the present area was worn down to base level and submerged. The process of base leveling was going on before the close of igneous activity and it was continued long enough to bevel across rocks of all sorts with marked success, but there is no necessity for regarding it as a very long geological time.

As erosion proceeded, sediments were deposited unconformably around the margins of the island of that time and perhaps also in some of the marginal valleys above sea level. These constitute the earliest shale beds of the "Younger series" and are believed to be of Eocene age. They are at least early Tertiary. Where more simple marine conditions came into control, as would happen when submergence or planation had masked or destroyed the more elevated sources of supply, the deposits became almost wholly reef limestones and shell limestones, with only minor amounts of strictly detrital material irregularly distributed. This gave a succession of somewhat irregular beds which are abundantly supplied with organic

remains and which bear evidence of the continued depression favorable for the growth of these accumulations for a considerable part of Tertiary time. There is some suggestion in the relations shown in the eastern portion of the island that this end was not wholly submerged and that differential subsidence gave to this portion less prominent development of the heavy, massive limestone beds.

In later Tertiary time there was marked reëmergence from the sea, accompanied by warping, so that the later limestones and reefs were lifted to very different elevations in different parts of the island margin. Since that event, the whole has been again subjected to erosional attack of the sea, and to wind work, with the result as now seen in the physical features. The comparatively easily destroyed shales, marls and limestones of the Tertiary series have been extensively removed, leaving only a fringe of these formations along the north coast and a part of the distance along the south coast, and developing all of the topographic forms characteristic of the erosion of emerged coastal deposits, together with some very special forms due to the peculiar makeup and attitude of the rocks themselves.

Since this first emergence there have been minor oscillations also, the record of which is observable in marginal terraces, deeply trenched flood-plain deposits, and thoroughly indurated wind deposits of presumably Pleistocene age. Apparently the latest movement has been one of slight emergence.

A summary, therefore, of the larger items in the geologic history includes the following:

1) A long geologic period of volcanic activity, accompanied by marginal attempts at assorting of fragmental and detrital material and organic accumulation disturbed from time to time by renewed or extended igneous activity.

2) A dying out of volcanic energy, greater stability of the mass with respect to elevation and subsidence, and erosional attack continued long enough to result in extended planation and partial base leveling with final extensive submergence.

3) The development of an unconformable overlying series of shales, reef limestones and related deposits chiefly of organic origin, brought to an end by final re-emergence.

4) The development of present surface features under stream erosion and marine marginal attack, with modifications arising from oscillation of level.

The geologic column forming the basis of this outline, avoiding minor details that are properly the subject of further study before specific statement should be made, is as follows:

Recent alluvial deposits.

Submergence with flood-plain deposits.

Younger Series.

San Juan dune sands (Pleistocene).

Submergence with terrace cutting.

Post-Arecibo emergence and erosion.

Organic limestones, marls etc. (Mid-Tertiary).

Arecibo reef limestones (Oligocene).

Lares shales etc. (Eocene ?).

Marked unconformity.

Older Series.

Interbedded limestones, tuffs and shales etc. (Cretaceous). Coamo tuff-limestone, Trujillo Alto limestone, Aibonito conglomerates and shales with many intrusives.

Interbedded foraminiferal shales and ash shales with tuffs, cut by many intrusives (Early Cretaceous ?). Fajardo shales, Mayaguez shales, Barranquitas shaly limestones, Sierra de Cayey tuffs, Comerio consolidated ash beds and tuffs, etc.

Future Problems

One of the objects of this exploratory study was to discover and define the problems that should be investigated by this organization. It is not supposed, in enumerating this list, that these cover every possible subject of special study, but they do indicate the fields in which there is promise of immediate and valuable scientific returns, and at the same time will add to the fund of usable information to be put within reach of the people of Porto Rico.

Base Map

One of the fundamental things as a basis for all sorts of detailed geologic work is a good contour map. The whole island ought to be mapped in the same manner as is done in the United States, using the same quadrangle system. On account of the density of population, the complexity of structure and relief and the variety of agricultural uses of the soil, the scale should be approximately one mile to the inch, or 1 : 62500, so that these maps could be used as base maps for all sorts of special purposes.

The maps now available are chiefly those of the Interior Department of Porto Rico, made to illustrate the various reports of the department and representing the progress of public works such as railways, telegraph and telephone lines and highways. On account of the care with which the different classes of roads have been shown, and the general accuracy of locations, these maps are especially useful in the present investigations. One of the most useful is a map of the Bureau of Public Works

on a scale of approximately $\frac{2}{3}$ inch per mile which has even the kilometer distances along the roads indicated. Until some sort of a contour map can be secured, such maps as these will be found eminently serviceable.

Along the south coastal margin within the region of irrigation developments, there has been some special mapping with contours. In no case do they cover much ground beyond the outer lowland and terrace border, and because of this limitation they are not so generally useful for our purpose as the Interior Department maps. They are, however, very much more accurate and detailed and for the territory covered are eminently suitable as base maps.

GEOLOGIC MAP

A geologic map of the island should be one of the results of this series of studies, whether a relief map is secured or not. Such a map of the whole island is necessarily an ultimate rather than an immediate product, but district maps can be undertaken at once, with no difficulty whatever. These preliminary districts can be selected so as to include some of the most promising investigation problems in special lines, and both kinds of work can thus be carried on at the same time. This therefore leads directly to the next item, which is district studies.

The only geologic map thus far attempted is that by R. T. Hill.

DISTRICT STUDIES

It is possible now to select areas which are known to contain geologic features of special interest and significance, and it will generally be convenient, if not indeed necessary, for the investigator to make a detailed geologic map as a secure foundation for his special studies. One of these is the Coamo Springs District, which may be made large enough to extend from the Descalabrado river on the west, to Salinas on the east, and reach as far north as Aibonito. It will include as features of special importance for investigation, in addition to the mapping, the hot springs, the great conglomerate series, one of the later of the great volcanic vent complexes, the genetic history and horizon of the Coamo limestone which is a striking mixture of volcanic and organic matters, the high floodplain deposits of the stream valleys and their bearing on late geologic history, and certain physiographic studies connected with the coastal terraces. This district promises, as can be seen, an unusually large range of topics inviting special study, all of which will be illuminating to further development of the geologic survey of the island.

Another district of equal promise in a very different manner is on the north coast extending from the Quebradillas to the Arecibo river and

reaching from the sea to Lares so as to include a strip of the older complex rock series beyond the inner margin of the Tertiary series of reef limestones and shales which constitute the greater part of the bed rock of the area. Beside the mapping and detail of structural relations, this district presents the best opportunity to investigate the question of exact age of the basal beds of the Tertiary series, the transition from lignitic shales of perhaps fresh water alluvial origin to massive limestones of reef type, a subdivision of the Tertiary series, the meaning of the thinning out and disappearance of the Lares shales toward the east, and a paleontologic study of the beds, all of which are fundamental in any additional study of other districts containing the Tertiary rocks. There are besides good opportunities to study the meaning of the high terrace-like shelf coming abruptly to the sea at Quebradillas river and the meaning of the deep embayments now occupied by such playas as that at Arecibo. This is also one of the best localities for a detailed study of the structural and petrographic features of the San Juan formation as well as the behavior of modern dune sands along the present coast.

Another district of still different features, and giving foundation for special studies of quite a different bearing, is that lying between Caguas and the Caribbean sea and perhaps extending as far eastward as Naguabo. This will include the largest massive igneous unit in the whole island and promises information bearing upon magmatic differentiation, origin of the magnetic iron ores, relation of the great intrusive masses to the other igneous representatives, petrographic range of the igneous rocks, and marginal metamorphic or other effects,—studies fundamental in a final statement of the igneous history of the island.

There are other districts which have special problems associated with the regular areal geologic work, but these are sufficient to indicate the range of such district studies and their variety.

Certain special investigations are of a sort requiring comparison and summary of many different localities, and for these it will not be wise to handicap the investigator by limiting work to a single district. Some of these are suggested below.

REEF-BUILDING ORGANISMS

The limestones of Porto Rico are remarkable for the great prominence of algæ and corals and other closely associated organisms lending themselves to the construction of reefs and accompanying deposits. These forms belong to practically every limestone formation of both the older and the younger series except those most closely related to the shales. It is a study requiring the training of a specialist in such lines.

PALEONTOLOGY

The total organic content is much greater than is intended to be included under "Reef-building organisms." There are immense numbers of splendidly preserved fossil species of organisms belonging especially to the Tertiary series. Probably a great many are new to science. There are probably few places in America or within territory belonging to the United States where the marine Tertiary succession is of more promise than in Porto Rico. This problem or line of investigation is closely related to the next topic, that of Tertiary subdivision.

TERTIARY SUBDIVISION

A faunal and structural summary will naturally lead to the establishing of subdivisions and the determination of horizons in the younger series of rocks culminating in a statement of the complete Tertiary history of the island.

SAN JUAN FORMATION

A study of the characteristics and detail of origin and historical steps associated with the Pleistocene fossil dune sands, referred to as the San Juan formation, is another problem.

SUBDIVISION OF PRE-TERTIARY COMPLEX

A discussion of this kind is one that will properly follow upon the completion of areal work in several of the typical districts. It is, however, one that will necessitate investigations throughout the interior of the island, and will include a summary of the characteristics of all of the prominent local formations. A grouping and correlation can no doubt be made in due time.

MINERAL RESOURCES

On account of the interest taken by the people of Porto Rico in the question of possible mineral resources, it is desirable to undertake an investigation of the kinds of products, their origin, distribution and probable economic value. In connection with this, because of the small amount of exploratory work that has been done, it would be especially useful if suggestions were made at the same time about the methods of exploratory development and the people cautioned concerning wasteful methods. This work should be done so as to cover the whole range of mineral possibilities in the island regardless of location. There are known deposits of copper, iron, gold, lead, silver and zinc among the

metals as well as a number of non-metallic products. But in no case is the real value, or the probable extent or the geological relation, known sufficiently well at the present time to serve as a basis for a discussion. This should be one of the first undertakings of this survey, both because of the fact that its value is fully appreciated by the people of Porto Rico and because its conclusions do not materially depend upon the other investigations or mapping progress.

PETROGRAPHY

On account of the great number of igneous rock occurrences and the very great variety that is certain to be shown in quality and minor petrographic character, and because of the considerable range in composition already known to characterize the intrusives, there would seem to be an ample and promising field in this line for a special investigation. It is possible that some genetic relationship is exhibited in the distribution of these variations and that a thorough comprehensive study would throw some light on the more obscure problems connected with the genesis of igneous rocks. This is a problem that can be taken up at any time, and that need not be regarded as dependent upon special district studies, although it is evident that the finishing of work on certain districts would facilitate a study of this kind.

PHYSIOGRAPHY

Enough is known of the physiographic features and their meaning to appreciate that a great deal of the detail of the later geologic history of the island is more or less intimately bound up in the physiographic development. The broader or larger physiographic features have already been suggested, but there are certainly many details, some of which may well be of much significance in understanding the geologic history, which will require the special attention of a trained physiographer. Porto Rico is a unit of geologic history, of geologic structure and of physiographic form. Each is of sufficient complexity and unity to be made independent subjects of investigation.

THERMAL WATERS

The hot springs in the vicinity of Coamo Springs suggest from their situation and reported composition the possibility of being representatives of juvenile waters. It is believed that a study, planned especially to investigate the origin and character of these waters, together with such others as may exist, would be a very suitable special investigation. On

account of the fact that the principal occurrence of this type of water is very local, it would be possible to combine a study of this kind with a district study such as has been referred to in a preceding paragraph.

GEOLOGIC HISTORY

The complete geologic history of the Island of Porto Rico cannot be written until all of these and perhaps other more special investigations have been made. A complete historical statement must be regarded as an end product of the whole range of studies carried out for more special purposes. It is, therefore, the final topic and may well be deferred to a time when most of these already suggested have been carried far enough so that the data of special importance secured by them are available for this general summary.

It is evident from the appearance of this list that there is a very great amount of geological work awaiting the investigator in Porto Rico, and that it is varied and complicated enough to require several years of study in large part by experts or specialists in all branches of the subject. It can be seen also that the Island of Porto Rico is a geographic unit of more than usual complexity and scientific interest and gives promise of results for effort expended in researches along geologic lines.

COLLECTIONS

A beginning has been made toward securing a representative collection of typical rocks and fossils. Several hundred specimens were brought to New York for use in formulating the accompanying description, and as a possible basis for further more special investigations.

As a first step in this direction, about a hundred thin sections of the rocks have been made for microscopic study and detailed comparison. They will form a basis in planning the special petrographic investigations which may be undertaken.

In like manner a large number of fossils have been gathered and their general relations are being studied. Additional investigations along paleontologic lines will be in large part outlined or suggested by the trend of these studies, for although the collection is very fragmentary it is nevertheless characteristic and fairly representative of the principal formations.

More than a hundred photographs were taken of strictly geological subjects illustrating typical physiographic features, structural detail of rock formations, structural relations, etc. These are all suitably labeled and form the beginning of a collection of illustrations of Porto Rican

geology. In addition to the regular photographs, a number of photomicrographs have been made from the thin sections of typical rocks.

Some of this material will finally serve as a foundation for the geological section of what it is hoped may become a Natural History Museum of Porto Rico.

Illustrations

Cross-sections

The note books of the party and field maps carry a record of field determinations and detail of structural relations and comments greatly in excess of what can be published in such a report. They are the property of the organization and are of particular service as guides in planning further work and in giving each new investigator his bearings, together with some suggestions about the character of his own district or the distribution of data bearing upon his special investigation. The note books contain observations along some of the principal roads in sufficient detail to serve as a foundation for complete generalized geologic cross-sections of the island on two especially important lines.

Cross-sections, therefore, have been drawn to illustrate the kind of surface relief, the grade of the road, the kinds of rocks or rock formations and the geologic structural relations, and are reproduced to accompany this report. An immense amount of detail is necessarily omitted or combined into generalizations in order to bring the sections within the scope of a publication of this kind. It is judged that some of these details will be suitable illustrative matter for future reports based on studies of special districts. One of the sections is based on data gathered along the road from Ponce to Arecibo. The line is drawn from Arecibo to Ponce direct and the data are projected to this line. This method tends to obliterate the windings of the road and secure practically normal proportions and relative positions for the associated formational units. The other section line is drawn directly from San Juan Point to Santa Isabel. By projecting to this line all the data gathered on the Bayamon-Comerio-Barranquitas-Coamo road a great deal more elimination of road curves is accomplished than in the other section, and it makes the grades of the road look somewhat abnormal by reason of this shortening of road distance of certain large curves, but on the whole the relations are shown without special difficulty except that attendant upon the need of generalizing the minor structural detail.

MAPS

A hasty reconnoissance examination is seldom a satisfactory basis for an areal map. This is quite true of the present investigation. On this account, therefore, if it were not for other considerations, an areal map would not be attempted. But in this case, where a good many more or less independent special investigations are to be carried on in which a reasonably accurate geological map will prove decidedly helpful, there is sufficient excuse for presenting a reconnoissance map. An earlier map of this kind prepared by R. T. Hill was made under conditions so much less favorable for travel, and seems to have been constructed in some particulars with so much less opportunity for observing the actual conditions in certain areas, that an entirely new map is believed to be the better solution of the present need. The accompanying reconnoissance map is intended, therefore, as a convenient guide or location map for subsequent more special investigations, and it is expected to be wholly replaced by one of much more detail and greater accuracy as a final product of this survey.

Acknowledgments

The members of this expedition have appreciated the very material help, the sound advice and useful suggestions given by the officials of the government of Porto Rico, and are indebted to Governor Yeager for his very practical aid in making arrangements for the field work and for his live interest in these investigations; to Colonel Shanton, chief of the Insular Police, for his willingness to give introductions to men acquainted with special mineral localities and for his precautions to insure protection against unnecessary delays; to Mr. Wheeler, of the Interior Department, for assistance in securing suitable maps as a basis for travel and notes; to Mr. Bonner, the Auditor, for facilitating the settlement of accounts; to Dr. Lippitt, of the Bureau of Sanitation, for information regarding sanitary precautions and hotel accommodations; and to Mr. Campbell, of the Bureau of Transportation, for the excellent equipment for travel which contributed largely to the success of the expedition.

Many others have been of assistance in pointing out localities of special interest, in giving names of reliable informants and in acquainting us with the usages and customs of the country.

Bibliography

The following papers contain descriptions of physical conditions and features and of some geologic observations in Porto Rico. A suggestion as to the range or character of the article in most cases follows the title.

Cleve, P. T.: "Geology of the Northern West Indies," with maps. Kongl. Svenska. Vetenskaps. Akad. Handlingar, vol. 9, No. 12. 1871.

———: "Outline of the Geology of the Northeastern West India Islands." Ann. N. Y. Acad. Sci., vol. 2, pp. 185-192. 1883.

Davis, Brig. Gen. George W.: Porto Rico—embracing reports of Brig. Gen. George W. Davis, arranged by topics. Government Printing Office, Washington, 94 pp. 1900.

Dinwiddie, W.: "Physical features of the Island" (Puerto Rico). Harper's Weekly, vol. 43, p. 248. Mar. 11, 1899.

———: "The great caves of Puerto Rico." Harper's Weekly, vol. 43, p. 293. Mar. 25, 1899.

Domenech, M. K.: "Mineral resources of Porto Rico." Mines and Minerals, vol. 19, pp. 529-532. 1899.

Falconer, J. D.: "Evolution of the Antilles." Scot. Geog. Mag., vol. 18, pp. 369-376, 1 pl. 1902. Discusses general geologic history of America, and especially that of Central America and West Indies.

Guppy, R. J. L.: "Geological Connections of the Caribbean Region." Trans. Canadian Institute, pp. 373-391. January, 1900. Discusses general regional relations and the probability of an Antillean continent.

Fiske, Amos K.: "The West Indies." G. P. Putnam's Son, New York. 1899. Folded maps, plates. Physical characteristics of Porto Rican history etc., social and economic conditions.

Hamilton, S. Harbert: "Notes on Some of the Ore Deposits of Porto Rico." Eng. and Min. Journal, vol. 88, p. 518. September, 1909.

Hill, Robert T.: "Cuba and Porto Rico with the Other Islands of the West Indies." New York. 1898. A book of over 400 pages containing a very large amount of information covering many matters in addition to the physical features and the geology.

———: "The Value of Porto Rico." Forum, vol. 27, pp. 414-419. June, 1899.

———: "Porto Rico." National Geographic Magazine, vol. 10, pp. 93-112. 1899. One of the best articles on the physical features of Porto Rico.

———: "The Geology and Physical Geography of Jamaica." Bull. Museum Comp. Zool., vol. 34. 1899. A study of a type of Antillean development.

———: "The Forest Conditions of Porto Rico." Bulletin 25, U. S. Department of Agriculture. 1899. Quoted in part in Public Opinion. Contains very brief description of physical features and has a good relief map.

Newberry, J. S.: "Geology of the West Indies." Trans. N. Y. Acad. Sci., vol. 1, pp. 23-24. 1882.

Nitze, H. C. B.: "Investigations of Some of the Mineral Resources of Porto Rico." Twentieth Ann. Rept., U. S. Geological Survey, Part 6, pp. 779-878. Gives a tabulation of the mineral occurrences, and a very brief note on the principal ones.

SPENCER, J. W.: "On the geological relationship of the volcanics of the West Indies." Victoria Inst. Jour. Trans., vol. 35, pp. 189-207, 1 fig. 1903. Discusses physiographic features and changes of the West Indies and the submerged platform upon which they rest, place of their igneous formations in geological history, etc.

VAUGHAN, T. W.: "Earliest Tertiary Coral Reefs in Antilles and United States." (Abstract.) Read before Geol. Soc. Wash. Feb. 26, 1902. Touches on coral reefs of Porto Rico being in part of Oligocene age. No Miocene reefs, because in Miocene Antilles stood at higher level than now. Pliocene reefs in Florida and Antilles.

WHARTON, W. J. L.: "Depth of the Ocean near Porto Rico." Geog. Jour., vol. 4, p. 255. Sept., 1894. The physical condition of the ocean.

WILSON, HERBERT M.: "Water resources in Porto Rico." Water supply paper No. 32, U. S. Geol. Surv. 1899. An excellent discussion of the physical features. Contains many good illustrations and two maps with reconnoissance contours.

———: "The Engineering Development of Porto Rico." Eng. Mag., vol. 17, pp. 602-621. July, 1899.

———: "Porto Rico, its Topography and Aspects." (With map.) Bull. No. 32, Amer. Geog. Soc., pp. 220-238. 1900. A good description of the physical features, climate and productive industries.

Author unknown: "Porto Rico, its Natural History and Products." Scien. Am. Suppl., vol. 46. July 30, 1898. No author mentioned—good general account, including report on geology and mines.

Author unknown: "Zur Kenntniss der Insel Puerto Rico." Geographische Gesells. Ham. Mett. 1899-2, pp. 217-236.

Author unknown: "North American and West India Gazetteer." London, printed for G. Robinson, 1778 (6) xxiv, 216 pp. Situation, climate, soil, produce trade—bays, rivers, lakes, mountains, number of inhabitants, etc. Maps. 2d edition.

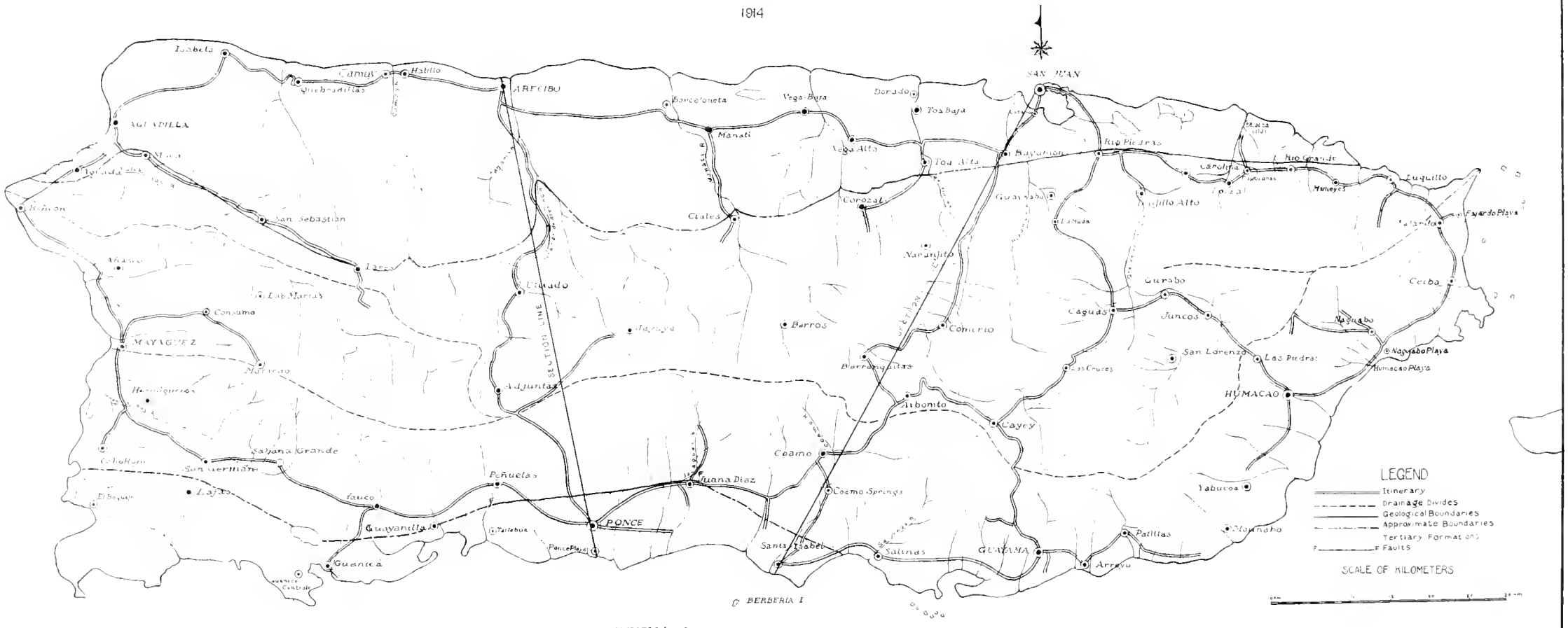
GEOLOGICAL RECONNAISSANCE MAP

OF

PORTO RICO

NEW YORK ACADEMY OF SCIENCES EXPEDITION

1914



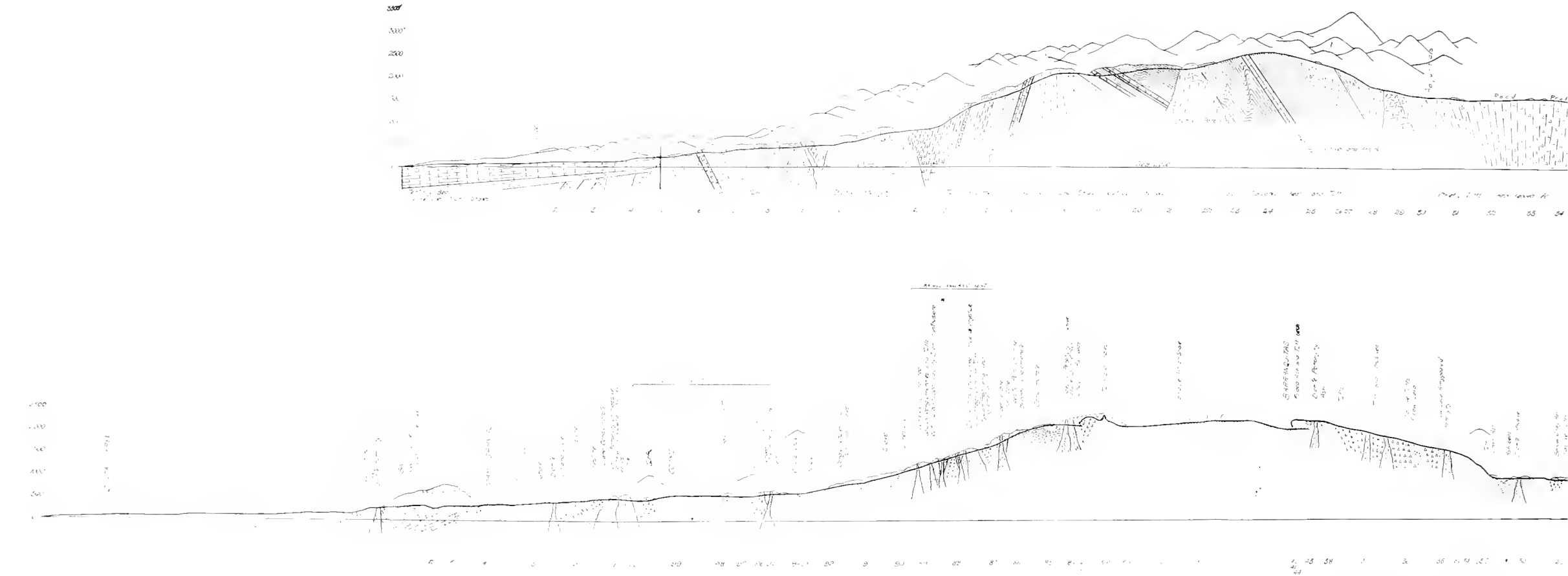


FIG. 1.—*Generalized geological cross-section of the Island of*

FIG. 2.—*Generalized geological cross-section of the Island of*

These sections are intended to show the road profile, some of the side relief and the geologic structure. They are based on observations made along the r

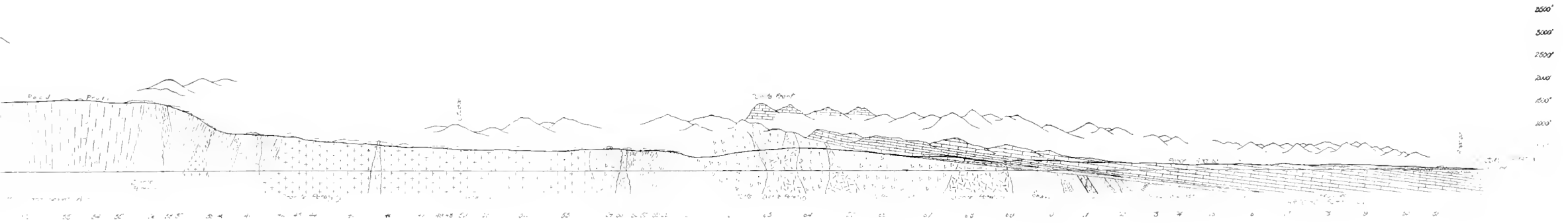


FIGURE 1

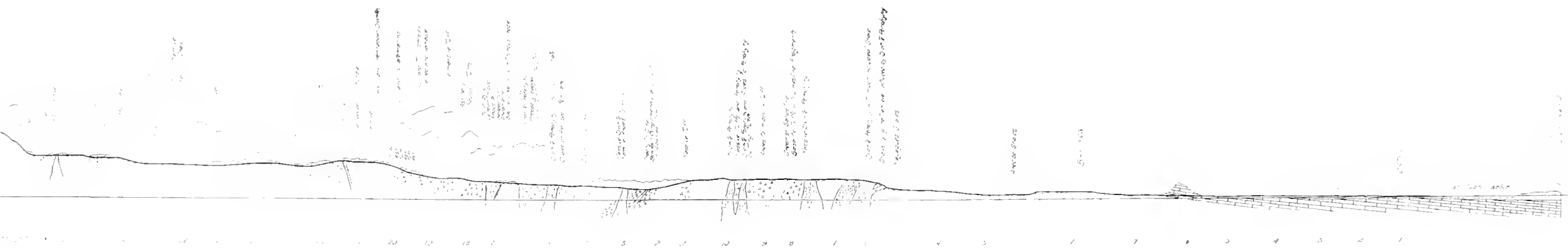


FIGURE 2

section of the Island of Porto Rico from Ponce to Arecibo
section of the Island of Porto Rico from Santa Isabel to San Juan

ations made along the roads and projected to a direct line. The numbers placed at the base of the sections correspond to the kilometer stations on the roads.

PUBLICATIONS

OF THE

NEW YORK ACADEMY OF SCIENCES

(Lyceum of Natural History, 1817; 1876)

The publications of the Academy consist of two series, viz.:

(1) The **Annals** (octavo series), established in 1823, contain the scientific contributions and reports of researches, together with the records of meetings and similar matter.

A volume of the Annals coincides in general with the calendar-year and is sold at the uniform price of three dollars per volume. The articles composing the volume are printed separately, each in its own cover, and are distributed in bundles on an average of three per year. The price of the separate articles depends upon their length and the number of illustrations, and may be learned upon application to the Librarian of the Academy. The author receives his separates as soon as his paper has been printed, the date of issue appearing above the title of each paper.

(2) The **Memoirs** (quarto series), established in 1895, are issued at irregular intervals. It is intended that each volume shall be devoted to monographs relating to some particular department of Science. Volume I is devoted to Astronomical Memoirs, Volume II to Zoölogical Memoirs, etc. The price is one dollar per part as issued.

All publications are sent free to Fellows and Active Members. The Annals are sent to Honorary and Corresponding Members desiring them.

Subscriptions and inquiries concerning current and back numbers of any of the publications of the Academy should be addressed to

The Librarian,
New York Academy of Sciences,
care of
American Museum of Natural History,
New York, N. Y.

PRESS OF JUDD & DETWEILER, INC., WASHINGTON, D. C.