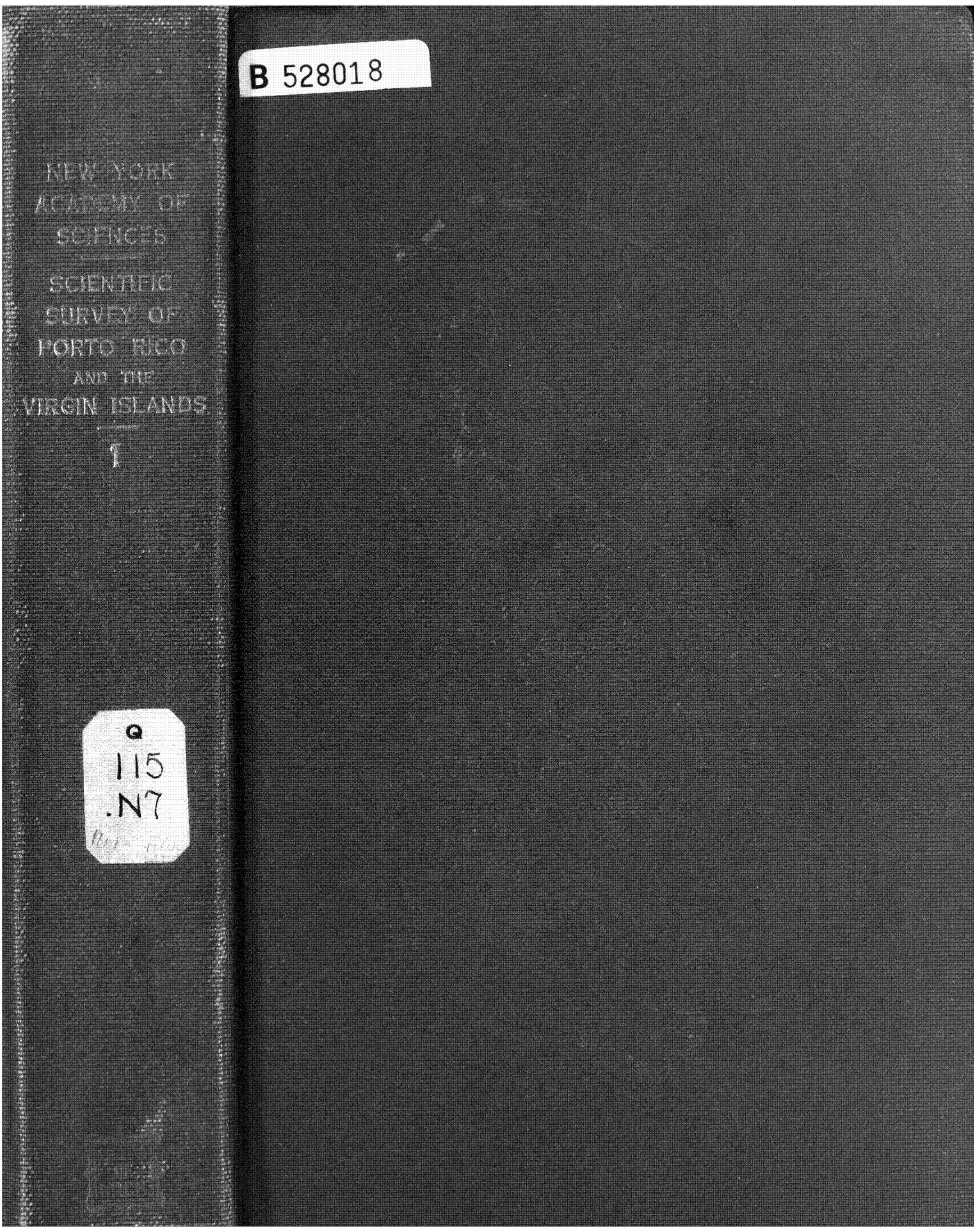
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NEW YORK ACADEMY OF SCIENCES

SCIENTIFIC SURVEY

OF

Porto Rico and the Virgin Islands

VOLUME I

NEW YORK:
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1919-1922

CONTENTS OF VOLUME I

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Part 1, September 26, 1919.

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ERRATA

Page 58, line 33, and page 59, line 8, read *Metis* for *Mctris*

NEW YORK ACADEMY OF SCIENCES

SCIENTIFIC SURVEY

OF

Porto Rico and the Virgin Islands

VOLUME I—Part 1

History of the Survey—*N. L. Britton*
Geological Introduction—*C P. Berkey*
Geology of the San Juan District—*D. R. Semmes*

NEW YORK:
PUBLISHED BY THE ACADEMY
1919

HISTORY OF THE SURVEY

By N. L. Britton

Chairman of the Committee

In the latter part of the year 1913, subsequent to a discussion in the Council of the Academy relative to proposed extensions of the Academy's ordinary activities, a proposition for a scientific survey of Porto Rico was approved and referred to a committee consisting of Professors Boas, Britton, Crampton, Kemp and Poor, at the meeting of the Council in November of that year, at which meeting the Council appropriated $500 annually for five years for the purposes of this investigation. Dr. E. O. Hovey and Dr. R. W. Tower, Recording Secretaries of the Academy, have acted with the Committee. Professor Charles P. Berkey succeeded Professor Kemp as a member of the Committee in 1917. Mr. Emerson McMillin, at that time President of the Academy, kindly offered to assist the work, and has contributed $3,000. The Porto Rico Government was also interested in the investigation, and has since made two appropriations of $5,000 for prosecuting the work. The coöperation of The American Museum of Natural History, The New York Botanical Garden, scientific departments of Columbia University and other institutions was secured, and both field-work and the study of the collections made has progressed almost continuously. The cooperating institutions already had some collections from Porto Rico. The two agricultural experiment stations of Porto Rico, one at Mayaguez and one at Rio Piedras, have also aided the investigation. A number of preliminary papers dealing with special phases of the work have been published. The publication of the final reports of the survey is herewith commenced and will be continued in the following sequence: geology, paleontology, botany, zoölogy and anthropology.

Professor Crampton proceeded to Porto Rico at the end of 1913 and carried out a zoölogical reconnaissance, traveling over a large part of the island, and discussed the plan with officials of the Insular Government. He subsequently published an account of Porto Rico.[1]

In January, February and March, 1914, Dr. J. A. Shafer prosecuted botanical exploration on the island Vieques, one of the small islands

[1] Am. Mus. Jour., XVI, pp. 59-70.

politically a part of Porto Rico, and made the first representative collection of plants obtained on that island.[2]

During February and part of March, 1914, Dr. Britton, accompanied by Mrs. Britton, Mr. John F. Cowell and Dr. Frank E. Lutz, made botanical and entomological collections in the northern and western parts of Porto Rico and in the small islands Desecheo and Mona, which yielded several thousand specimens and much information. Dr. Britton contributed to the twenty-fifth anniversary celebration of the Missouri Botanical Garden a paper on The Vegetation of Mona Island.[3]

In the summer and autumn of 1914, zoölogical collections were made over considerable portions of the island by Messrs. Roy W. Miner in marine invertebrates and myriopods, John T. Nichols in fishes, and Frank E. Watson and H. G. Barber in insects and arachnoids. Many thousand specimens were obtained and important additions were made to the knowledge of these groups of animals. The spiders of this collection, taken with those previously obtained by Professor Crampton and Dr. Lutz, yielded important information, which was utilized by Dr. Lutz in his List of Greater Antillean Spiders, with Notes on Their Distribution.[4] Nichols has published some of the results of his work under the title Fishes New to Porto Rico.[5]

The geological investigation was commenced by Dr. Charles P. Berkey and Dr. Clarence N. Fenner, who spent parts of August and September, 1914, in a reconnaissance and laid a substantial foundation for subsequent studies. Professor Berkey has published an illustrated account of this reconnaissance under the title Geological Reconnaissance of Porto Rico.[6]

In July and August, 1914, Dr. J. A. Shafer devoted about six weeks to the study of the forests of the Sierra de Naguabo, and added a number of species of plants to the known flora of Porto Rico.[7]

Under the auspices of the New York Botanical Garden, Professor N. Wille, Director of the Botanical Garden at Christiania, Norway, spent the period from the latter part of December, 1914, until the end of March, 1915, in collecting and studying the fresh-water and aerial algæ over considerable areas of the island. He obtained many thousand specimens of these organisms, which proved to be more abundant there than

[2] Jour. N. Y. Bot. Gard., XIV, pp. 103-105.

[3] Ann. Mo. Bot. Gard., II, pp. 33-58, Pls. I, II. (Contributions from N. Y. Bot. Gard., No. 175.)

[4] Ann. N. Y. Acad. Sci., XXVI, pp. 71-148.

[5] Bull. Am. Mus. Nat. Hist., XXXIV, pp. 141-146.

[6] Ann. N. Y. Acad. Sci., XXVI, pp. 1-70. (Contributions from Dept. of Geology, Columbia Univ., Vol. XXV, No. 20.)

[7] Jour. N. Y. Bot. Gard., XVI, pp. 33-35.

had hitherto been supposed. This collection has not yet been critically studied, but Professor Wille is confident that it contains some undescribed genera and numerous undescribed species. Since his return to Norway, subsequent to the expedition, Professor Wille has been much occupied with administrative duties, but it is hoped that he will yet find time to enumerate and describe the elements of this rich collection, the first comprehensive one that has been made of these minute algæ within the American tropics. He has published a narrative report of his field-work.[8]

The greater portions of the months of February and March, 1915, were spent by Dr. Britton, Mrs. Britton, Mr. John F. Cowell and Mr. Stewardson Brown in continuing botanical exploration, especially in western and southwestern portions of Porto Rico, including a study of the coasts from Mayaguez south to Morrillos de Cabo Rojo and westward to Ponce and Cayo Muertos. Large collections were obtained, which added much to the knowledge of the geographical distribution of the flora, and a series of rock specimens were collected and turned over to the geologists of the survey for examination.[9]

Based on the observations made on this and preceding trips, Dr. Britton outlined a plan of forest policy for the Porto Rican Government, which he presented at the spring meeting of the National Academy of Sciences, held at Washington in April, 1915, and it was transmitted to the Governor of Porto Rico. The reforestation of Porto Rico is acutely necessary. A recent report on the forests of Porto Rico by Mr. Louis S. Murphy, Forest Examiner of the United States Forest Service, is of great value in this connection.[10]

Dr. Chester A. Reeds and Mr. Prentice B. Hill devoted the months of June and July, 1915, to paleontological studies and collections in the western part of the island, obtaining over 10,000 specimens rich in fossil corals and fossil mollusks. They detected a stratum containing large quantities of fossil leaves; this noteworthy discovery, supplemented by further collections subsequently made by Mr. Bela Hubbard, gives us the first knowledge of the Tertiary flora of the West Indies. The collections of fossil plants made by Messrs. Reeds and Hubbard are being studied by Dr. Arthur Hollick. Dr. Reeds has published three maps. He discovered remains of a new fossil Sirenian, which has been described by Dr. W. D. Matthew.[11]

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[8] Jour. N. Y. Bot. Gard., XVI, pp. 132-146.
[9] Jour. N. Y. Bot. Gard., XVI, pp. 103-112.
[10] Bull. U. S. Dept. Agric., 1916, No. 354, p. 99.
[11] Ann. N. Y. Acad. Sci., XXVII, pp. 23-29.

Mr. Edwin T. Hodge spent the summer and early autumn of 1915, first, in an investigation of the supposed petroleum oil shales in the western part of the island, obtaining samples from 26 different localities, and later in the year submitted a report upon them, which gave negative results, Mr. Hodge concluding that oil-carrying shales do not exist in Porto Rico. Mr. Hodge subsequently made a detailed geological study of the Coamo region, and his results have been made ready for publication. He also made a study of the thermal springs of the island, especially those of Baños de Coamo.

Mr. D. R. Semmes prosecuted geological investigations of the section of the north central portion of the island, which, taken with the work of Mr. Hodge to the south, furnishes data for a complete geological cross-section from coast to coast. The studies of Mr. Semmes are published herewith.

Mycological studies and collections were made from June to August, 1915, by Professor F. L. Stevens, in continuation of similar investigations prosecuted by him while Dean of the College of Agriculture at Mayaguez. He visited nearly all parts of the island and collected many thousand specimens; his trip was under the auspices of the University of Illinois and of the New York Botanical Garden.[12] Professor Stevens described and illustrated the species of the large genus *Meliola* as represented in Porto Rico, under the title The Genus *Meliola* in Porto Rico, which includes descriptions of sixty-two new species and varieties.[13]

Professor Crampton continued zoölogical field-work during January, 1915, especially in the northwestern portion of the island, at which time he supplemented previous collections by obtaining large numbers of specimens in the various groups of invertebrates.

In the spring and early summer of 1915, Dr. Frank E. Lutz and Mr. A. J. Mutchler made extensive entomological collections in various parts of the island, adding some 15,000 specimens of insects and large numbers of spiders to collections previously made. Mr. Roy W. Miner and Mr. H. Mueller spent several weeks in the summer in the study and collection of marine invertebrates, especially in the vicinity of Guanica, some 8,000 specimens being obtained at that time from this region. Professor Raymond C. Osburn carried on studies of the organisms of the deeper waters in the vicinity of Guanica during the summer, obtaining over 2,000 specimens, principally by dredging.

Professor Franz Boas prosecuted anthropological and archæological investigations at several points during May and June, 1915, aided by Dr.

[12] Jour. N. Y. Bot. Gard., XVII, pp. 82-85.

[13] Illinois Biological Monographs II, No. 4, pp. 1-86, Pls. I-V.

H. K. Haeberlin, Dr. J. Alden Mason and Mr. Robert T. Aitken. Professor Boas obtained data which caused him to doubt the general assumption that children reach maturity earlier in tropical regions than in the temperate zone, and other data which are important as regards the hygiene of childhood in the tropics. His observations on the teeth of Porto Rican children have been published by Mr. Leslie Spier.[14] He obtained cordial coöperation in this investigation from the Department of Public Education of the island. He also concluded from his observations at this time that the Porto Rican race has been influenced in its development by environment.

Professor Boas referred the collection of folk-lore data to Dr. J. Alden Mason, who prosecuted this study from June, 1915, until 1916, and accumulated an immense collection of folk tales, riddles, ballads and songs, which was subsequently referred for editing to Professor Aurelio M. Espinosa, of Leland Stanford University, whose work on this important contribution is now approaching completion, and who has reported to the Committee that the documents are the most important contribution of its kind made to literature. Professor Espinosa and Dr. Mason have published Porto Rico Folk Lore—1. Riddles.[15]

Dr. Haeberlin made excavations in the Jobo district, including that of one stone enclosure and a cave, which contained ceremonial objects and large numbers of bones of an extinct mammal. A large cave in the vicinity of Utuado, excavated by Messrs. Mason and Aitken, proved to be the burial ground of an ancient community, and here also large numbers of bones of an extinct mammal were found.[16] One of these mammals proved to be new to science, and has been described by Dr. J. A. Allen under the title An Extinct Octodont from the Island of Porto Rico, West Indies.[17] Dr. Haeberlin has published a paper entitled Some Archæological Work in Porto Rico.[18]

An ancient village site at Capá, located by Professor Boas and subsequently investigated by Messrs. Mason and Aitken, proved to be the most important of all archæological localities thus far discovered in Porto Rico. Efforts were made by the Committee to induce the Porto Rico Government to purchase and preserve this site as a national monument, but hitherto without success. A preliminary description of the site has been given by Dr. Mason.[19]

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14 Am. Anthropologist, XX, pp. 37-48.
15 Jour. Am. Folk-Lore, XXIX, pp. 423-504.
16 XIX Congress of Americanists, pp. 224-228.
17 Ann. N. Y. Acad. Sci., XXVII, pp. 17-22, Pls. I-V.
18 Am. Anthropologist, XIX, pp. 214-238.
19 XIX Congress of Americanists, pp. 220-223.

Dr. Marshall A. Howe spent parts of June and July, 1915, in continuation of his previous studies of marine algæ, principally along the southwestern coast from Ponce and Cayo Muertos to Cabo Rojo. During this trip he obtained about 3,000 specimens, including some species additional to the known flora of the island.[20]

Professor Bruce Fink, of Miami University, proceeded to Porto Rico in November, 1915, and spent part of the winter there in making extensive collections of fungi and lichens. He has generously contributed information obtained by him to the Committee.

Dr. Herbert J. Spinden prosecuted archæological work at several points during the spring and summer of 1916 and made extensive collections, the study of which yielded interesting and valuable information. He excavated certain shell heaps and obtained specimens and information therefrom, which he regarded as throwing light upon the origin of Porto Rican aborigines. He also studied the aboriginal petroglyphs or rock-carvings.

Mr. Bela Hubbard carried out a geological survey of the northwestern section of the island in the summer of 1916, and his description of this work is in process of completion for publication. Dr. Charles R. Fettke studied the southwestern districts of the island in an areal geological survey, which included a detailed study of the extensive areas of eruptive rocks. The study of the large collections made by him is progressing.

Mr. A. K. Lobeck studied, during the latter part of 1916 and January, 1917, the physiography of the entire island, and the results of this investigation are prepared for publication.

During the summer of 1916, a very important study of the parasitic fungi of Porto Rico was made by Professor H. H. Whetzel, of Cornell University, and Dr. E. W. Olive, of the Brooklyn Botanic Garden, aided by a grant from the New York Botanical Garden, and several thousand specimens of these plants were obtained, which are under investigation by a number of different experts.

Mr. H. E. Anthony prosecuted studies of recent and fossil mammals in Porto Rico during the summer of 1916, and made some highly interesting and important discoveries, which have been described by him in three illustrated papers:

Preliminary Report of Fossil Mammals from Porto Rico.[21]
Preliminary Diagnosis of an Apparently New Family of Insectivores.[22]

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[20] Jour. N. Y. Bot. Gard., XVI, pp. 219-225.
[21] Ann. N. Y. Acad. Sci., XXVII, pp. 193-203.
[22] Bull. Am. Mus. Nat. Hist., XXXV, pp. 725-728.

New Fossil Rodents from Porto Rico, with Additional Notes on *Elasmodontomys obliquus* Anthony and *Heteropsomys insulans* Anthony.[23]

During the progress of the survey, Dr. John A. Stevenson, of the Insular Experiment Station at Rio Piedras, has made botanical collections in various parts of the island, which have contributed much to our knowledge of the flora; he is now preparing a list of the fungi of Porto Rico. Dr. Basil Hicks Dutcher, U. S. A., stationed at San Juan, has given valuable aid to nearly all our field parties by advice, information and personal assistance.

A number of reports of progress and other presentations of parts of the work have been made at meetings of the Academy from time to time. An outline of the proposed survey was presented by members of the Committee in the form of a symposium at the meeting of April 13, 1914.[24] Another symposium was given at the meeting of December 14, 1914.[25] At the meeting of the Section of Geology and Mineralogy on November 1, 1915, preliminary reports on field-work were given by Messrs. Semmes, Hodge and Reeds.[26] At the meeting of the Section of Biology November 8, 1915, communications were presented by Messrs. Reeds, J. A. Allen and Matthew.[27] The Committee submitted a report of progress at the annual meeting of December 20, 1915.[28]

At the meeting of the Academy held January 24, 1916, Dr. Boas, Mr. Aitken and Dr. Haeberlin[29] presented communications on ethnology and archæology, and at the meeting of May 15, 1916, geological communications were presented by Messrs. Hodge, Semmes, Reeds, Fettke, Hubbard,[30] Lobeck and Professor Berkey.[31]

During several months of 1917, Mr. Graham J. Mitchell prosecuted an areal geological survey of the southwestern portion of Porto Rico, and his report of this work is in progress of preparation for publication. Dr. Charles R. Fettke has recently published, with the approval of the Committee, a paper entitled The Limonite Deposits of Mayaguez Mesa, Porto Rico.[32]

The final geological reports are being written, for the most part, by the

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[23] Bull. Am. Mus. Nat. Hist., XXXVII, pp. 183-189.
[24] Ann. N. Y. Acad. Sci., XXIV, pp. 369.
[25] Ann. N. Y. Acad. Sci., XXIV, pp. 398, 399.
[26] Ann. N. Y. Acad. Sci., XXVI, pp. 433-436.
[27] Ann. N. Y. Acad. Sci., XXVI, pp. 436-439.
[28] Ann. N. Y. Acad. Sci., XXVI, pp. 456-462.
[29] Ann. N. Y. Acad. Sci., XXVII, pp. 250, 251.
[30] Bull. Am. Inst. Mining Engineers, No. 135.
[31] Ann. N. Y. Acad. Sci., XXVII, pp. 277-282.
[32] Bull. Am. Inst. Mining Engineers, No. 135, pp. 661-676.

several geologists who have participated in the field-work, and, as already stated, considerable portions of them are ready for publication. Dr. T. W. Vaughan, of the United States Geological Survey, has kindly consented to study the collections and prepare the descriptions of the fossil corals, and those obtained up to the present time have already been sent to him.

The final botanical reports are being prepared by the following investigators:

Flowering Plants.—Dr. N. L. Britton and Mr. Percy Wilson, the grasses by Professor A. S. Hitchcock.

Ferns and Fern Allies.—Preliminary work by Miss Margaret Slosson.

Mosses.—Mrs. N. L. Britton and Mr. R. S. Williams.

Hepatics.—Professor A. W. Evans.

Lichens.—Professor Lincoln W. Riddle.

Fungi.—Dr. W. A. Murrill, Dr. F. J. Seaver, Professor J. C. Arthur, Professor F. L. Stevens, Professor H. H. Whetzel, Dr. E. W. Olive, Dr. John A. Stevenson.

Algæ (marine).—Dr. Marshall A. Howe.

Algæ (fresh-water and aerial).—Professor N. Wille.

No arrangement has yet been made for the study of Porto Rican diatoms.

The zoölogical collections are being studied and final reports prepared as follows:

Mammals.—Mr. H. E. Anthony.[33]

Birds.—Mr. Alex. Wetmore has published an exhaustive report on the birds which may be taken as a basis for our document.[34]

Reptiles.—Preliminary work by Miss M. C. Dickerson.

Amphibians.—Preliminary work by Miss M. C. Dickerson.

Fishes.—Mr. J. T. Nichols and Professor C. F. Silvester.

Insects:

Orthoptera.—Mr. J. A. G. Rehn and Mr. Morgan Hebbard.

Coleoptera.—Mr. C. W. Leng and Mr. A. J. Mutchler.

Hemiptera.—Mr. H. G. Barber.

Lepidoptera.—Mr. F. E. Watson.

Hymenoptera.—Mr. J. Bequaert and Dr. F. E. Lutz.

Myriopods.—Mr. Roy W. Miner.

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[33] Mem. Am. Mus. Nat. Hist., N. S., II, Part 2.

[34] Bull. U. S. Dept. Agric., 1916, No. 326, p. 140.

Mollusks.—Preliminary work by Dr. L. P. Gratacap.
Ascidians.—Dr. Willard Van Name.
Crustaceans.—Mr. Roy W. Miner and Dr. Willard Van Name.
Annelides.—Professor A. E. Treadwell.
Echinoderms.—Preliminary work by Mr. D. M. Fisk.
Bryozoans.—Dr. R. C. Osburn.
Coelenterates.—Mr. Roy W. Miner.

Representative collections of Porto Rican protozoans have not yet been made.

The anthropological and archæological documents are being written by the several investigators who have conducted the field-work. Preliminary papers, in addition to those already noted in this report, are being prepared by Professor Boas on anthropometrical observations in Porto Rico, by Dr. Mason on the archæological investigation of the very important site at Capá, by Dr. Aitken on the cave sites near Utuado, and by Dr. Mason and Professor Espinosa on Porto Rican folk tales.

As to the general progress of the survey, it may be stated that over two-thirds of the necessary geological field-work has been completed. Except for an investigation of the diatoms, which has not yet been arranged for, no additional botanical field-work is really essential, although the final reports would be more complete if additional collections were made, but this is of course true all over the world. Considerable additional zoölogical field-work and additional collections in several of the groups of animals are highly desirable, and, as before remarked, the protozoa have not been collected. Anthropology and archæology still offer widely attractive fields for further examination. No oceanographic work has as yet been possible.

In cooperation with the Insular Government, portions of the collections made have been returned to Porto Rico to form the basis of a Natural History Museum, and other portions will be forwarded to Porto Rico as the study proceeds. The remainder is to be divided among the coöperating institutions and investigators.

The islands St. Thomas, St. Jan and St. Croix, recently purchased by the United States from Denmark, lie close to Porto Rico, to the east and southeast. It is highly desirable, before our survey is brought to a close, that these should be studied geologically, zoölogically and archæologically. Their botany is fairly well known. I have recently contributed a catalogue of their known flora to the Brooklyn Botanic Garden, and this has been published in the volume of papers presented on the occasion of the opening of the new laboratories of that institution.[35] The survey will thus be made to include all the Caribbean insular possessions of the United States as they stand at present, and be entitled A Scientific Survey of Porto Rico and the Virgin Islands.

The Chairman of the Committee gratefully acknowledges aid from the other members in the preparation of this historical sketch of the survey.

[35] Mem. Brooklyn Bot. Gard., I, pp. 19-118. (Contributions from N. Y. Bot. Gard., No. 203.)

INTRODUCTION TO THE GEOLOGY OF PORTO RICO

By Charles P. Berkey

CONTENTS

INTRODUCTORY STATEMENT

The Island of Porto Rico lies between latitude 170° 54′ and 18° 30′ north and longitude 65° 13′ and 67° 15′ west. It is the most eastern and southern of the Greater Antilles. Thus it lies within the trade-wind belt, which is an important factor in the local variations of its tropical climate.

In the Atlantic immediately north of Porto Rico lies Brownson Deep, which reaches the profound depth of 24,000 feet, and in the Caribbean farther to the south lies Tanner Deep, reaching 15,000 feet. Although its loftiest mountains do not exceed 4000 feet elevation above the sea level, the whole island appears to be just a portion or segment of a great mountainous mass or chain that rises from a submerged platform above which its true relief might well be measured. A relief difference of 28,000 feet such as is given from the bottom of Brownson Deep to the top of El Yunque is not exceeded in many places the world over within such moderate distances, but it must not be assumed that this is the elevation above the submarine platform.

Porto Rico may thus be regarded to some advantage in the present consideration as a badly eroded uppermost portion of a great mountain mass which probably at one time formed a part of a chain with general east-west trend, most of which is now submerged. Certain very elevated segments of this chain still stand above sea level and form the islands of the Greater Antilles. Whether or not the structural relations of these exposed segments are of fault-block type and what relation such an island as Porto Rico may have to a former continental mass extending toward and possibly connecting North and South America, however interesting or suggestive they may be, are questions that might be better discussed in the summary at the conclusion of this survey rather than in this preliminary statement. Such questions are involved in the final solution of the geologic history of the island, on which a whole projected series of district and special studies have a bearing.

Porto Rico is very mountainous. A central cordillera extends nearly east and west, starting abruptly at the sea near Rincon on the west coast and continuing to El Yunque, the great mountain summit which forms the central feature of the eastern end of the island. It is not by any means as simple, however, as this statement would suggest, for there are branches of the main range both east and west, but especially to the east, where the Sierra de Luquillo, culminating in El Yunque, and the Sierra de Cayay, 10 miles farther south, form very distinct features. At either end of the island the chief mountain relief is centrally located, but throughout the whole of the middle portion and for two-thirds of the total length of the island, including the Sierra de Cayay, and thence westward for 60 miles, the chief mountain range lies only about 10 miles from the south coast. Almost two-thirds of the total area, therefore, belongs to the northerly slopes of the chief mountain range.

Although the topography on the whole is very rugged and the island has a decidedly mountainous aspect, there is almost everywhere a very moderate relief along the coast and at many places the coastal lands are almost flat. These very flat areas lie always at the mouths of rivers and undoubtedly have been made in large part by deposition of the silts of the streams. Such alluvial tracts are called playas in Porto Rico.

All relief forms except these playas are of erosional origin. Exceedingly steep slopes are the rule, suggesting early maturity in physiographic history. This phase of the geologic history of Porto Rico has been made the subject of a special study by Mr. Armin K. Lobeck and will soon be published in this series. One of the most surprising things is the way the soils cling to these steep hillsides, and it is possible to repeatedly see slopes under cultivation that measure from 30 to 40 degrees.

Numerous small islands lie along the coast. Two of comparatively large size, Vieques and Culebra, which are respectively 20 and 7 miles in length, mark the continuation of the Porto Rican land mass toward the east. All are included as a part of the studies of Porto Rico.

Streams are numerous and surprisingly large. Mr. H. M. Wilson (1899, 1900) has published an excellent account of the hydrology of the island, and to this reference should be made for details of this nature. He credits this small island with 39 large and 1300 small streams.

Rainfall is very unevenly distributed. At the east end, near El Yunque, there is an annual rainfall of 123 inches. On the other hand, at Cabo Rojo, at the extreme southwest corner, there is seldom any rain at all. Because of the high mountain ranges, there is an abundance of rain on the windward side, which includes the east end and most of the north side of the island, and since the principal range stands far south of the middle, the larger portion of the island is fairly well watered. A comparatively narrow strip along the south side, especially to the west from Guayama, and again a strip at the northwest corner, are comparatively arid. Extensive irrigation works have been constructed along the south side.

In most districts the bed rock is compact enough to discourage underground circulation and the run-off is correspondingly responsive to rainfall. But in the northwest corner of the island, on a broad limestone belt reaching from Aguadilla to Camuy, and less prominently even farther eastward, there are many caves and sinks, and a most remarkable minor topography,[1] where underground water circulation is locally of much importance. In some cases large streams rising on other ground farther inland are completely lost here for long distances, following subterranean channels in these limestones.

There are no inland lakes and but few coastal lakes. All of these appear to be related either to playa development or to comparatively recent elevation and subsidence. One near Guanica still retains internal evidences of its former marine relations.

The climate is strictly tropical, but it is so tempered by reason of the trade-wind breezes and by the mountainous aspect and elevation of much of the country that it is usually very agreeable indeed. The entire lack of great changes of temperature and the prevailingly moist conditions

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[1] For discussion of this feature in much more detail, see the following article by Douglas R. Semmes on The Geology of the San Juan District, Porto Rico.

over most of the island have a direct influence on the character of rock decay and disintegration and also on the quality of the soil.

The average daily temperature is 80 degrees, and it rarely rises above 90 or drops below 70, while the maximum is said to be 99 degrees.

In area Porto Rico covers 3,670 square miles, and is therefore about three-fourths the size of the State of Connecticut. It is roughly rectangular in outline, with the longer axis east and west, and in actual dimensions is approximately 35 miles in average width and 105 miles long.

It is the fourth in size of the West India Islands. Porto Rico is very productive and is said to be the most densely populated country in the world.

GEOLOGICAL RECONNAISSANCE

The Island of Porto Rico has never had a systematic survey, and comparatively few articles have been written on its geology. A few papers, however, have described certain special features and general physical conditions in a very instructive way. The writings of R. T. Hill (1898, 1899), especially, contain a comprehensive outline of the geologic history of the Island of Porto Rico, and those of H. M. Wilson (1899, 1900) and W. Dinwiddie (1899) give as good general description of its physical features as is anywhere to be found.

In the summer of 1914 the writer, in company with Dr. Clarence N. Fenner of the Geophysical Laboratory, Washington, made a geological reconnaissance of the island, with the object of determining the chief lines of its geologic history and outlining the major problems to receive further study. This reconnaissance was undertaken as a part of the Natural History Survey planned by the New York Academy of Sciences and was intended to lay the foundations of a complete geological survey which it was expected would become the work of several subsequent expeditions and might extend over 4 or 5 years. Observations made at that time, together with additional studies of material secured on this first expedition, served as the basis of a report entitled Geological Reconnaissance of Porto Rico (Berkey, 1915), which was published the following year, and has been the guide for several special expeditions and district studies since that time. This paper still constitutes the fullest statement of the structure and origin and geological history of the whole island; but it has now been supplemented by several district studies which have been made in much greater local detail, and also by a special investigation of the physiography of the island; all of which, with yet others to be made, form a part of the plan for this Survey.[2] Seven such districts

[2] A detailed list of these topics and studies is given at the end of this article.

and areal studies and four general investigations were originally planned. Five of the district or areal studies have been made and one general investigation has been completed.

MAJOR GEOLOGIC FEATURES

Determination of the principal rock types and larger structural units, together with their relations and the principal problems deserving further investigation, may be considered the chief work of a general geologic reconnaissance. To this task the energies of the first expedition was directed with sufficient success, as it now appears with respect to its major lines, to stand the test of the more detailed subsequent work. A brief outline of the more important geologic features characterizing the whole island follows.

Rock Formations

There is an exceedingly large number of formational rock units in this field and a very great number also of rock types or varieties, and the confusion as a consequence is so great, at first sight, that it all appears a hopeless muddle. This is especially true of the interior of the Island rather than the coastal margins. In the higher interior regions igneous rocks and clastics derived more or less directly from igneous action such as tuffs and ashes prevail, although formations of simpler sedimentary (water laid) habit are very abundant and sedimentation structures are at least as prominent as are the massive structures of the true igneous rocks.

Along the coastal margin, on the other hand, especially along the north coast west of San Juan and along the south coast west of Juana Diaz, the rock formations are much simpler in aspect. Soon one comes to realize, therefore, that two distinct formational series are represented and, judging from the very marked differences in habit, one would expect them to be separated by a more or less profound break or unconformity.

To this extent at least the first suggestion in an attempt to organize the complex structure of the island is correct. There are undoubtedly two very distinct formational series which, on more extended inspection, prove to be readily distinguished and separated. The one referred to as characterizing the interior is much the more complex in make-up and structure and most of its members have been extensively deformed and modified since their deposition. The simpler series is made up of a succession of sedimentary and organic accumulations, including shales, marls, chalks and limestones, little disturbed. As should be expected, there is a very distinct unconformity between these two major series represented by an erosion plane which bevels the upturned members of the older complex and seems to have all of the earmarks of a peneplain. The complexity of the older of these two series suggests again the possibility of a subdivision of it, but all studies so far have failed to show a major line of separation. The formational groupings are therefore in approximately the order suggested in their original reconnaissance, essentially as follows:

THE YOUNGER SERIES

This includes shale and limestone beds, reef limestones and occasional sandstone and pebble accumulations. These are readily recognized as belonging to the Tertiary period, but the greater detail of age relation is a matter necessarily left for the more elaborate studies of those districts where these formations are prominent or to the results of general stratigraphic and paleontologic study.

The Younger Series as used in these studies includes at least two very readily differentiated but very unevenly developed members which were referred to in the reconnaissance under names taken from their most typical occurrence.

(*a*) The *San Juan Formation* is the most recent consolidated representative in the island. It is confined to the immediate coast margins, especially the north coast, and the adjacent small islands, the most striking occurrence forming the promontory on which the city of San Juan is built.

(*b*) The *Arecibo Formation* is a thick series of limestones, marls and shales. This is a much more extensive and geologically important member than the San Juan. Subdivision is doubtless possible with further study, and it has been convenient from the very first to distinguish certain particular facies or the beds of particular localities by special locality names; but these do not necessarily represent subdivisions of wide applicability. They have been, however, of distinct usefulness in all studies thus far made. The most commonly used are the following:

1. The *Arecibo limestone*
   upper limestone member on the north side of the island.
2. The *San Sebastian shales*
   lower, shale member on the north side of the island.
3. The *Juana Diaz marls*
   south side shales and marls near Juana Diaz.
4. The *Ponce Chalk beds*
   very white chalks near Ponce on south side of the island.

The greater part of all these beds are satisfactorily determined to be of Oligocene age, but the latest studies indicate the presence of representatives of both Eocene and Miocene age as well.

THE OLDER SERIES

This includes a complex association of tuffs, ashes, shale, conglomerate, limestones and a very great variety of intrusives and occasional lava flows. These are readily seen to be enough older than the other series to have suffered much additional modification of petrographic character and deformation, and it is comparatively simple also to determine that the members of the series as far as they bear fossil evidence seem to be confined to late Mesozoic age, perhaps wholly to the Cretaceous period.

The Older Series thus far has failed to show even as distinct lines of subdivision as the Younger. Perhaps there are breaks as great as that between the San Juan and the Arecibo formations of the Younger Series, but the structures are much more obscure, by reason of deformation and other changes, and are less fully exposed. There is a suggestion of a possible structural break marked by one belt of limestones found by Dr. Semmes in the San Juan district (see San Juan District geologic map) and perhaps in the La Muda Limestone of the original reconnaissance account, but no other supporting evidence is yet at hand, even after a study of more than half of the island in detail.

The Older Series is apparently a fairly continuous accumulation of no greater complexity and structural difficulty than should be expected from a long and almost continuous volcanic history.

Although still regarded as a single series of formations, it has been found very convenient in this case also to designate certain well marked units by locality names. No assumption is made as to their extent or the possibility deserving recognition in attempts at correlation. The Reconnaissance expedition made free use of such terms to much advantage in the field, and later still others have been used by the investigators of special districts. As a matter of fact, the great difficulty found in the beginning in following any single field unit very far or identifying it at other places made the use of many locality and arbitrary names particularly serviceable at that time. Subsequent studies have not successfully eliminated them, and it may well be that the accumulating proof of the great variability of all these formations as well as other units will compel the retention of such local names. Among the terms that belong to the reconnaissance stage and that bid fair to be retained are the following:

1. The Fajardo shales, a very widespread type of blocky shale.
2. The Mayaguez shales, similar to Fajardo shales in general structural habit.
3. The Coamo Tuff-Limestone, a heavy limestone carrying abundant tuff fragments.
4. The Trujillo Alta Limestone, a very limited occurrence of dense limestone.
5. The "Shred" Limestone, a name suggested by the appearance of the chief fossil form.
6. The La Muda Limestone, a formation that seems to mark a break of more than average consequence.
7. The Mountain Limestone, of Hill—thin-bedded, shaly limestones and limy shales of very extensive development along some of the mountain ridges.
8. The Corozal Limestone, a peculiar local occurrence of limestone breccia at Corozal.

PETROGRAPHIC RANGE

The petrographic variety of this older series is very great, but the types of large consequence are not numerous. They may nearly all be included within such group terms as limestone, marls, shales, sandstones, conglomerates, tuffs, ashy tuffs, ashes, and ash shales among the organic sedimentary, and clastic rocks; andesites, andesitic porphyries, diorite, syenite and granite as the chief crystalline igneous rocks; and serpentines and graywackes and rarely some contact products as the chief badly modified types.

Although the range of different types when stated in this form is not at all remarkable, there is almost every conceivable variation of minor composition, quality, structural or textural peculiarity, physical condition, degree of modification and state of preservation represented in each one.

Most of them, furthermore, occur in an almost countless succession of beds and sills or other field units of all sizes from masses of many square miles in areal extent or hundreds of feet in thickness to thin layers or stringers or dikes of only a few inches. As a matter of fact, the most striking thing about these occurrences is the exceedingly great number of small units which alternate or change so many times in short distances that detailed mapping of them, or even an attempt to represent this detail by the most carefully constructed geologic cross-sections, seems hopeless. All practicable representations of the geologic structure are necessarily generalizations.

Maps of any kind covering portions of districts must be done on the basis of a grouping together of great numbers of individual units in recognition of the domination of some particular type. Thus it seems to be possible to mark out belts or areas of dominant limestones, shales, tuffs or conglomerates, some of which are fairly satisfactory as a basis for a geological map. But even in some of these cases the smaller individual constituent units vary so rapidly along their strike that the average quality is wholly different within distances of a few miles. This character makes detailed geologic mapping a difficult and most discouraging undertaking.

The Younger Series, on the other hand, is very much simpler, since no igneous rocks are represented at all. But even here, within the limits set by the shales and sands of one extreme and the marls, chalks, reefs and massive limestones at the other, there is every gradation, the character being evidently under the control of such local conditions, and so poorly marked off in succession by fundamental differences, that here again a subdivision for mapping purposes is extremely difficult to apply. A strictly paleontologic subdivision, however, is being more successfully applied as the investigation of certain districts proceeds.

STRUCTURE

The general geologic structure of the Younger Series of formations is simple. The beds lie, for the most part, dipping gently toward the sea. This is especially true of the broad belt of these rocks forming the north side of the island. On the south side there is some deformation, chiefly due to faulting and crowding. In many places also there is slumping due to sink-hole development.

The Older Series has, on the contrary, a very complex structure. Only rarely do the bedded rocks have their original attitude. They commonly stand much tilted and even vertical, or in rare cases overturned, and faulting is common. But the most prominent structural feature is the association literally of multitudes of thin-bedded ashy or limy shales and equally thin igneous intrusive sheets or sills. It is not at all rare to see an alternating series of such units, a few inches or a few feet thick, so regular that when well weathered the whole succession looks simply like a series of alternating shaly and more massive beds. The number and complexity of the igneous intrusions are surprisingly great and at many places the intrusive members dominate in the formation. In most cases there are no noticeable contact effects.

Much larger intrusive sills, which are almost always dioritic in composition, are also very common and there are a few large bosses several miles across of granite, syenite and serpentine. In a few places the local interruption of the beds by massive tuffs cut by intrusive complexes seems to mark old volcanic vents which must have been active after the adjacent strata had formed and perhaps had attained something of the quality and attitude that they now have. One large old vent of this kind is now the site of the Jacaguas Reservoir. The occurrence of beds of limestone breccia, including great amounts of tuff fragments, and a continuation of the same regular beds beyond such complexes, are further supports to this interpretation.

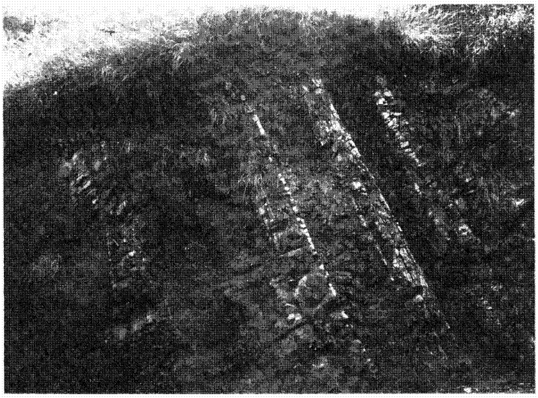

FIG. 1.—*Diorite porphyry sills*

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.

Minor structural features such as xenolithic inclusions in the intrusives are extensively developed. Sometimes a sill or dike is literally crowded with tuff fragments so closely packed together that the whole has more the general outward appearance of a tuff than a bona fide intrusive. Repeated inspection of the structure, however, has removed every doubt as to the essential correctness of the observation. A rather remarkable minor structure in the San Juan formation, which is believed to be a consolidated dune sand, is illustrated in the accompanying figure. It

FIG. 2.—*Detail of the double structure in the San Juan formation at Arecibo*

This photograph was taken 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.

shows nearly horizontal bedding at the base, with highly inclined thin beds (cross-bed structure) above, on which or in which a less pronounced horizontal structure is also preserved completely crossing the inclined layers. This formation has not been deformed at all, so the structures must be connected with the original sedimentation and perhaps the induration processes in some way. No better explanation has been offered than that of the Reconnaissance report, which regards the cross-bed structure as a wind-laid deposit and the horizontal structure, crossing it, as a cementation or induration structure developed in standing water during successive steps of subsidence and elevation.

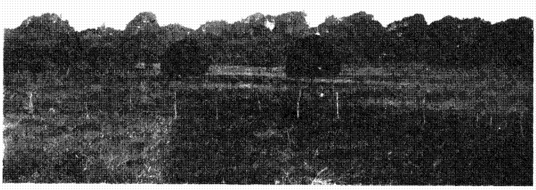

FIG. 3.—*Haystack (pepino) hills*

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.

RELIEF FEATURES

The present relief features of Porto Rico are all those of simple erosion. In the interior the structure is so complex and variable that surface forms seem to show little structural control. The mountains are rugged, steep and irregular in outline. Mountain tops are almost everywhere knife-edge divides, no matter whether they cross or follow the rock structure.

The features of the coastal margins, however, are much more influenced by formational attitude. The younger series of beds lie on the rather evenly eroded (peneplained) surface of the complex older series. Erosion has stripped back much of this younger cover from the old land, thus developing the usual inner lowland and cuesta forms with traces of the old peneplain well preserved on the adjacent ground on the inner side. A full treatment of these features is included in a physiographic study of the island which has already been made by Mr. Armin K. Lobeck, and whose report will soon be published as a part of this Survey.

On the cuesta and the outer slopes, wherever limestones are the surface rock, great numbers of caves have developed. A most striking surface feature is thus produced with sink-holes as the first distinct stage which by enlargement develop flats separated one from the other by remnants of the old walls. In some districts these last remnants form great numbers of small conical hills, referred to by Hill as the *pepino* hills and by Berkey as haystack hills. This is the most unusual and remarkable of the surface features of the island.

Immediately along the coast one may find occasional traces of a step-like form which has attracted much attention. They were taken at once to be sea terraces, and subsequent studies seem to confirm that conclusion. Such forms, therefore, indicate that the island has been elevated in comparatively recent time. Other related features, among them the occurrence of marginal islands, suggest that at one time the island may have stood even higher than now. Probably there has been a succession of elevations and subsidences in later as well as in the earlier geologic history of the island.

Geologic History

In barest outline the geologic history of Porto Rico is simple. A complete or even a reasonably full account of the geologic history of Porto Rico cannot be written at this step of the investigation.

There is no record of very ancient rocks at all. But in Cretaceous time, or perhaps immediately before, this region was the scene of violent and long-continued explosive volcanic activity which resulted through many vicissitudes in the accumulation of thousands of feet of volcanic clastic matters, partly in massive unassorted condition, partly worn, transported and assorted, partly mixed with weathered detrital matters and organic growths, all together forming a great succession of tuffs, ashes, shales and limy rocks.

The summary of the major historical items formulated in the original Reconnaissance report is still serviceable:

(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 baseleveling 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.

PROBLEMS OF THE SURVEY

The problems that were suggested in the Reconnaissance report have engaged the endeavors of several expeditions. Altogether seven have been made and four studies have been completed. Others are yet to be made. The whole plan with its accomplishments may be listed as follows:

Expeditions

(*a*) Expedition of 1914 to make a reconnaissance.

1. Dr. Charles P. Berkey and Dr. Clarence N. Fenner. Reconnaissance report (Berkey, 1915).

(*b*) Expeditions of 1915.

2. Dr. Chester A. Reeds. Study of Tertiary stratigraphy, and especially an attempt to establish the subdivisions of the Younger Series and make paleontologic collections. New base map prepared (published with this paper).
3. Mr. Douglas R. Semmes. Study of the San Juan District (Semmes, 1919).
4. Mr. Edwin T. Hodge. The Coamo-Guayama District.[3]

(*c*) Expeditions of 1916.

5. Mr. Bela Hubbard. The Aguadilla-Lares District.[4]
6. Dr. Charles R. Fettke. The Humacao District.[4]
7. Mr. Armin K. Lobeck. A general study of the physiographic history of the island.[3]

(*d*) Expedition of 1917.

8. Mr. Graham John Mitchell. The Ponce District.[4]

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[3] Report ready for publication.
[4] Report interrupted by the war.

Classes of Studies

The whole list of studies of all kinds fall into three classes:

(*a*) General studies, covering certain features affecting the whole island.

(*b*) Areal or district studies, with accompanying geological maps.

(*c*) Special investigations on problems suggested by local conditions or the material collected.

GENERAL STUDIES

Among the general questions which have been considered to belong to the island as a whole are the following:

New Base Map.—The making of an accurate detailed map, such as might be represented by topographic sheets of the kind prepared by the U. S. Geological Survey, is an undertaking much beyond the scope and facilities of this Survey. Each investigator of a district has undertaken the correction of the maps available for his own area in enough detail for the purpose. These districts, however, are not complete to such a point that a general relief map for the island could yet be constructed from them. As a step, therefore, preliminary to that result, the data of all previously published maps, together with such notes as were available from field observation, have been compiled, under the direction of Dr. Chester A. Reeds, in the form of a new relief map which is published herewith.

Physiography of Porto Rico.—After the reconnaissance and first district studies were made, it became apparent that a general physiographic study covering the whole island would be particularly desirable. The opportunity to make a complete study of an isolated land mass, with a physiographic history probably similar to most of the West Indian islands, seemed to be particularly good. Mr. Armin K. Lobeck undertook this study and his work is completed.

Tertiary Stratigraphy.—This general problem, which was considered too broad for a district study, was recognized as a difficult investigation that deserved to be considered by itself. Dr. Chester A. Reeds entered upon the investigation by making a collecting expedition in the season of 1915. It was the intention to include in this study a determination of the principal subdivisions and boundaries of the Tertiary strata for the whole island, and it was hoped that this could be done on simple enough lines and promptly enough to be of service to all of the men doing district mapping and making local studies. The problem has been found especially difficult and final results are not yet reached. In the meantime the practical matter of mapping has been solved in each district as well as may be, and probably no full statement of the Tertiary stratigraphy will now be attempted till all of these separate studies are available.

Mineral Resources.—Considerable money has been spent in Porto Rico in mineral exploration. It is said that gold was secured in paying quantities by the Spaniards in the early days. One can see gold panning in a few places now. Many ores of other metals are also formed as well as other economic products. Almost none, however, have proven attractive as the basis of an industry, although much interest is attached to such possibilities. Mineral resources of sufficient value to establish these industries are much to be desired, and it is one of the purposes of this Survey to make a final summary of all matters relating to this question in a general study after all of the districts have been fully investigated and reported.

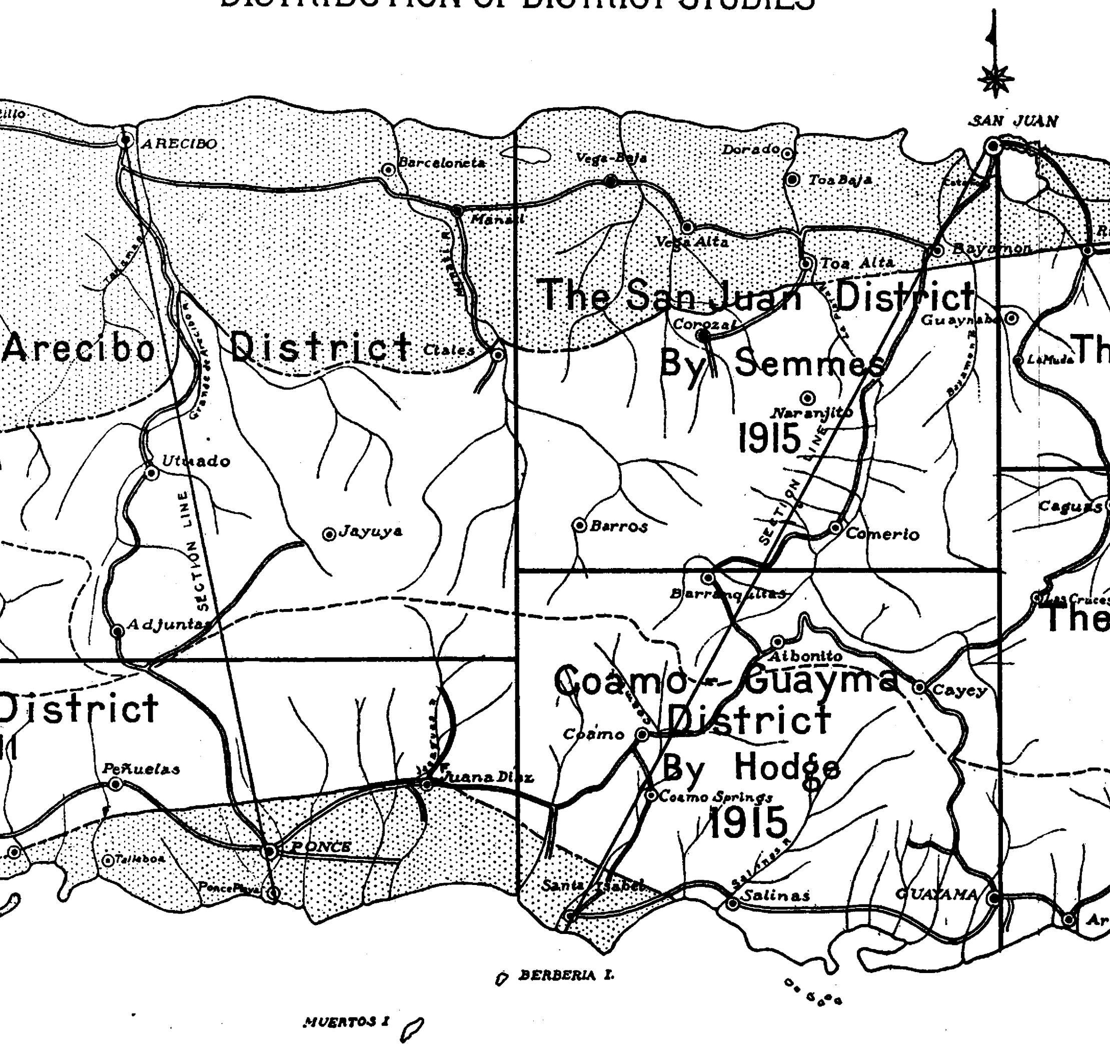
DISTRICT STUDIES, WITH OUTLINE MAP

The basis of all detailed investigations is the district or areal study. It has been found possible to divide the island into areas, each of such size that it could be studied in sufficient detail for the purpose in a single season by one man. These districts are not necessarily of the same size or form. Their boundaries have been chosen, in part, in consideration of transportation facilities and field accommodation, and, in part, in consideration of the occurrence of special features deserving particular attention or special study. It has been possible to assign to each investigator of a district of this kind some important problem of a fundamental sort in addition to his regular district mapping and description. On this basis the area of the whole island has been covered by seven districts. They vary considerably in size, depending upon the nature of the country and somewhat upon the complexity of the geological problem, and to some degree also on the amount of previous investigation in adjoining areas (see outline map).

The first two districts to be studied completed a broad belt entirely across the island from north to south, extending from San Juan to a point beyond Vega Baja along the north coast and from Guayama to a short distance beyond Santa Isabel along the south coast. This belt was chosen as a guide study and was intended to more firmly establish the major geological lines for further study of the rest of the island.

The belt across the island was divided by a line from east to west in the vicinity of Barranquitas into a northerly and a southerly district.

OUTLINE MAP
OF
PORTO RICO
SHOWING
DISTRIBUTION OF DISTRICT STUDIES



The northerly one has for convenience been designated the **San Juan District** from its principal city. A study of this district was completed by Mr. Douglas R. Semmes and the report on its geology, with geologic map, forms a part of this bulletin.

The south end of the belt, south of Barranquitas, was studied by Mr. E. T. Hodge. His area has been commonly referred to as the **Coamo-Guayama District.** A special study of the nature and probable origin of the hot springs at Coamo has been included by Mr. Hodge in his studies of this district.

The **Aguadilla-Lares District** occupies the northwest corner of the island, extending southwest as far as Mayaguez. This was studied in 1916 by Mr. Bela Hubbard. The district includes the best material for a detailed investigation of the Tertiary stratigraphy.

The **Humacao District** of the southeast corner of the island extends as far west as Guayama and as far north as Ceiba. This district contains one of the large areas of granite as well as the principal iron occurrence. The geology of this district was studied by Dr. Fettke in 1916. It involves these special discussions in addition to the district geology.

The **Ponce District** of the south and southwest quarter of the island extends from a few miles east of Juana Diaz to the west coast and from the south margin to Mayaguez. This was studied by Mr. Mitchell in 1917 and was made to include the special problem of elevation and subsidence as marked by terraces, and also the problem of faulting.

Two other districts are still to be studied.

One lies in the northeast corner, occupying the area north of the Humacao District, and may be called the **Fajardo District.** The other lies west of the San Juan District, extending to the vicinity of Camuy on the west and Adjuntas and the mountain divide to the south, where it touches the Ponce District. This is known as the **Arecibo District.**

The accompanying outline map indicates the location of these districts and gives the names of the men who have been responsible for their individual study (see outline map).

SPECIAL INVESTIGATIONS

Special scientific studies not already covered by the general investigations of group (*a*) or included in the district studies of group (*b*) are chiefly concerned with pure science investigations connected with paleontology. Immense collections have been made and seem to be worthy of elaborate study. It is expected that they may ultimately form a volume on the paleontology of Porto Rico.

A considerable list of special topics enumerated in the original Reconnaissance do not deserve so elaborate treatment as that suggested above, and indeed are quite logically cared for in the different district studies. Some of them have been mentioned in that connection already. Among those considered as representatives of the class are the following:

(*a*) Mapable subdivision of the Younger Series.
(*b*) Mapable subdivision of the Older Series Complex.
(*c*) Nature and origin of the San Juan formation.
(*d*) Reef-building organisms.
(*e*) Changes in character and composition of the igneous products at different stages in Porto Rico volcanic history.
(*f*) Thermal springs.
(*g*) Studies in magmatic differentiation in an isolated volcanic center.
(*h*) Origin of the Iron Ores, etc., etc.

An occasional special topic has been the basis of a separate paper (Fettke and Hubbard, 1918), and some of these have been or will be published separately in an effort to furnish useful information as promptly as possible.

In spite of the complexity and extent of the original undertaking, most of it has already been completed so far as relates to the general studies, district descriptions and special problems. One season's field-work on the scale of that of 1915 or 1916 would complete such work, and it would then be possible to make a final geological map of the island and to write the summary of its areal, structural and economic geology and its geological history.

A completion of it to that consummation may be regarded as the immediate object of these geological field studies. The paleontologic studies, in so far as they are necessary to the historical treatment and stratigraphy, are to be included in the geologic investigations. Subsequent studies of all kinds and to any extent may be based on the collections, and additional investigations along paleontologic lines will then be included in a separate volume under paleontology.

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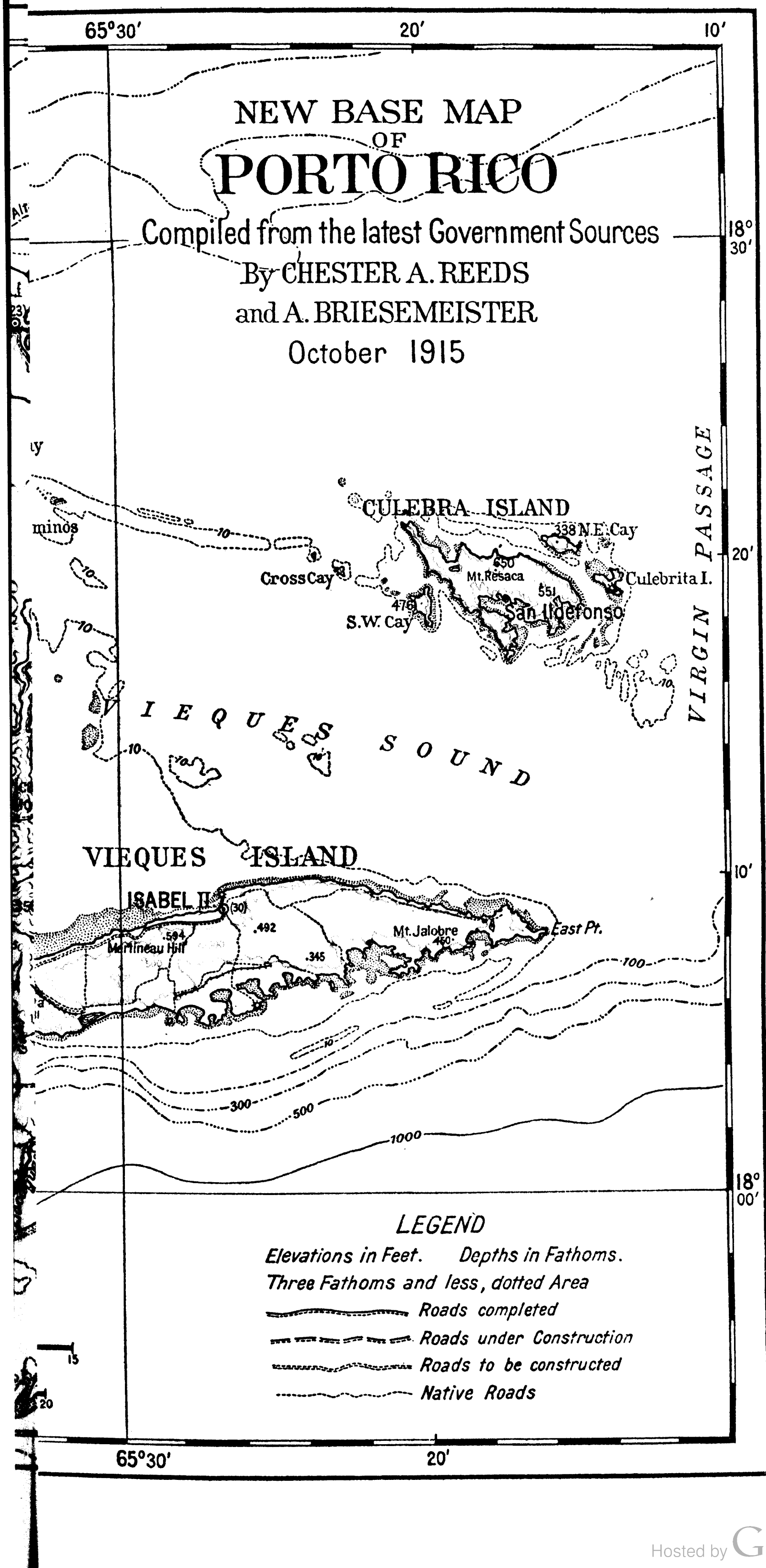
NEW BASE MAP OF PORTO RICO

By Chester A. Reeds

Following a short fossil-collecting season in Porto Rico in June and July, 1915, for the New York Academy of Sciences and the Porto Rican Government, the American Museum of Natural History cooperating, it seemed desirable for plotting results that a small outline map of Porto Rico should be prepared. During October, 1915, such a map was drawn at The American Museum of Natural History by Mr. A. Briesemeister under my direction. Most of the data for the base sheet was obtained from a large map which had been prepared by the engineers of the Interior Department of the Porto Rican Government. The four-sheet edition of the U. S. Coast and Geodetic Survey and the U. S. Post Route map of Porto Rico were also used. Before the end of October a solio print edition of one hundred copies of this new base map of Porto Rico was published by The American Museum of Natural History. Complimentary copies of the preliminary edition were distributed to the members of the Porto Rican Committee of the New York Academy of Sciences, to certain officials of the Porto Rican Government, to the various field men sent out by the New York Academy of Sciences to Porto Rico and to other interested persons.

During December, 1915, the 100, 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000 and 4500 foot contour lines were drawn on a separate sheet for superposition on the base map of Porto Rico which had been prepared in October. Data for this topographic map of the island were taken from various sources, chiefly the U. S. Coast and Geodetic Survey maps, the profiles and sketches of the engineers of the Porto Rican Highways Commission, the contour map of a portion of the south side of the island prepared by the Irrigation Service, the U. S. Geological Survey's topographic sheet of the Luquillo Forest Reservation, together with H. M. Wilson's topographic map of Porto Rico, prepared for the U. S. Water Supply and Irrigation Paper No. 32, 1899. Numerous photographs by Professors C. P. Berkey and H. E. Crampton of the Porto Rican Committee of the New York Academy of Sciences as well as a large number by myself were of considerable assistance in the preparation of the topographic sheet. Fifty solio print copies of this contour map were issued


65°30′
20′
10′
NEW BASE MAP
OF
PORTO RICO
Compiled from the latest Government Sources
By CHESTER A. REEDS
and A. BRIESEMEISTER
October 1915
18° 30′
VIRGIN PASSAGE
CULEBRA ISLAND
338 N.E. Cay
Culebrita I.
Mt. Resaca
650
551
San Ildefonso
Cross Cay
S.W. Cay
476
20′
VIEQUES SOUND
VIEQUES ISLAND
ISABEL II
(30)
.492
.594
Martineau Hill
.345
Mt. Jalobre
East Pt.
10′
100
300
500
1000
18° 00′
LEGEND
Elevations in Feet. Depths in Fathoms.
Three Fathoms and less, dotted Area
Roads completed
Roads under Construction
Roads to be constructed
Native Roads
65°30′
20′

by the Museum and complimentary copies were distributed as had been done with the base map.

Early in 1916 the 10, 100, 300, 500 and 1000 fathom lines were added to the base sheet of October, 1915. Areas less than three fathoms in depth were dotted. This information was compiled from the various Porto Rican charts of the U. S. Coast and Geodetic Survey.

This map should be of interest not only to the scientist and tourist but also to the million inhabitants of Porto Rico, for it is legible, convenient in size and contains a vast amount of information.

THE GEOLOGY OF THE SAN JUAN DISTRICT, PORTO RICO

By Douglas R. Semmes

CONTENTS

SYNOPSIS

The area described in this report, which has been designated the San Juan district, lies on the northern side of the island of Porto Rico. It extends from the city of San Juan on the east to a point about two miles east of Manati and southward as far as Barranquitas—an area roughly 500 square miles in extent. The San Juan district is a typical north-south section through the northern half of the island, the geologic and physiographic history of which may be regarded as essentially the same as that of the whole island.

The physiographic history of the San Juan district is that of a complex mountainous oldland, which has been peneplaned, partially submerged, overlapped by a coastal plain, uplifted, maturely dissected, again slightly submerged and partially uplifted, erosion continuing in the interior from the time of first uplift.

The formations of the district may be primarily divided into the younger series, or those that form the coastal plain, and the older series, or those that lie below it. The youngest formation consists of a coastal deposit of indurated lime dune sand of presumably Pleistocene age overlying unconformably a limestone series, which forms the coastal plain proper. This limestone series, termed by Berkey the Arecibo formation, lies almost horizontal (dip 6° N.) and is now maturely dissected, giving rise to the typical *pepino* or haystack topography of the island. The Arecibo formation is regarded as upper Oligocene in age. In the northwestern portion of the island, but not appearing in the San Juan district, is a lignitic shale member (the San Sebastian shale) which underlies the Arecibo formation. The age of this shale member is uncertain, but in all probability it is lower Oligocene.

The older series consists of marine and volcanic sediments with numerous intrusives. It is highly tilted and locally folded, resting unconformably below the younger series. The sedimentary types represented are limestone, shales, sandstones, conglomerates, tuffs and ashes. With hardly an exception, these sediments are either of volcanic origin or were deposited through volcanic processes. Even the limestones show brecciated structure and are, with few exceptions, merely accumulations of limestone fragments derived from older beds shattered by volcanic outbursts. The foraminiferal content of certain shale and limestone beds in the upper part of the older series indicates that the beds are upper Cretaceous and Eocene in age. The lower part of the series is no doubt Comanchic. The peneplanation of the older series culminated along the coast before the deposition of the coastal plain, for the peneplane surface can now be traced underlying the Arecibo formation. In the interior, however, erosion continued until the uplift, which occurred in late Oligocene time.

The older series is everywhere intruded by igneous rocks of many varieties. The predominant type is an andesitic porphyry. The tuffs and other sediments directly derived from volcanic sources are also of this general composition. The igneous rocks occur as extrusive sheets, sills, dikes, and small and moderate sized stock-like intrusives.

The mineral resources of the district are not large. About 100 ounces of gold are panned annually from the rivers in the vicinity of Corozal. Gold quartz veins have been worked in the hills south of Corozal, but without success. In the barrio Pasto, southwest of Morovis, several copper prospects have been slightly explored.

INTRODUCTION

The Antilles and the Central American region have remained until the close of the nineteenth century almost a *terra incognita* as regards their geological structure and history. Unfortunately, little study has since been devoted to this critical region which connects the two Americas, and until more accurate information regarding it is available our ideas of the geologic correlation of the two continents must remain largely conjectural. At the close of the Spanish-American war Porto Rico, being the closest of our newly acquired insular possessions, attracted a good deal of attention. During the first years of the American occupation much was written about the island and its inhabitants. Several very good papers describing its general configuration and geology were published during this period,[1] and a number of articles on particular features or the general aspects of the country appeared in current periodicals and in

[1] Dorsey (1902), Hill (1899*a*), (1899*c*), Wilson (1899), (1900).

proceedings of learned societies. Interest in Porto Rico, however, soon waned, and from 1902 to 1915 nothing regarding its geology was published. In 1915 a paper by C. P. Berkey appeared in the Annals of this Academy, which gives the first detailed and purely geological description of the island that has yet been written.

Geographic Location

Porto Rico, the smallest and easternmost of the Greater Antilles, averages 35 miles in width and 100 miles in length, presenting a regular rectangular outline three times as long as broad and alined nearly exactly east-west. Its shoreline is nearly straight and quite regular. The coast is usually low, with a few low promontories. The fringing keys and deep indentations characteristic of a more youthful stage in coastal development, and so abundantly developed on the Cuban coast, are entirely wanting. Its area is 3670 square miles, just 500 square miles less than the area of Jamaica, or about three times that of Rhode Island. Its population, considered as a whole, is the densest of any country on the globe.

Natural History Survey of Porto Rico

In 1914 an appropriation was made by the Insular Government of Porto Rico for the establishment of a Natural History Survey which was to be carried on in conjunction with the New York Academy of Sciences. The geological phase of the survey was begun in 1914 when Dr. Berkey and Dr. Fenner spent a month on the island, making a geological reconnaissance, preparatory to a subsequent and more detailed survey. The following year the writer was assigned to the San Juan district to begin this more detailed work.

San Juan District

The region selected may best be called the San Juan district, as San Juan, the capital, is situated in the northeastern corner. The district is that area comprised between longitude 66° 05′ and 66° 27′ west, and an east-west line through the town of Barranquitas about 21 miles south of the northern coast. The areal extent of the district is roughly 500 square miles. A corresponding area of similar width to the south was studied at the same time by Mr. E. T. Hodge. In this way a belt 25 miles wide was surveyed entirely across a typical portion of the island. Three months were spent in the field, in which time a topographic map was constructed, the mineral resources studied, and the geology plotted in as much detail as possible, considering the shortness of the time and the size of the area involved.

THE PHYSIOGRAPHY OF THE ISLAND

The general configuration and topography of the island have been well described by several writers. Dorsey (1902) has written an admirable description of the several types of topography one meets on crossing the island, with an especially detailed description of the limestone topography of the coastal plain. Wilson (1899) also has given a good general description of the physical aspects, and Hill (1899) described the physiography in connection with his geological reconnoissance of the island. The recent article by Berkey (1915) gives the most modern and detailed description of the physiography and physiographic history of the island.

The island of Porto Rico may be described as a complex mountainous oldland, in the n^{th} cycle of development, which has been peneplaned, or reduced to an old stage of topographic development, submerged, overlapped by a coastal plain, uplifted and maturely dissected, partially submerged, then re-uplifted and further dissected.

Complex Mountainous Oldland

The most characteristic topographic feature of Porto Rico is its complex mountainous aspect. That portion of the island that rises above sea level is merely the eroded crest of a submerged mountain range of great complexity and magnitude. This eroded crest rises steeply from the sea to an average altitude of 2500 feet along the divide. Owing to difference in rainfall on the northern and southern side, the divide has been pushed to the south by the encroachment of the larger northern streams until it now stands two-thirds of the way toward the southern coast. The present position of the divide has also been accounted for by a theory of block faulting of the whole island with the front face of the block facing south (Berkey, 1915, p. 40). In the western portion of the island the divide is double, where it is parted by westerly flowing streams. Near Adjuntas the two divides join at the headwaters of the Anasco River to form a single ridge, which continues to Cayey, where it first swings southward, and then sharply to the northeastern corner of the island. The Luquillo range forms another westward extending branch of the divide nearer the northern coast.

The texture of the mountainous topography is medium to fine, except for certain lowland areas of coarser texture. The interior topography i predominantly the ridge or *cuchilla* type. The slopes are extraordinarily steep, slopes of 30–40 degrees being often seen. Between these ridges the streams run in V-shaped valleys. Some of the valley walls are very steep, but all variations from a canyon-like gorge to mature, open valleys are to be found. The streams north of the divide are very numerous and of large volume, due to the abundant precipitation of the large per cent of run-off. Loisa, the largest river, rises only eight miles north of Arroyo

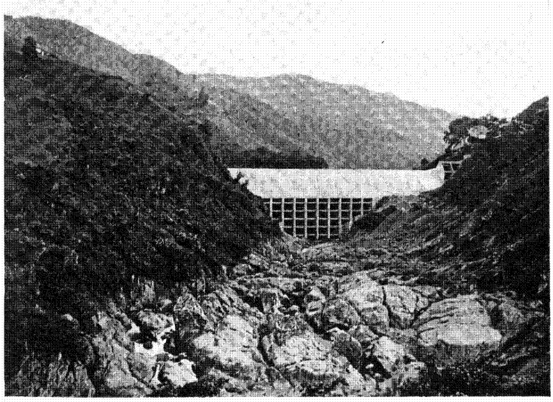


FIG. 1.—*Valley of the Plata, just below the power dam at K 19, Comerio Road*

Such steep valley walls and boulder-strewn beds are characteristic of almost all of the mountain streams.

on the southern coast. The Plata, next in size, rises the same distance north of Guayama. The larger streams rise high up in the mountains, and in the first few miles develop steep gradients characterized by falls, rapids and boulder-strewn beds (Fig. 1); then passing out into the lower coastal margins they acquire much more mature courses and finally swing in large meanders over the flat playa plains bordering the coast. Thus a typical stream such as the Plata on the northern coast may show every stage in development from youth to late maturity in its comparatively short course to the sea. The complexity of this mountainous oldland is readily recognized from even the most cursory observation of its geologic structure. An endless variety of sediments and volcanics, steeply tilted and locally folded, are to be found intruded, permeated, and saturated by igneous rocks of many kinds, assuming an endless variety of forms.

Peneplanation

If one stands upon the summit of one of the central sierras and looks out over the innumerable ridges that rise in all directions he may be impressed by the even crest line formed by the general accordance of summits. This crest line apparently marks the present level of a peneplane the development of which began in Eocene and culminated in late Oligocene time. It is quite possible that the peneplane was never developed in any degree of perfection over the entire island. In some districts, however, its present position is clearly defined, and near Mayaguez and Rincon undissected portions of this old upland surface can be seen. In this vicinity the level-topped areas are locally known as mesas. In other parts of the island no trace of an accordant skyline can be found. However, a discordant skyline might well be developed in local areas through differential erosion or by subsequent warping. The evidences for and against peneplanation are discussed in more detail in another part of this report.

The present elevation of the peneplane ranges from 2000 to 2200 feet near the divide to sea level along the coast. On the northern side it is partially covered by the younger coastal plain strata, but in the stream valleys it can be seen still preserved beneath the coastal plain. Elevations rising decidedly above its maximum elevation, such as El Yunke (3790 feet), Los Picachos (3700 feet), Ala de la Piedra (3650 feet) and Guilarte (3600 feet), must be regarded as monadnocks upon the peneplane surface.

The Coastal Plain

Overlapping the mountainous region, there extends for nearly the whole length of the northern coast a coastal plain of limestone and shaly beds, which reaches as far inland as Lares and to an elevation of 1200 feet. A similar coastal plain appears along the central portion of the southern coast. They are both of early Tertiary age, but whether they are exactly contemporaneous is uncertain. This fringing coastal plain varies in width from a mere line of isolated limestone hills, as seen south of San Juan, to a belt over ten miles broad north of Lares. On the southern coast it nowhere exceeds two or three miles in width. Overlying the coastal plain on the northern side, and occurring as a string of fringing islands or low coastal promontories, is the San Juan lime sand. It is essentially an indurated dune sand composed of shell fragments and quartz grains. This sand extends nearly the whole length of the northern coast, except for the extreme eastern part, but it has not yet been reported upon the southern coast.

Mature Dissection

The coastal plain is characteristically mature in its stage of development. Some portions of it might be regarded as sub-mature, and towards the eastern end of the district, south of San Juan, dissection has continued to late maturity. The larger area comprised between these two extremes, however, shows the rugged appearance of maximum dissection, characteristic of maturity.

Recent Submergence and Uplift

Since the deposition and uplift of the Tertiary coastal plain there is evidence of still later movement. The rock terraces described by Berkey (1915, p. 48) on the southern side of the island indicate that the sea was once at that level, while the presence upon them of recent shells fixes the time. On the northern coast recent marine shells are found some distance up the larger valleys at elevations of 100–200 feet. The subsequent uplift was not as great as the previous subsidence, for large areas of the San Juan sandstone, which must have originated at or above sea level, are now submerged, forming islands fringing the coast. The available evidence seems to indicate, moreover, a series of minor oscillations extending from Pleistocene time until the present, that is, the submergence which formed the fringing island was not continuous but consisted of numerous positive as well as negative movements.

THE PHYSIOGRAPHY OF THE SAN JUAN DISTRICT

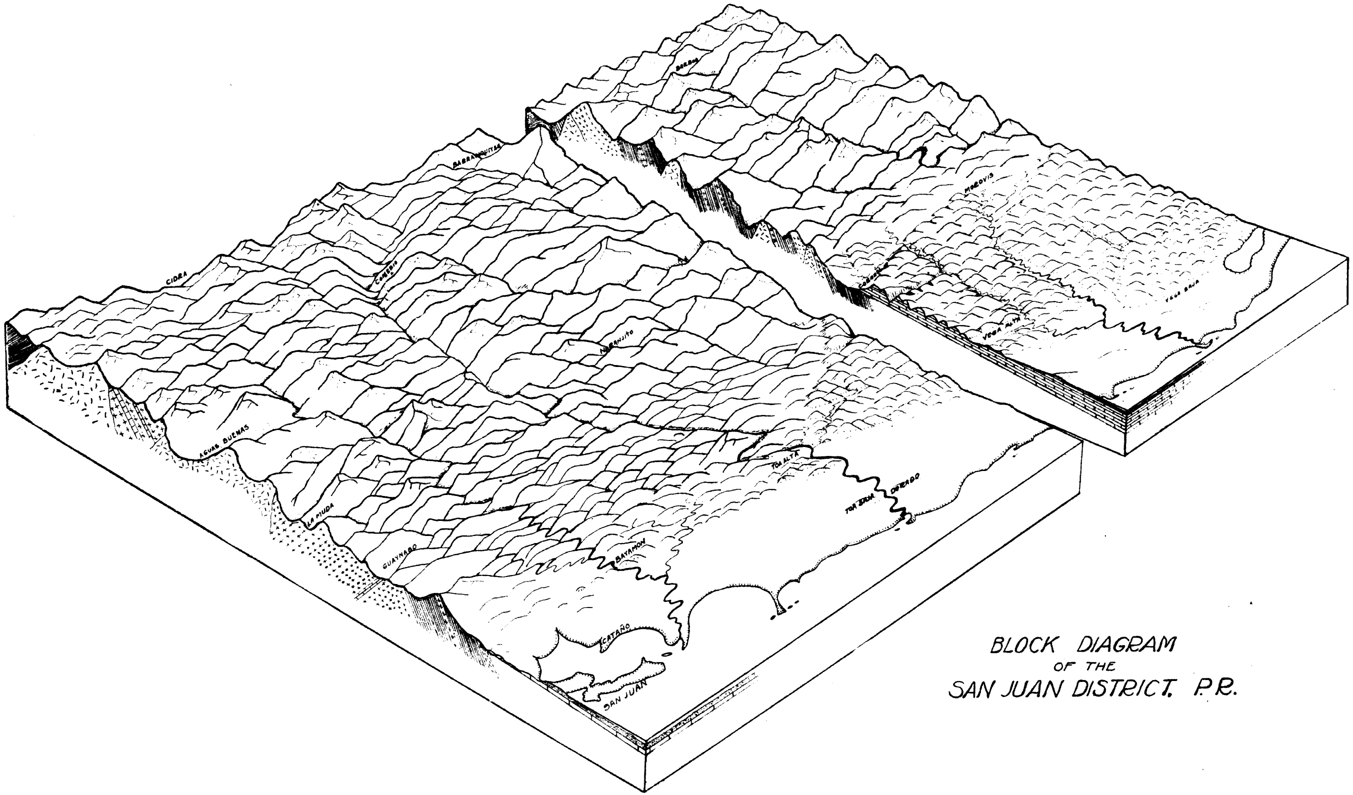
The San Juan district, as already stated, extends from San Juan westward to a point two miles east of Manati and southward as far as Barranquitas. Lying in the central part of the northern side of the island, it enjoys a very uniform humid climate. The mean annual rainfall varies from 50 to 90 inches. The dryest months are December and January, and the wettest month is May. The mean annual temperature varies from 74° to 78°. Though the climate is strictly tropical, the heat is rarely oppressive; a breeze is always stirring, and at least one or two showers may be expected each day.

The district represents a typical section of the northern half of the island, and its physiographic history has in general been the same as that given for the island as a whole. The accompanying block diagram (Pl. I) is an attempt to picture graphically the topography of the San Juan district. Traversing the district from the coast to the southern boundary, one would cross successive belts of differing topography, which may be regarded as the topographic provinces of the district. On the coast is a narrow belt of modern sand dunes, in some places overlying the older Pleistocene consolidated sand dunes. Following this, there is an expanse of flat plains locally known as playas. These extend from the coastal dune area inland to the Tertiary limestones. In places the flat expanse of the playas is broken by low, rounded hills of the Tertiary limestones rising through it. To the south of the playa plains the typical *pepino* or haystack topography of the limestone belt begins. This belt extends inland and adjoins the oldland. It is occasionally broken by transverse valleys, such as the valleys of the Plata and Cibuco Rivers, which have completely removed all the limestone so that the alluvial plains of the river valleys rest directly on the oldland. Separating the coastal plain and the mountains proper is a low-lying area called by Hill (1899*a*) the "parting valley." This is the inner lowland developed between the coastal plain cuesta and the oldland. It is well developed as it crosses the San Juan district, broadening out towards the east to form a lowland area several miles wide between Bayamon and Guaynabo. The mountainous area extends southward from the inner lowland to the southern boundary of the district.

The Dune Area

The dune area presents topography of two types: first, the low promontories and coastal islands developed in the consolidated dune sand of Pleistocene (?) age; and, second, the modern dune topography that borders the coast. The first type is best represented in San Juan City. The promontory, rising some 75 feet above the sea, on which the city stands, is entirely made up of the consolidated dune sand. To the west it can be traced either as a string of low islands, or occasionally as a promontory jutting out into the sea. Near Vega Baja Playa the island type is well developed, the islands ranging in size from a few yards to several hundred yards in length, and occurring out as far as a quarter of a mile from the coast (Fig. 2).

The second or modern dune type of topography is a narrow strip of live dunes composed of lime sand similar in composition to that which forms the consolidated deposits. The dune belt follows the coast for the entire length of the district, varying in width from a few feet to several



BLOCK DIAGRAM
OF THE
SAN JUAN DISTRICT. P.R.

hundred yards. It is broadest in the western part of the district, but its maximum width is developed farther west than the San Juan district extends. The origin and source of the Pleistocene, as well as the modern dune sand, will be discussed under a subsequent heading.

The Playas

The playa plains, a name given by Hill to the fan-like plains that extend from the foothills of the dissected limestone cuesta to the coast, are to be seen along the entire coast of the San Juan district. Separated from the sea by the dune belt, they extend inland to the Tertiary limestones, and follow up the larger valley until they lie directly on the rocks

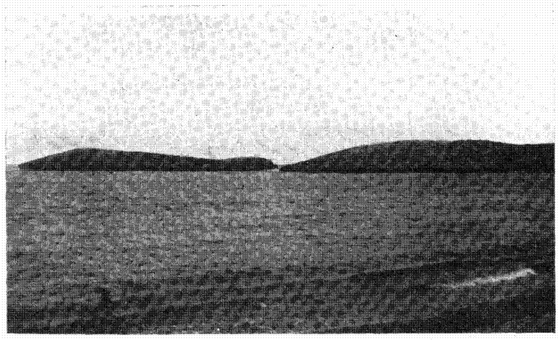


FIG. 2.—*San Juan consolidated dune sand forming fringing islands at Vega Baja Playa*

at the interior complex. The playa plains rise only a few feet above sea level, and until recent years large areas of the plains in the San Juan district have been covered with water, forming inland swamps and lagoons. Since the value of the land has been recognized for sugar-cane production, all the available areas have been drained, and now constitute the most productive and valuable lands on the island. The low, flat, monotonous expanse of the playa plains is occasionally broken by low, rounded hills of the Tertiary limestones rising above the alluvial (Fig. 3). These limestone hills are isolated remnants of the coastal plain here buried beneath the recent deposits. Owing to the slight elevation that they afford above the blistering heat of the surrounding plains, they are selected as town and dwelling sites. Both Dorado and Toa Baja, the only two towns situated in the center of the playas, are built upon these limestone remnants. Others are chosen as sites for the individual dwellings of the natives. The playa plains follow the three principal valleys of the Cibuco, Plata, and Bayamon Rivers for some distance inland, and in the case of the latter two extend well beyond the limestone belt.

The geological history of the formation of the playa plains has, no doubt, been complex. It is evident that they are in part of fluvial origin, for they grade directly into the true alluvial plains of the river valley.

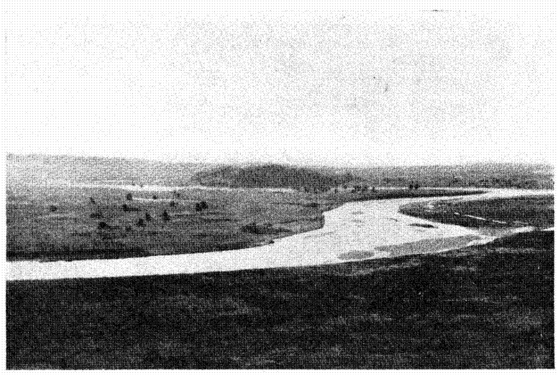


FIG. 3.—*The playa plains near Arecibo*

Showing a limestone remnant rising above the floodplain deposits and the limestone hills of the Arecibo formation in the background. Photographed from report of Bureau of Soils, U. S. Department of Agriculture, 1902.

Just how important a rôle the sea has played in their formation is not definitely known. It is the writer's opinion, however, that both factors have been influential. This point will be further discussed below.

THE TERTIARY LIMESTONE BELT

As the northern coast of Porto Rico is approached, one readily distinguishes two kinds of topography; the rugged mountainous skyline, and the lower, angular, maturely dissected limestone coastal plain. On closer inspection it is seen that the topography of the coastal plain consists of numerous isolated or closely grouped angular hills not exceeding 100 feet in altitude, but of such angular and rugged outline, and so densely covered with tropical vegetation that they form the most inaccessible and impassable regions of the district. Slopes of 40° are quite common and occasionally vertical faces of limestone rising 10 or 20 feet are to be seen. Though from a distance the hills appear well rounded, yet at close range they are exceedingly rough and jagged, and are, as one of the Americans living in the vicinity expressed it, "very hard to scramble up." The unusual appearance of these limestone hills was early noticed by the na-

FIG. 4.—*Typical haystack topography as developed in the western portion of the San Juan District*

Photographed by H. E. Crampton.

tives, who call them *pepinos* or cucumber-shaped hills. Berkey has used the term "haystack hills," a term peculiarly fitted to picture their appearance, rising abruptly as they do from comparatively level plains (Fig. 4).

Both Dorsey (1902, p. 800) and Berkey (1915, p. 52) have independently come to the same conclusion as to the origin of the haystack topography. Berkey summarized the steps in their development as follows:

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 repeated 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 the surface.

This is no doubt the best explanation for the origin of the typical haystack hills. Towards the south boundary of the limestone belt, however, the haystack hills are not typically developed. The topography of this region is more rounded, with better drainage pattern. Occasional sinkholes are developed, but the topography as a whole resembles more that developed by normal stream erosion. This difference is due to the change in character of the limestone. The haystack type is developed on pure limestone, the latter on shaly limestone and shales.

TERRACES

The haystack hills rise abruptly from almost level plains, just as haystacks on a grass field. The plains are local developments and do not continue over extended areas. On passing from one of these plains to another, one is conscious of the fact that they rarely are of the same altitude, that is, they are not separated portions of a continuous base-level. On the contrary, they assume a step-like succession, forming a series of seaward-facing terraces. The level of an upper terrace corresponds roughly with the summits of the haystack hills on the next succeeding lower terrace. The terraces are best developed west of Vega Baja. Two can be recognized on following the road from Vega Baja to Morovis at K[2] 42-43 and K 3-4 (Morovis road) respectively (see topographic map). Others less prominent can be detected by means of the aneroid.

There are two possible explanations for the origin of the terraces:

[2] K indicates kilometer posts on the public roads.

(*a*) The presence of a shaly layer in the purer reef limestones may be the controlling factor in the development of a plain at a particular level through difference in solubility. The pure limestone would soon develop large caves, extending down to the level of the shaly layer, which, collapsing, would leave the haystack hills on a fairly level base. This plain would slope gently with the limestone strata towards the sea. After a time erosion would finally break through the shaly layer and a new terrace would be formed with the next shaly layer as its base (Fig. 5). In this way successive terraces would be formed facing the sea. The difference in appearance of the pure limestone and the shaly layers might well be so slight as to escape notice, so the apparent absence of shaly beds throughout the upper limestones would not disprove the theory. The writer located several shaly beds in the upper limestone that might easily have caused the terraces, but no exact correlation could be made from the barometric readings.

(*b*) It is also possible that these may be marine terraces. Evidence for recent subsidence has already been mentioned, and marine terraces of

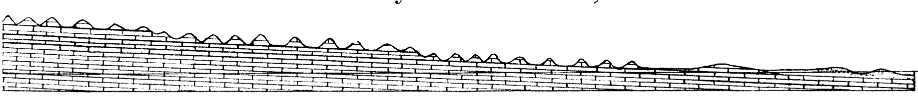


FIG. 5.—*Section through the Arecibo formation*

Illustrating the possible origin of terraces from differential solution caused by shaly layers at A, B and C.

about the same elevation have been described from the southern coast (Berkey, 1915, p. 48). Both causes may have been influential, but the writer is inclined to adopt the first, since no marine shells have yet been found on the terraces. Moreover, the haystacks on the plains are more numerous and more promiscuously scattered than marine stacks should be, unless one considers the possibility of marine terraces later dissected to form the haystack hills.

The limestone belt extends across the whole district. It is wedge-like in general outline, being about five miles wide on the western border of the district, and thinning to a mere string of isolated hills on the east. Its inner margin reaches the elevation of 700–800 feet north of Corozal. In this locality and to the west its southern boundary is a well-defined cuesta which is locally known as "The Walls" (Fig. 6). To the east of Corozal the cuesta form is destroyed by more advanced erosion.

THE INNER LOWLAND

This topographic province, described by Hill as the "parting valley" (Hill, 1899*a*, p. 105), extends entirely across the San Juan District. It lies between the infacing cuesta of the coastal plain on the northern and the mountainous region to the south. It is best defined at Corozal (Fig. 7) and to the west. Eastward it broadens as the limestone cuesta wedges out, until south of Bayamon it is represented by a broad expanse of rolling country, extending southward past Guaynabo and merging gradually into the interior mountain. Its topographic development is more than that of the interior mountains, that is, its stage of development is late maturity, with mature streams crossing it in broad and often meandering courses.

THE INTERIOR MOUNTAINOUS REGION

South of the inner lowlands the topography of the San Juan District is typically mountainous. On approaching the island the rugged serrate

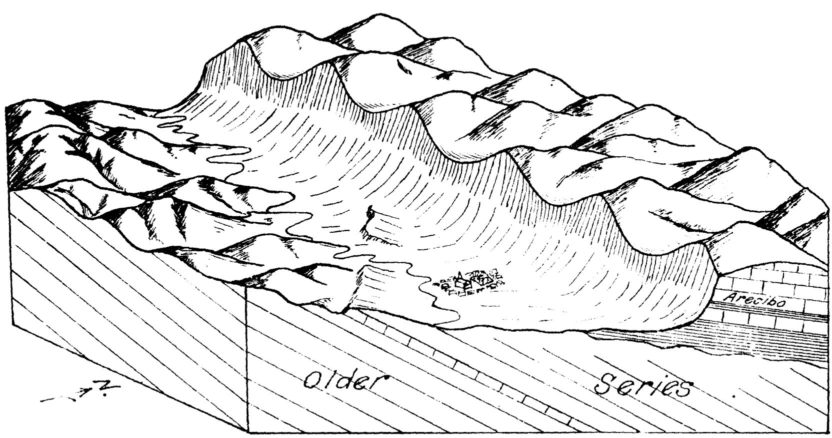


FIG. 6.—*Inface of cuesta and inner lowland near Corozal*
Showing relation of the Corozal limestone in the older series.

character of the skyline can be distinguished soon after its outline rises above the horizon. Passing through the mountainous area one is impressed with the extreme degree of the dissection. Almost no level ground is to be seen. Throughout most of the mountainous region of the San Juan District the country has attained the maximum ruggedness characteristic of a fully mature stage in topographic development. Other portions show more or less advanced stages, but the topography of the region as a whole is mature. Between the numerous streams the divides form a network of sharp ridges, so steep that the natives have appropriately named them *cuchillas* or knives. These are likewise closely and deeply corrugated by ravines and gullies, the whole region assuming very much the appearance of a wrinkled handkerchief, a simile said to have been used by Columbus in describing the topography of the Antilles to Queen Isabella.

The drainage of the mountainous area as a whole is dendritic in pattern. The adjustment of the stream courses to underground structure is very rare. A few cases were noted where some adjustment had taken place, but nowhere was it conspicuous. Although the mountainous region is underlain by a complex of formations of much variety, yet there is little or no evidence of this in the topography. Occasionally a dike could be traced for a short distance as a poorly discernible ridge, and it was noticed that the highest points were usually underlain by highly indurated siliceous tuffs, as, for example, Torrecillo, northwest of Barranquitas, and Helechal, some distance south of Bayamon.

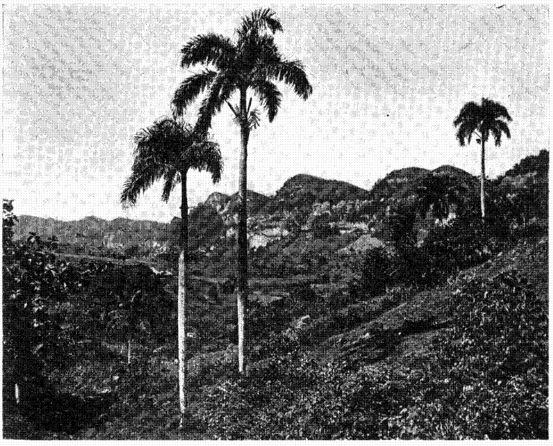


FIG. 7.—*The inner lowland and the inface of the cuesta at Corozal*

The almost vertical inface is locally known as "The Walls." Photographed by H. E. Crampton.

INCISED MEANDERS

Some of the streams have developed deeply intrenched meanders as they pass out from the mountainous oldland. The best example is that of the Orocovis River south of Morovis. In this region the stream shows larger swinging meanders entrenched to the depth of 800–1000 feet (see topographic map). The origin of these incised meanders and their restriction to the inner lowland and the adjoining mountainous region is comparatively simple. At the time peneplanation reached its maximum the streams passing out over the flat oldland surface acquired meandering courses on nearing the sea, which then reached inland as far as the present mountainous region. Subsequent gradual uplift has slowly entrenched these meanders as the coastal plain emerged and assumed the present position.

STREAM CAPTURE

Although there are undoubted cases of stream capture in other portions of the island, no striking examples are to be found in the San Juan district. Near Comerio, however, there is a wind gap that was evidently at one time occupied by a tributary of the Plata River. This tributary, now represented by Mora Creek, formerly flowed from the southeast through the wind gap and occupied the upper valley of the Arroyato River (see topographic map). Subsequently another tributary of the Plata, working down from the north, intercepted the larger stream, forming the present Arroyato River, which joins the Plata at K 23 on the Comerio Road. Both streams are now completely readjusted, but it is still evident that Mora Creek occupies a much larger valley than would be expected, considering its volume.

PENEPLANE

It has already been stated that the interior mountainous region has been partially truncated by peneplanation. In the San Juan district practically nothing of the upland surface remains. In some portions, however, its present elevation is well marked by the even character of the crest line. In the southern part of the district it can be traced at an elevation of 2000–2200 feet or less towards the eastern corner. From this elevation it slopes to the edge of the mountainous region, where it is approximately 1200 feet. At this point the mountainous region breaks sharply down to the inner lowland, forming a well-defined escarpment. The escarpment can readily be traced on the topographic map, especially in the central portion of the district just north of Naranjito. The peneplane level, occasionally discernible among the crests south of the escarpment, is not again recognizable until it plunges below the limestone strata of the coastal plain. At Corozal its elevation as it passes under the coastal plain is about 300 feet. From this it would appear that the peneplane surface was slightly upwarped along the southern edge of the coastal plain; but these irregularities in the present surface of the peneplane may well have been original. The peneplanation was by no means perfect. In some portions of the district no indications of its former existence are to be found. Between Barranquitas and Barros much of the country rises far above the peneplane level. Such an area can be regarded as a monadnock group. On the other hand, near Cidra, in the southeastern corner of the district, the general elevation of the country lies below the peneplane level. In this area the peneplane either was less uplifted originally or its original elevation has been entirely destroyed by subsequent erosion or warping. Indeed the present irregularities of the skyline and the variations in the general elevation of the upland surface are of such magnitude that the writer is forced to admit that the area may never have been peneplaned, and that the apparently even crestline that can be seen in parts of the district may be partly the result of an optical delusion on the part of the observer, and in part a real evenness, not necessarily caused by peneplanation, but due to weathering *in situ* and the formation of a thick soil mantle, which would tend to destroy the minor irregularities in the skyline.

ROCK FORMATIONS

The formational units of Porto Rico may be primarily divided into those that form the coastal plain and those that lie beneath it. These have been named the Younger and Older Series by Berkey. They are everywhere separated by a marked unconformity, so that they are entirely distinct structurally as well as lithologically and faunally. In the San Juan district the younger series includes all the formations encountered in passing from the coast to the inner lowland. These are, in the order of their respective ages, as follows:

1. The modern sand dunes of the coast and the adjoining playa plains.
2. The Pleistocene (?) San Juan lime sand.
3. The Oligocene limestones and shaly limestones (Arecibo formation).
4. The San Sebastian shales, developed near Lares, but not in the San Juan district. Probably Upper Eocene or lower Oligocene in age.

A detailed subdivision of the younger series will, no doubt, be possible when its fauna has been studied with care. The Arecibo formation is essentially a unit, though somewhat complex, and showing considerable variation laterally. The lower shale member is evidently a separate formational unit, merely representing a local development, which is not found in the San Juan district. A subdivision of the underlying older series, however, is quite another matter. The complexity of the formations and their lateral variations are so great that nothing more than a general subdivision will probably ever be possible. The local development of many of the formations, together with their disturbance and alteration by igneous agencies, make even the most generalized correlations largely conjectural.

Younger Series

RECENT DEPOSITS

Unconsolidated Lime Sand.—The modern dune sand, the occurrence of which as a narrow belt along the coast has been mentioned, consists of shell and coral fragments with occasional grains of quartz. Its constituents are almost identical with those of the associated consolidated deposits—a fact which leads one to infer that this sand is but a modern representative of the older consolidated San Juan sand. The belt of modern sand dunes is usually narrow, its greatest elevation of 8–10 feet being reached within 75 yards of the coast; from this point it slopes gradually inland and merges into the adjoining playa plains.

Playa Plains.—The playa plains, which occur as an east-west belt across the district, lying immediately south of the dune district, are partly fluvial and partly marine in origin. They are composed of material derived from the interior of the island through the ordinary processes of stream erosion and deposited by the streams passing out of the mountainous interior upon the comparatively level coastal plain.

These streams are now slightly entrenched, giving occasional exposures of a few feet in thickness. Such exposures show typical torrential bedding and deposits of fluvial character; however, marine shells are occasionally found upon the playas. These can be accounted for through temporary inundations. During the hurricane of August, 1898, practically the entire expanse of the playa plains of the district was flooded. At this time the simultaneous occurrence of heavy rains and strong northeast gale caused the inundation. It is evident, moreover, that the sea has not had direct access to the plains since the consolidation of the San Juan sand. Indeed the formation of an offshore sand bar in Pleistocene time may have been the controlling factor in the formation of the playa plains. In the sheltered lagoons formed behind the bar the alluvial material may have been deposited and subsequently uplifted with the San Juan formation. This would account for the typical fluvial appearance of the deposits, as well as their occasional evidences of the action of marine agencies.

PLEISTOCENE (?) DEPOSITS

San Juan Formation.—This name has been given by Berkey to designate the formation upon which the city of San Juan is built. It here forms a striking promontory that extends as a spit several miles out from the adjoining mainland and at its extremity attains an altitude of almost a hundred feet. This maximum elevation is crowned by the picturesque El Morro, the massive walls of the castle being built upon the very edge of the steep seaward face of the promontory (Fig. 8).

FIG. 8.—*Morro castle and a portion of the city of San Juan, built upon a promontory composed of the San Juan consolidated lime sand*

Photographed by H. E. Crampton.

The San Juan formation as seen at this point is a very porous, medium to coarse grained sandstone composed of minute fragments of shells and well-rounded quartz grains, bound together with calcareous cement (Fig. 9). The calcareous grains predominate and in some localities form practically the whole of the rock, so that the formation is essentially a lime sand. In other localities the quartz content is higher, but in no case did it constitute as much as fifty per cent of the rock. In the vicinity of San Juan two distinct types of the formation were found. First, that which occurs well above sea level near Morro Castle. At this point the lime sand is exceedingly porous. The cementing material does not fill all the interstices, the grains being cemented only at the actual points of contact. This mode of cementation has created a rock in which the volume of the pore spaces is about 20–30 per cent of the entire rock. The second variety of lime sand was taken from a quarry near Borinquen Park, about three miles east of the first locality. The material from this

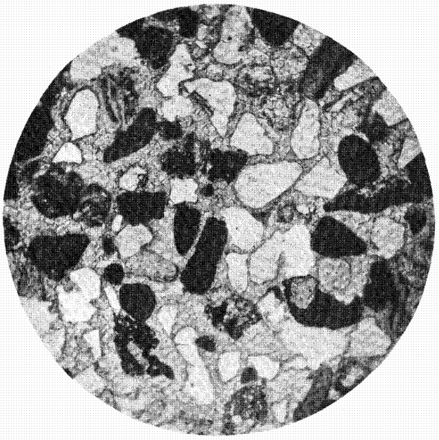


Fig. 9.—*San Juan consolidated lime sand*

quarry, coming from below sea level, is dense and closely cemented, being locally used as a building stone. It is evident, therefore, that the degree of cementation is dependent upon the length of time the formation has been exposed to the free circulation of calcareous solutions. The upper portion of the formation, being re-elevated after only a short period of submergence, now shows only the initial stages of consolidation, while the lower portion, still submerged, has consolidated into a dense and very durable rock. The question then arises whether the porosity of the upper portion of the formation is not due to subsequent leaching rather than to initial poor cementation. A microscopic examination of the lime sand, however, shows no evidence of any appreciable amount of subsequent leaching, for a subsequent dissolution would have affected the readily dissolved calcareous fragments as well as the calcareous binding material.

West of the extremity of the San Juan spit, the continuation of the San Juan formation can be traced by a series of islands, the largest of which, Cabras, rises just in the center of the harbor entrance. Small fringing islands of this type, wholly composed of the consolidated lime sand, can be traced along the coast far beyond the western boundary of the district. All the headlands and points that rise above the general level of the coast are likewise composed of this material. Throughout this entire area one finds that the lime sand is characterized by very pronounced cross-bedding of an eolian type. This cross-bedding character is well shown in the face of the promontory below Morro Castle, as well as in numerous other localities to the west. The eolian type of cross-bedding, together with the fact that the San Juan lime sand is almost everywhere associated with modern dune sands, indicates that it was formerly of similar character to the modern dune sands, merely having been subsequently consolidated.

Age.—The exact age of the San Juan formation is uncertain. None of the modern sand dunes shows even the initial stages of consolidation. Indeed, much of the material composing them appears to have been derived from the destruction of the San Juan formation. Moreover, evidence of the final oscillations of the coast is clearly seen in the cliffs of this formation. Large portions of the consolidated sand still remain beneath the sea, so it is evident that the formation was formed before these coastal movements occurred. The formation contains no conclusive faunal evidence of its age. The shell fragments are so minute that none could be determined. Occasional foraminifera occur, but these proved valueless as an index of the age. The formation has been regarded by Berkey as being of Pleistocene age. This conclusion is derived from its general appearance, situation, and close association with modern dune sands of similar composition. Indeed, the upper portion of the formation might possibly be post-Pleistocene in age, though as yet no direct evidence has been found to support this view.

TERTIARY LIMESTONE SERIES

Arecibo Formation.—Underlying the San Juan formation, but separated from it by an extensive erosion interval, is the Arecibo formation, so called by Berkey from its type locality, the town of Arecibo. The formation consists of a series of reef and shell limestones alternating with layers of calcareous shale. Towards the base of the series the shales become predominant. In the vicinity of San Sebastian, in the northwestern part of the island, there is locally developed beneath the Arecibo formation a series of dark, lignitic shales, quite different from the yellowish, calcareous shales that occur in the base of the Arecibo in the San Juan district. No equivalent of these shales could be found in the San Juan district. It is the writer's opinion that the San Sebastian shale is merely a local development, which is not equivalent to the Arecibo, probably being much younger in age (see discussion of age of younger series). At Juana Diaz, on the southern coast, a similar shale member is to be seen. At this point, however, the beds dip as steeply as 36°, according to Berkey (1915, p. 13), which would seem to indicate either that they underlie the Arecibo unconformably or that they have been tilted by later movements. In the San Juan district the Arecibo formation dips 6° to the north. Its maximum thickness is not developed, but towards the western boundary it is at least 500 feet thick. It extends entirely across the district, forming a belt several miles broad on the west, but wedging to a mere line of isolated hills to the east. Much of its former extent has, no doubt, been destroyed by erosion, but it still covers an area many times larger than that occupied by any other single formation.

Along the valley of the Plata, where a good section of the formation can be seen, it consists, in the upper part, of a series of white reef and shell limestones of medium density, with occasional layers of yellow, impure, shaly limestone. The shaly layers increase in number and become essentially light-colored calcareous shales towards the base. The basal shales are of this character in this locality, and are entirely unlike the dark lignitic shales of the San Sebastian region. East of the Plata Valley the base of the formation is not exposed, but there is no evidence that its basal shales differ in composition from those seen in the Plata Valley. The Arecibo formation as a whole appears to be a structural unit. Although it is not uniform in character and composition throughout its vertical extent, yet there are no unconformities or erosional breaks, nor are the variations in general appearance distinct enough to warrant a closer subdivision. Since the formation varies laterally as well as vertically, no specified section would hold true for the entire district, yet as one passes over the formation certain general changes are observable, which are continuous throughout the district. The upper part of the series, as has been noted, is characterized by the predominance of a white or pinkish, chalky, poorly bedded limestone, partly composed of shells. Locally this limestone assumes a hard, dense, and massive character, being quite brittle and ringing when struck by a hammer. It is in this phase of the limestone that the caves, which are so numerous through the limestone belt, are developed. The absence of shaly material makes it readily soluble by underground waters. Locally the upper purer limestones show the characteristics and content of a coral reef. Near Morovis the limestone has such an appearance. Close examination shows that it is composed almost entirely of corals and is even more irregular and massive in structure than the white, chalky limestone. On passing downward through the series, one notes that the bedding becomes better defined and occasional layers of shaly limestone are to be seen. Thin, shaly layers occur even in the highest beds, but they do not become noticeable until better developed towards the base. In the lower portion of the formation the shaly layers become predominant and the massive, purer limestone is entirely lacking. The base of the series is entirely composed of calcareous shales, which are porous, coarse-grained, and well bedded. Such a succession would naturally be expected under the conditions which seem to have prevailed. After submergence the coarser, shaly material would be laid down first near shore, followed by finer shales and shaly limestones, with occasional beds of purer limestone marking temporary periods of clearer waters. Finally, the upper limestone beds and coral reefs would be deposited when clear-water conditions had been established.

Age.—The fauna of the Arecibo formation has never been carefully studied. The fossils are as a rule poorly preserved, nothing remaining but the internal molds which are rarely determinable. The older series was formerly thought to be Paleozoic, but the limestones of the coastal plain were early recognized to be of Tertiary age.

In 1868 Cleve (1883, p. 189) first approximately determined the true age of the older and younger series. He stated "that the island of Porto Rico consists largely of very thick, almost undisturbed limestone beds of Miocene age; but in the interior of the country, around Utuado, rocks similar to the Cretaceous of the Virgin Islands are met with."

In 1898, after a reconnoissance of the island, Hill concluded that the ages of the Tertiary formation were as follows (Hill, 1899*a*, p. 109):

The upper part of the Pepino hills is made up at their surface of a rather hard lime marl full of coralheads, with occasional indurated strata of firm white porous limestones. These rocks (the Pepino formation) are of Miocene age, as determined by Mr. T. Wayland Vaughan from the corals collected by me, similar to certain rocks of Antigua hitherto not known in the geologic sequence of the Greater Antilles. Their tilted position, standing at 1200 feet where they meet the older volcanic mass, testifies to the great geologic movements which have taken place in the West Indies in late geologic time.

Below this limestone, which is at least 100 feet thick, are fossiliferous

greensand marls of undetermined age (Eocene or Oligocene), which in turn rest upon a great thickness of thinly stratified reddish lignitic clays and sands of Eocene age (the Richmond formation) which outcrop near San Sebastian, Guatemala and Mocha on the western end of the island, and near Carolina on the northeast coast.

The *pepino* formation is in part equivalent to the Arecibo. No greensand marls were found in the San Juan district, but these probably correspond to the lower shaly Arecibo. The lignitic clays and sands are what has since been termed the San Sebastian shales. In the older limestone beds of the interior, Hill mentions the occurrence of a Cretaceous fossil (Rudistes), thus confirming Cleve's earlier supposition that the older series was of Cretaceous age.

Through the aid of Dr. William H. Dall, the material which the writer collected in the San Juan district, as well as some of that collected by Dr. Berkey the summer previous, was roughly determined. The material consisted almost entirely of internal molds, some of them being so poorly preserved that even the genus could not be determined. In only one case was a species positively identified, but the accumulation of evidence from quite a number of genera, as well as the general appearance of the forms, made the determination of the ages of the respective members of this series fairly reliable. The forms studied should be divided, according to the locality from which they were collected, into three groups:

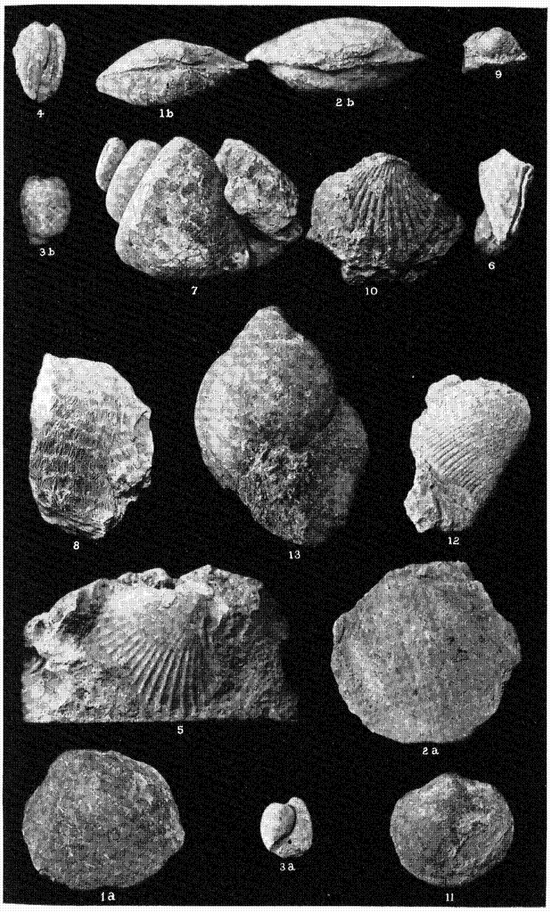
1. Collected by the writer from the base of the Arecibo, near Toa Alta and from the upper part of the same formation near Vega Baja. The forms from these two localities are so much alike that no attempt was made to distinguish between them.

2. Collected by Berkey from the Ponce formation just northwest of Ponce, on the southern coast.

3. Collected by Berkey from the San Sebastian shales (upper portion) near Lares.

The fauna from the Arecibo formation consisted of pelecypods, gastropods, and corals, of which the following genera were identified:

Metris trinitaria (Dall), an index of the Bowden formation, upper Oligocene of Jamaica, found throughout the Arecibo formation in the San Juan district (Pl. II, 1*a*, 1*b*).
Pecten sp. (Pl. II, 5).
Mittha sp. (Pl. II, 2*a*, 2*b*).
Haminea sp. Very abundant (Pl. II, 3*a*, 3*b*).
Cypræa sp. Abundant (Pl. II, 4).
Amauropsis sp.
Conus sp. (Pl. II, 6).
Ampulina sp.



FAUNA OF THE ARECIBO FORMATION

Strombus sp. (Pl. II, 7).
Orbicella aff. cavernosa (Linn.).
Fungid coral, not determinable, but similar to those found in the Oligocene of Antigua, Anguilla and Cuba (Pl. II, 8).
Venus sp. (Pl. II, 9).

Although only the first of these forms may be regarded as even an approximate index, yet the fauna as a whole from its general appearance is regarded by Dall as Upper Oligocene. The occurrence of *Metris trinitaria* at the base as well as in the upper portion of the formation would indicate that the entire Arecibo formation as developed in the San Juan district is Upper Oligocene.

The second group of fossils was collected from the Ponce formation on the southern coast. This material was also so poorly preserved that the genus could not always be determined. This group includes:

Lucina sp.
Lucina sp. small specimens much like forms from the Chattahoochee (Middle Oligocene of the Gulf Coast). (Pl. II, 11.)
Pecten sp. like *P. thetidis* (Sowerby). (Pl. II, 10.)
Fasciolaria (Pl. II, 12).
Amauropsis ocalana (?) similar forms in Ocala limestone, Vicksburg formation, lower Oligocene of the Gulf Coast (Pl. II, 13).

As the relative position of the specimens in the Ponce formation was unknown, the geologic range could not be determined. It is probable that the specimens were collected from the lower portions of the formation. These forms at least indicate that the formation is lower to middle Oligocene and that it is in part practically equivalent to the Arecibo formation of the northern coast.

The third group was collected near Lares from the first shell bed of the San Sebastian shales. This shell bed is located in the upper portion of the shales. It contained:

Venericardia sp.
Ostrea sp.
Conus sp.

None of the forms of this group could be used as an index of its age, but from their general appearance Dall concluded that they were lower Oligocene or possibly upper Eocene. Therefore, since these forms were collected from the upper part of the San Sebastian shales, it is probable that these shales are, in greater part, of lower Oligocene age.

Older Series

Underlying the Arecibo formation is a complex series of sediments of both aqueous and volcanic origin, intimately associated with numerous igneous rocks. It is this complex that Berkey has termed the older series, since it is unconformably separated from all the formations that have been described and is in appearance much older than these strata. The older series outcrops in all parts of the San Juan district south of the inner lowland, an areal extent of roughly two-thirds that of the whole district. The contrast in appearance of the two series is strikingly evident as one passes abruptly from the nearly horizontal beds of the Arecibo formation, showing comparatively simple structure and only minor variations in lateral and vertical extent, to the steeply tilted beds of the older series, where sediments and volcanics of all varieties are dissected by an infinite number of igneous rocks, both intrusive and extrusive, ranging in size from small stringers to major intrusives of many square miles in extent. The subdivision of this intricate series is an exceedingly difficult task. Many of the formations are of such insignificant thickness that they would necessarily have to be grouped to appear on a geologic map of moderate scale. Such grouping would be on an arbitrary basis, for the formations involved do not naturally fall into larger groups. Consequently, only generalized subdivisions have been made on the geologic map, the detail in structure and composition being shown on the accompanying cross-sections (Pl. IV). The rocks of the older series include:

Sediments essentially marine.
Sediments essentially volcanic.
Igneous rocks.

Marine sediments which have been wholly derived from the land through the ordinary processes of erosion and stream transportation are almost unknown in the older series of the district. Practically all of the marine sediments contain volcanic material. Some are composed wholly of volcanic material cemented by carbonates. These sediments have been well assorted and bedded, and often contain marine organisms. The marine sediments—that is, those that show more strongly the characteristics of marine rather than those of volcanic sediments—include limestones, shales, sandstones, and conglomerates. These form only a small percentage of the total thickness of the older series. Occasionally shale and conglomerate beds of 100 yards or more in thickness are to be seen, but the limestone beds are usually less than 100 feet in thickness. With the marine sediments, the extended series of volcanic ashes and tuffs is intimately associated. The ash beds are usually well bedded and a certain degree of assortment can be seen in the material that has been either ejected directly into the sea or subsequently reworked. The tuffs are in greater part massive; others are well bedded and show evidence of marine assortment. The ejectmental material is of all sizes from fine ashes composed of grains less than .01 mm. in diameter to coarse tuffs containing fragments a foot or more in diameter. A continuous series is formed between these two extremes, so that the distinction between ashes and tuffs is merely an arbitrary one based on size of grain. The complexity of the older series is primarily due to large number of igneous rocks that occur closely associated with the sediments. But for the fact that the older series has been so thoroughly dissected by igneous intrusions, its correlation and geologic mapping would be a comparatively simple matter. As it is, however, correct mapping can only be done after detailed study of areas where outcrops are numerous.

RESIDUAL SOIL AND DEPTH OF DECAY

None of the rock formations of the district is free from surface alteration and decay. The older series, longer exposed to the weathering agencies, has been altered to considerable depths and is now almost everywhere covered by a residual soil locally reaching many feet in thickness. Its greatest development is in the inner lowland, where the relief is moderate and stream transportation slower. In this region it is often possible to make excavations of 15 feet in depth without encountering bed-rock. Consequently, in this lowland region outcrops are uncommon and the few that occur are often so highly decomposed that the exact nature of the original rock remains uncertain. Even in the mountainous region where outcrops are plentiful many of them are badly decomposed. The stream beds and recent road cuts afford the best opportunities for the study of extended surfaces of fresh rock. Even though the temperature changes are small, exfoliation is common, producing peculiar concentric arrangements that are strikingly prominent in many of the shales, volcanics, and igneous rocks (Fig. 10).

One of the most striking characteristics of the topography of the oldland is the remarkable stability of the soil mantle. As has already been noted, the soil mantle, remaining practically *in situ*, might well be regarded as an important factor in determining the regularity of the crest line, in many places giving rise to well rounded hill summits that have been regarded as good evidences of peneplanation. Hillsides that slope as steeply as 40° can be cultivated with little or no loss of soil. Knife-edge divides with 40° slopes on either side retain their soil to the very summit and can be ploughed without fear of washing, even after the heaviest rain. Berkey ascribes the causes of the stability of the soil mantle to three factors (1915, p. 35); first, the dense cover of vegetation; second, the small range in daily and annual temperature; and, third, the low content of inert or refractory material, such as quartz, in the rocks whose destruction has furnished the soil. Neither of the first two of these factors would explain the stability of the soil when unprotected, subsequent to cultivation. The third, however, is of vital significance. The igneous rocks as well as the volcanic material are predominantly of andesitic composition, contain large amounts of feldspars and ferromagnesian minerals, and little or no quartz. This on weathering would give rise to an argillaceous soil, essentially a clay, which would be very impervious. A soil of this character would not permit the free circulation of ground water and would not readily be removed and transported by the surface run-off.

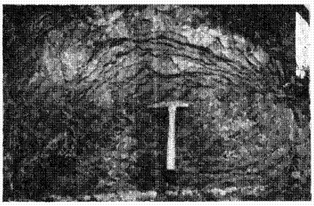


Fig. 10.—*Exfoliation producing concentric arrangements in ash beds south of Bayamon*

The presence of a widespread mantle of such impervious soil might well explain the peculiar absence of meteoric springs throughout the island. True springs are almost unknown in the San Juan district. The so-called springs are merely rivulets of surface water, hidden in their upper courses by dense vegetation. On the southern coast several thermal springs have been found, but it is now believed that these derive their water from magmatic rather than meteoric sources. Whether the imperviousness of the soil is the sole cause of the absence of springs is not yet determined, but it is at least a possible explanation of an otherwise unexplained phenomenon.

COROZAL LIMESTONE

Just southwest of the town of Corozal, as one crosses the river at the ford on the road to Barros, can be seen an outcrop of limestone. Close inspection shows that it is a dense, grayish, brittle rock, comparatively easily dissolved, as is indicated by the few outcrops that rise above the residual soil. Moreover, the limestone is strongly fragmental. It consists of angular limestone fragments, usually less than 2 inches in diameter, and occasional particles of feldspars or ferromagnesian minerals, thoroughly bound together by a calcareous cement. The strike of the bed is roughly N. W.–S. E. Its dip could not be accurately measured, as none of its structural relations could be determined from the few limited outcrops. The dip, however, was judged to be about 15°–20° N. E., since it was apparently conformable with the neighboring types which show approximately that dip. The thickness of the bed is also uncertain, but it is not believed to exceed 100 feet. This limestone can be followed from a mile southeast of Corozal until it plunges below the Tertiary strata to the northwest.

The origin of the fragmental structure, which is characteristic of this limestone, is quite puzzling. An examination of the rock under the microscope shows that the fragments are angular, indicating that they have undergone little or no transportation. Moreover, particles of feldspars and ferromagnesian minerals, which are perfectly fresh, occur with the limestone fragments, so one must also infer that consolidation took place very soon after deposition. It is the writer's belief that the fragmental structure in the limestone is directly due to volcanic agencies, that is, brecciation was caused by volcanic eruptions which probably took place as submarine eruptions through a limestone bed. The shattered limestone was then deposited with intermingled feldspars and ferromagnesian minerals, and the whole cemented by further precipitation of $CaCo_3$ from the sea. The presence of marine organisms in the interstitial $CaCo_3$ makes it evident that the breccia was at least reworked by the sea, and the angularity of the fragments would indicate that the ejectmental material was thrown directly into the sea, or that the eruption itself was submarine. Such an explanation for the origin of the Corozal limestone breccia is not without its defects. The breccia is of considerable extent, yet no traces of the older limestone beds, which were shattered to form the breccia, could be found. It is possible that the locality just south of Corozal, where the brecciated structure is best developed, marked the locus of the eruption, and that in other unexposed portions of the limestone bed the fragmental structure might be lacking. In this case the fragmental material would be practically *in situ,* forming only a brecciated phase in the original limestone bed. If such were the correct interpretation, however, one would expect the breccia to contain a large amount of volcanic material. In reality it is composed almost wholly of fragments of pure limestone, but it occurs closely associated with an extended series of bedded tuffs, indicative that the deposition of the limestone fragments occurred first, followed by that of the tuffaceous material. The Corozal limestone breccia contains abundant foraminifera, which will be described with the other foraminiferal beds under the discussion of the age of the older series.

LA MUDA LIMESTONE

Berkey (1915, p. 22) has described the occurrence of this limestone just east of the San Juan district near La Muda. The same limestone was found by the writer just south of the town of Guaynabo, where it is exposed in a small quarry as one leaves the town by the trail to La Muda. Its strike is N. 48° W. and dip 30° S. W. The thickness of the bed was roughly determined as about 40 feet at this point. To the east, according to Berkey, its thickness materially increases. The formation could be traced along its strike for a distance of about 5 miles. Northwest of Guaynabo it finally disappeared under the heavy residual soil of the inner lowland. To the southeast no outcrops could be found beyond K 26 on the military road. It possibly continues farther, as no careful search was made for it east of the San Juan district.

The Muda limestone shows a fragmental structure similar to that seen in the limestone near Corozal. It is not so striking, however, as that seen in the Corozal limestone, because of closer cementation of the fragmental material which gives rise to a dense, grayish-white limestone, in which the fragmental structure is only betrayed by its somewhat mottled appearance. Microscopic examination of the limestone shows the fragmental structure well defined, as well as small amounts of tuffaceous material and foraminifera scattered throughout the cementing material. The limestone, on the whole, is very similar to the one at Corozal and both, no doubt, have originated in the same manner. The Muda limestone is likewise closely associated with tuffaceous formations.

AGUAS BUENAS LIMESTONES

Two miles south of the town of Aguas Buenas are the great caves of Porto Rico (Dinwiddie, 1899). These are developed along the strike of a limestone bed about 100 feet in thickness. The strike of this bed is roughly N. 50° E. and dip 20° N. W. In the valley of the Bayamon River, to the west of the caves, two limestone beds are to be seen, which are apparently conformable. To the southwest the same beds may again be seen in the valley of the Arroyato River, so the strike was closely determined by plotting the outcrops. The strike of these limestone beds is practically normal to the general strike of the formations throughout most of the district. This pronounced variance in strike indicates that the Aguas Buenas limestone beds are unconformably related to the other beds of the older series. Above the thickest of these two limestones, in which the caves occur, is a coarse conglomeratic tuff which contains fragments of the older limestone. Beneath the limestone are other tuffs, or rather tuffaceous limestones, which resemble Muda limestone, except that they contain larger amounts of tuffaceous material. No foraminifera or other organisms by which the age of these formations could be determined were found, but from the structural relations it would be inferred that the Aguas Buenas limestones lie below and are unconformably separated from the limestones previously described. The structure of this area, however, was not satisfactorily worked out. If the area to the east of the San Juan district is eventually mapped, the relationship of the Aguas Buenas to the Guaynabo limestone may be made clear, for the former should be truncated by the latter in the valley of the Loisa River north of Caguas, provided each continues that distance along its line of strike.

LIMESTONE AT K 29

On the Comerio road, at K 29, a thin bed of impure limestone approximately 5 feet thick occurs interbedded with tuffs and ashes. The limestone contains a large amount of tuffaceous material, being in reality merely a tuff that has been highly carbonated. Although insignificant in size, this limestone bed serves as a typical illustration of the frequent occurrence of limestones partly of volcanic origin, occurring intimately associated with volcanic sediments. Impure limestones were also noted on the trail from Barros to Corozal and in the lower valley of the Barrancas River.

JUAN ASCENCIO CHERT BEDS

Northwest of the Aguas Buenas limestones in the barrio of Juan Ascencio there is a chert bed of considerable thickness, the strike of which is approximately parallel to the limestone beds (N. 50°–60° E.). The dip and thickness of the bed could not be determined from the few scattered outcrops that were found. This chert is a hard, dense, grayish white rock, which consists wholly of an exceedingly fine-grained aggregate of silica, showing an absence of any bedding. Just north of the ridge on which this chert outcrops a siliceous rock showing fine crumpling was discovered. A microscopical examination of this rock proved that it was essentially the same composition as the chert to the south, except that it was quite highly colored in the weathered outcrop by iron oxides. The first of these chert beds probably originated through the silicification of some sedimentary bed, either a limestone or a calcareous shale. The second chert is either a phase of the same formation or a different one, which slumped before solidification. Subsequently the formation was silicified, the intense crumpling due to solifluction being preserved in the secondarily formed chert. Still later, the iron content of the chert has

FIG. 11.—*Crumpling due to solifluction in the Juan Ascencio chert*

been oxidized to limonite and hematite which occur in bands following the crumples, thus serving to emphasize the intensity of the crumpled structure (Fig. 11).

COROZAL JASPER BED

A bed 10 feet thick of Jasper was found in the Corozal River two miles above the town. Only one outcrop was located, from which it appeared that the bed was conformable with the surrounding formations. From the amount of jasper float found in the streams it was inferred that the bed was of considerable extent.

SHALES

One might conclude from a hurried examination of the island that shales are commonly encountered in great extent, but in reality typical shales are only occasionally found. Many of the formations that have been recorded as shales are well-bedded ashes. Indeed, such a gradation exists between the shales and ashes that in some cases one cannot be sure in just which class a given formation belongs. All the shales found in the San Juan district contain some volcanic material. Many of them are composed almost wholly of ashy material. The intimate association of shales and ashes would lead one to infer that either might have been deposited under essentially the same physical conditions, that is, the change from shale to ash accumulation need not mark any noticeable change in the climatic or physical conditions under which they were deposited. Many of the shales are calcareous. Some contain such large quantities of calcareous material that they have formerly been regarded as limestones. Foraminiferal shells occur in some of the shales and occasionally a shale is almost entirely composed of these minute organisms.

The largest accumulation of shale in the district is near the town of Barranquitas, where the aggregate thickness of the shale series must be several thousand feet. These shales are very calcareous, so much so that they were originally regarded as limestones by Hill (1899, p. 108). They represent the calcareous extreme in the shale series, but strictly speaking they should not be termed limestone. The shales extend from about K 40 on the Comerio-Barranquitas road to a point a good distance south of Barranquitas on the road to Aibonito. They form the crest of the island in this vicinity, extending down some distance on either side of the principal divide. The shales contain a good deal of ashy and tuffaceous material and are locally interbedded with ashes and tuffs. The strike of this series is roughly N. W.–S. E., which indicates that it is now simply a phase in the extended series of tuffs and ashes that form the basis of the island.

On the Bayamon-Comerio road, at K 5, there is an outcrop of well stratified shales dipping 45° to the S. W. and apparently striking parallel to the general N. W.–S. E. strike of the region. Fresh specimens can be obtained in the road cut, which when examined under the microscope show an exceedingly fine-grained texture. The material is in such a fine state of subdivision that nothing can be recognized except minute grains of quartz. The rock is very dense, with little or no pore space. Faint banding can be discerned in the hand specimen, but no orientation or bedding is visible under the microscope. Berkey has suggested that these shales may be equivalent to those exposed at Mayaguez and Fajardo. The material from Fajardo, however, is quite different in appearance. It is a light, porous shale, the porosity of which is due to numerous minute cavities which apparently were previously occupied by foraminiferal shells. The leaching of these calcareous organisms has produced a porous structure which is not to be found in the dense shales exposed at K 5. It is possible that this shale may be equivalent to those exposed at Fajardo and Mayaguez, but the writer does not believe that correlation of such widely separated formations can yet be made with any degree of certainty.

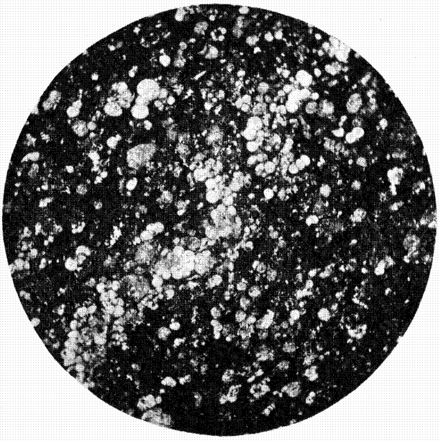


FIG. 12.—*Typical foraminiferal shale*

In a road metal quarry just off the Comerio road, at K 8, there is an exposure of sandstone with included fragments of shale. The shale is dark, dense, and very fine-textured. Its occurrence as angular fragments in the sandstone leads one to infer that it has undergone much the same process of formation as the Corozal limestone breccia. This shale occurrence is insignificant in size, but it is of great interest in that it contains numerous foraminifera, which not only indicate the conditions under which it was deposited, but also give an idea of its age (Fig. 12). The foraminifera will be described in the discussion of the age of the older series.

A somewhat extensive series of shales was discovered in barrio Piñas, southeast of Toa Alta. These shales are well stratified. Their strike is about N. W.–S. E. and dip 20° S. W. On the weathered outcrop the shale appears as a light, porous rock, which is composed of an aggregate of very fine, shaly material with numerous minute cavities, some of which are now filled with quartz and zeolites. These cavities were in part at least originally occupied by foraminiferal shells, which have been leached out and the cavities in part refilled with quartz and zeolites. A large percentage of them, however, is still empty and as a result the shale is exceptionally porous. This shale is very similar to a specimen collected by Berkey from Fajardo, but as yet too little is known about either of the formations to attempt any correlation.

Another shale of similar character occurs in barrio Cuchilla, where the Morovis trail crosses the Unibon River. The shale strikes N. W.–S. E. and dips 30° to the N. E. It contains a great deal of ashy material, together with numerous foraminifera. The formation might equally well be described as a volcanic ash series that has been thoroughly reworked and assorted by the sea.

SANDSTONES

Pure quartz sandstones are almost unknown in Porto Rico. This is due to the fact that so few of the rocks contain quartz in any appreciable quantity. Only the granites and rhyolites, which are comparatively rare in the San Juan district, could afford a source of quartz sand, so it is not surprising that quartz occurs only as an unessential constituent of the sandstone formations. The few sandstones that are found in the district are composed chiefly of tuffaceous material that has been well sorted and somewhat rounded by stream and wave action.

The most interesting occurrence of sandstone that was found is to be seen in the quarry at K 8 on the Comerio road. It is a dense, medium-grained, dark greenish rock showing good bedding and containing numerous inclusions of shales. The formation dips 42° to the S. E. and apparently strikes N. 65° E. This is nearly normal to the general strike of the district, and agrees more closely to the limestones south of Aguas Buenas than with the conglomerates and tuffs just to the south. It is the writer's opinion that this sandstone is of limited extent, representing an ancient delta or fan. Such a theory of its origin would explain its abnormal strike. The sandstone is composed of a granular aggregate of ferromagnesian minerals, feldspars, and occasional grains of quartz. This material is undoubtedly of volcanic origin. In other words, this sandstone is merely a fine-grained tuff, the constituents of which have been somewhat rounded and assorted in being transported from the point of eruption to the point of accumulation. The angularity of many of the grains, and especially of the shaly fragments, leads one to infer that the material has not undergone extended transportation.

In barrio Padilla, where the Corozal-Morovis trail crosses Piedras Muellas Creek, there is an interesting occurrence of arkose sandstone. The sandstone is a medium to coarse-grained, greenish rock, consisting of an aggregate of feldspar and quartz grains with interstitial chlorite. The feldspar grains, which are predominantly plagioclase, are somewhat murky, but no actual decomposition has yet set in. This sandstone also is essentially a volcanic tuff. The presence of such a large percentage of unaltered and angular feldspar grains indicates that the material was deposited almost at its source.

A fine-grained, reddish quartzite was discovered in barrio Santa Olaya, just south of Helechal Peak. This was the only sedimentary rock found in the district that consists chiefly of quartz. It appears to have been first deposited as a fairly pure quartz sand. Later this sandstone was further silicified, probably under some degree of pressure, as a faint orientation of the grains can now be seen. The quartzite apparently does not represent the product of regional or contact metamorphism, but is merely a highly silicified sandstone.

CONGLOMERATES

Conglomerate beds are frequently found in the older series. In aggregate they form a large percentage of its total thickness. They are, however, much more abundant on the southern than on the northern side of the island. The conglomerates occur in belts trending N. W.–S. E. or parallel to the major tuff series, which apparently form the backbone of the island. It has been suggested that the conglomerate belts represent breaks in the older series, separating it into disconformable or possibly unconformable groups.

The only important conglomerate that was found in the San Juan district can be best seen in the cuts along the Comerio road at K 12-13. This is a boulder conglomerate, which must be over 500 feet thick, though there are not enough outcrops to determine its exact thickness. Its strike is about N. W.–S. E. The material of which this conglomerate is composed is almost entirely volcanic in origin. The boulders are chiefly igneous rocks, especially andesite porphyries. Occasional boulders of older tuffs were also found. It is possible that this conglomerate was formed by the erosion of some older tuff formation, but it is more probable that it represents an accumulation of tuffaceous material directly derived from volcanic sources, and rounded by stream action during transportation to its point of deposition. This view is supported by the fact that the material is exceedingly poorly assorted. Large boulders and very fine tuffaceous material are intermingled in all proportions. If this conglomerate were produced through the ordinary agencies of stream erosion, some assortment of the material would be expected.

The conglomerates are in many places closely associated with igneous activity. At K 12.5 on the Comerio road a felsitic dike, 10 feet thick, intrudes the conglomerate (Fig. 11). At other points it is intruded by larger igneous bodies. Northwest of Aguas Buenas, in the bed of the Bayamon River, there is a conglomerate which appears to have been saturated by the still molten magma, for boulders can now be seen in a crystalline matrix. The phenomenon has been reported by Berkey as occurring in some of the conglomerates on the southern side of the island. The extensive series of Muda tuffs also shows conglomeratic phases, but as this formation is essentially a tuff, it will be described below under that head.

TUFFS

The conglomerate formations in many places grade imperceptibly into bedded and massive tuffs, which constitute the most abundant rock type that is found on the island. They occur in an extensive series of great variety, forming the most dominant structural feature of the older series. The tuffs for the most part are massive in structural habit. Bedded tuffs, however, are frequently encountered which have been worked over and somewhat assorted during deposition. The finer material shows better bedded structure, and the finest ashy material is often perfectly bedded.

The tuffaceous material shows a good deal of variety in composition. For the most part, however, they are composed of fragments of igneous rocks, predominantly the porphyritic andesitic type, so that this variety may be termed andesitic tuffs; yet a close examination of a large amount of the volcanic material reveals the fact that practically all the rock types of the older series are represented. Fragments of all the important igneous rock types were found, as well as occasional fragments of older tuffs. At K 7.5, on the Comerio road, a tuff containing numerous fragments of limestone was found. The limestone fragments are dissolved out on the weathered surface, giving the tuff a pitted aspect. Near this point is the tuffaceous sandstone which contains large fragments of shale. It is evident, therefore, that the tuffaceous material, though of general andesitic composition, contains a large variety of rock types of different composition, some of which locally constitute large portions of the entire tuff formation.

The composition of the tuffs is often locally modified by the intrusion of igneous rocks. The cutting of tuffs by igneous dikes and larger intrusions usually has little effect upon them, but it often happens that the magma, while still molten, has permeated the tuff and there crystallized, forming a tuff with a crystalline matrix. In consequence, it is often exceedingly difficult to distinguish between a tuff that has been invaded by an igneous magma and a true intrusive igneous body that contains numerous inclusions.

The tuffaceous rocks are especially liable to alteration and modification. As they are usually poorly consolidated when first deposited, they form mediums readily permeated by aqueous solutions of all kinds. Consequently, many of the tuffs have been so highly altered that their original structure is almost wholly obscured. The commonest process that has modified the tuffaceous rocks is a thorough silicification, which changes the formerly non-resistant tuff to an indurated, exceedingly resistant rock. Silicified tuffs of this character underlie the most pronounced topographic features of the island. In the San Juan district it was noted that they formed both Torrecilla and Helechal peaks, the two most prominent features in the topography of the whole district. The latter peak rises abruptly from a rolling surface of about 500–800 feet in altitude to the height of 1800 feet.

It would be impractical to describe individually the numerous tuffaceous formations of the district. They occur in N. W.–S. E. belts and are especially well developed in the southwest portion of the district. In this region they form practically all the country rock, with the exception of the tuffaceous shales and igneous intrusives. An excellent development of tuffs can be seen along the entire stretch of road from Barranquitas to Barros. In the vicinity of Comerio they are also well developed. The Muda tuffs represent the most extensive series found in the northeastern portion of the district. These also strike N. W.–S. E. and their aggregate thickness is probably several thousand feet. They are well exposed in the bed of the Guaynabo River, and also along the Guaynabo-Muda-Aguas Buenas trail.

AGE

The distinctly older appearance of the older series, as well as its highly tilted position, leads one to infer that an erosion interval of some magnitude separated it from the overlying coastal plain. Moreover, the evidence of extraordinary igneous activity throughout the deposition of the older series and its complete absence in all the subsequent formations indicate either an extended time interval or a rather sudden change in physical conditions. It was the consideration of these points that led the first observers to regard the older series as probably Paleozoic in age. This idea, however, was soon abandoned; for, as above noted, Cleve, in 1868, suggested that the formations of the older series much resembled the Cretaceous of the neighboring islands. Hill later confirmed this view

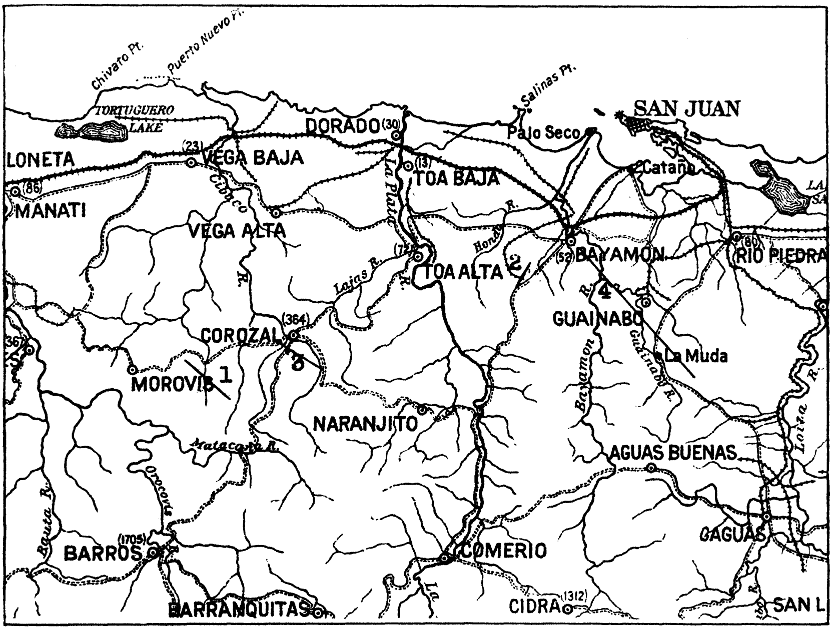


FIG. 13.—*Chart showing the relative positions of the principal foraminiferal beds*

1. Unibon shale.
2. Shale inclusions in the sandstone at K 8, Comerio Road.
3. Corozal limestone.
4. Muda limestone.

by the discovery of the Cretaceous fossil Rudistes in a grayish limestone bed that strikes from Cabo Rojo eastward to about 15 kilometers north of Ponce on the Adjuntas road.

The formations of the older series of the San Juan district are, with the exception of certain foraminifera, almost universally unfossiliferous. The few other forms that have been found come without exception from the southern side of the island. In the upper part of the series, in the San Juan district, the beds of foraminiferal shales and limestones which have been mentioned serve to throw some light on the age of the series.

On the accompanying chart (Fig. 13) the four most important of these formations have been indicated numerically:

1. *Unibon shale,* at juncture of the Morovis trail and Unibon River. Strike, N. W.–S. E. Dip, 30° N. E.

2. *Shale* fragments in *sandstone at K 8,* Comerio road. Strike, N. 65° E. Dip, 42° S. E.

3. *Corozal limestone breccia.* Strike, N. W.–S. E. Dip, 15–20° N. E. (?).

4. *Muda limestone.* Strike, N. W.–S. E. Dip, 30° S. W.

The Unibon shales show typical chalk foraminifera (Upper Cretaceous). Since only sections of the forms are obtainable, it was often impossible definitely to determine the species. Through the assistance of Dr. R. M. Bagg, of Appleton, Wisconsin, the writer was able to recognize a sufficient number to leave little doubt as to the age of the formation. The following forms were identified:

Globigerina cretacea, d'Orbigny[3] (Pl. III, 1).
Globigerina bulloides, d'Orbigny.[4]
Truncatulina lobatula, Walker and Jacob[5] (Pl. III, 2).
Nodosaria communis, d'Orbigny[6] (Pl. III, 4).
Nodosaria farcimen, Soldani.[7]
Textularia sp.

While none of these forms is a conclusive index of the chalk horizon, yet considering their abundance and general aspect, they could hardly be regarded older than Upper Cretaceous.

A foraminiferal fauna very similar to this was found in the shale at K 8. Its forms are even more like those characteristic of the English chalks. This fauna comprises:

Globigerina cretacea
Globigerina bulloides
Orbulina universa
Truncatulina lobatula
Textularia globulosa (Pl. III, 3)
and a few Rotaline forms.

The foraminifera of the two limestone beds are essentially the same. They are characterized by numerous Miliolidæ, as well as Rotaline and Textularia-like forms. In these limestones were found:

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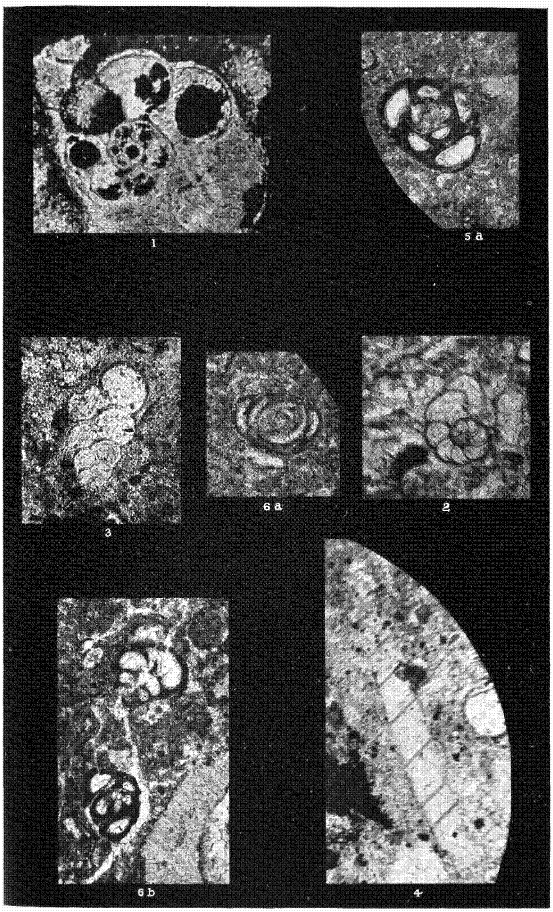
[3] Report of *Challenger* Expedition. IX, p. 596, Pl. LXXXII, 11*a*-*c*.
[4] Op. cit., p. 593, Pl. LXXIX, 1-7.
[5] Op. cit., p. 660, Pls. XCII, 10; XCIII, 1, 4, 5.
[6] Op. cit., p. 504, Pl. LXII, 9-20.
[7] Op. cit., p. 498, Pl. LXII, 17-18.



FORAMINIFERA

Miliolina seminulum, Linné (Pl. III, *5a, 6a, 6b*).
Nonionina sp.
Pulvinulina sp.
Textularia sp.
Truncatulina lobatula (?).

Though few species could be definitely determined, owing to the altered condition of the limestones, yet the general appearance of the material under the microscope was that of a typical Miliolina limestone, which suggests lower Tertiary age. These limestones, however, lie unconformably below the Arecibo formation, which is not later than Oligocene. From these species one may be forced to conclude that the upper part of the older series of the San Juan district is of Eocene age.

The lower members of the older series are wholly unfossiliferous. It is the writer's opinion, however, that the older series as expressed in this district is entirely post-Jurassic and probably post-Comanchic in age.

SUMMARY

The material composing the limestones, shales, and conglomerates, as well as the tuffs and ashes of the older series, is in great part derived from volcanic sources or through volcanic agencies.

The discordance in strike of some of the limestone beds, especially those near Aguas Buenas, indicates the presence of an unconformity in the older series, the limestones being older than the rest of the series. The conglomerate belt that extends across part of the district may also be taken as an indication of another break in the series.

The low content of inert refractory material in the rocks of the older series gives rise to an impervious soil that clings tenaciously to exceptionally steep grades.

Many of the formations show the effects of subsequent alteration. The tuffs are especially liable to the attack of modifying processes which have resulted in many cases in their being altered to extremely indurated and resistant rocks.

The formations of the older series are everywhere associated with igneous activity, expressed either as intrusions or by the invasion of liquid magma forming fragmental rocks with crystalline matrices.

The age of the older series is regarded as Cretaceous in its greater part. The uppermost portion is doubtless Eocene, and it is probable that the lower part is Comanchic in age.

IGNEOUS ROCKS

Modes of Occurrence

In all parts of the island the older series is characterized by an abundance of igneous rocks, showing a variety of forms and complex structural relations. After the deposition of the coastal plain strata, igneous activity apparently ceased, for in these formations no igneous rocks of any kind are found. It is possible, but improbable, that post-Oligocene intrusion has occurred in the older series of the interior, which has not affected the limestone strata of the coast. The modes of occurrence of the ignous bodies of the district are somewhat variable. Extrusive and intrusive rocks occur as lava flows, sills, dikes, and irregular intrusive masses, varying in complexity from a simple flow or single dike to an interrelated series of complex intrusives so intimately associated that accurate and complete differentiation is often wholly impossible.

LAVAS

The occurrence of lava flows in the San Juan district is comparatively rare. Several examples of such flows are to be found on the Comerio-Barranquitas road near K 35. At this point the lava flows occur associated with bedded and massive tuffs, dipping at steep angles. The lavas often show a vesicular habit which distinguishes them from the sill-like intrusives. In this locality and near the Bairoa River just north of Aguas Buenas strongly vesicular lavas are found. The vesicules are often filled with quartz, calcite, and zeolites, forming a fairly well developed amygdaloidal structure. The liquid lava occasionally seems either to have permeated the underlying ash and tuff beds, or to have been saturated with ashy and tuffaceous ejectments, forming a rock of tuffaceous appearance but of crystalline groundmass, which often proves very confusing to the geologist. The lavas found were almost invariably andesitic in composition.

SILLS

The most abundant of the simpler forms assumed by the igneous rocks are the intrusive sheets or sills. These are conformably intruded in the ashes and tuffs which are now tilted at steep angles or locally folded. The individual sills are usually thin, being often less than a foot thick and rarely more than a few feet in thickness, yet they are so numerous that they add materially to the total thickness of the formation in which they occur (Fig. 14). Except where modified by subsequent disturbance, the sills are almost perfect in form, and often show so indistinctly their intrusive nature that on weathering they are hardly distinguishable from the neighboring strata. Incorporation of tuffaceous material by the intruding magma frequently occurs, giving the sill a decidedly fragmental structure. Should such a sill occur in a series of tuffs composed of similar fragmental material, it might readily be entirely overlooked.

DIKES

Intrusives assuming the form of dikes are not uncommon in the district. Many of the existing dikes were probably overlooked or mistaken for

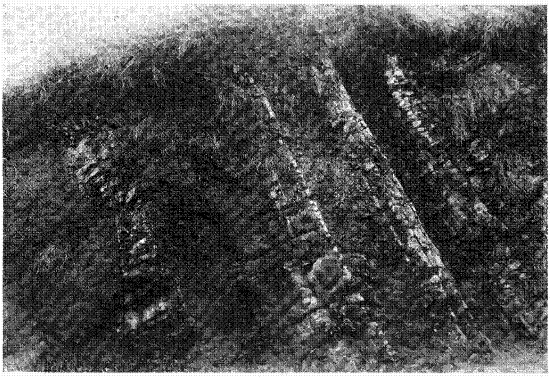


FIG. 14.—*Diorite porphyry sills intruded between layers of shales and ashes at K 20, Comerio Road*

The light-streaked and banded layers are shales and ashes; the massive portions, best seen on the left side of the print, are sills. Photographed by C. P. Berkey.

more massive intrusives, where the outcrop showed none of the structural relations. It sometimes happens that a dike cutting some non-resistant formations such as the conglomerate at K 12.5 Comerio road, now stands out as a plainly visible topographic feature (Fig. 15). Such cases, however, are rare, for a dike intruding an igneous body of similar composition and resistance would only be revealed by a careful, detailed study of suitable exposures. Good exposures are to be had along the carreteras and principal stream beds; elsewhere the residual soil is so widespread

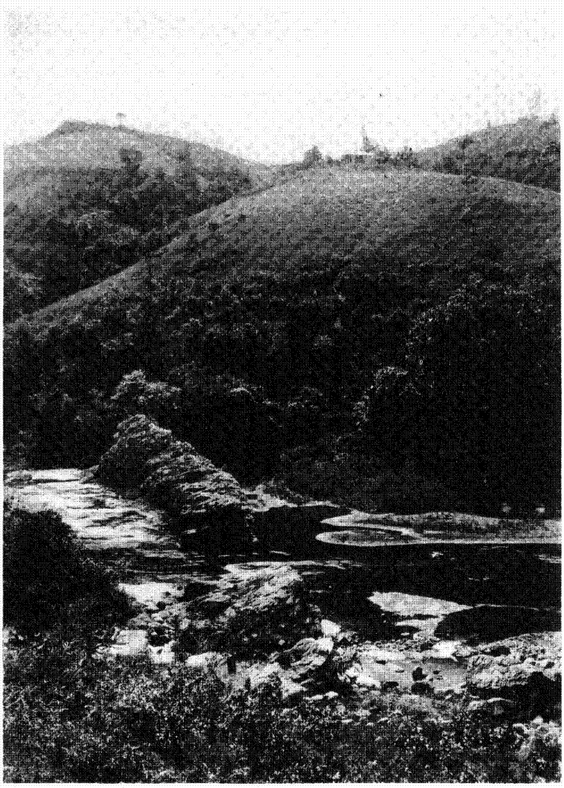


FIG. 15.—*Faulted trachyte dike crossing the La Plata River*

This dike is intruded in the conglomerate that crosses the Comerio Road at K 12-13.

that it is usually impossible to determine the underlying structure. The dikes vary in size from narrow stringers and apophyses from neighboring intrusives to massive structures many feet in width. The dike rocks are usually of felsitic texture. No relation between the coarseness of texture and the size of the dike could be discovered. The smallest dikes sometimes showed micrograinitoid or even granitoid texture. The texture seemed rather to depend upon the conditions of intrusion than upon the size of the intrusives.

STOCKS AND BOSSES

The majority of the intrusive masses of the district should be classified as stocks and bosses, the term stock including all small batholithic intrusions, and boss being restricted to those stocks roughly circular in ground plan. It is often difficult to make this distinction unless the boundaries of the intrusive are accurately known. The stocks of the San Juan district are as a rule small. In the bed of the Bayamon River a perfectly formed stock not measuring over 20 feet in diameter was found. On the other hand, southwest of Morovis a large intrusive of granite covers an area of several square miles, and in other portions of the island intrusives 10–12 miles in diameter have been found. Large intrusives, however, are rare in the San Juan district. Only two, covering an area of over a square mile, were located. The majority were less than 100–200 yards in diameter. Fragmental inclusions are characteristic of all the stocks of the district. In the larger ones these inclusions may be of large dimensions. In the granite southwest of Morovis inclusions of the adjacent tuffs measuring many feet in diameter were found. It frequently happens that the invading magma incorporates quantities of tuffaceous material. Such a rock, after consolidation, will so resemble a massive tuff that it will often be confused with one. Several specimens collected from supposedly massive tuffs proved after microscopic examination to have a crystalline structure. The variation from the massive crystalline to the tuffaceous phase of an intrusive may be so gradual that no line of demarcation can be made, or so sudden that it appears as if the boundary of the intrusive has been passed and that the tuffaceous phase of the intrusive is a separate formation of massive tuff.

TEXTURE

Rocks of felsitic texture proved the most abundant in the district. Almost all of these showed porphyritic habit, often not discernible in the hand specimen but evident from microscopic examination. An evidence of the almost universal tendency toward the porphyritic texture in the felsitic rocks is that many of them show three generations of crystals more or less perfectly developed. The larger phenocrysts occur in a matrix of smaller phenocrysts and a felsitic groundmass (Fig. 23). Though the rocks are predominantly porphyries of felsitic texture, yet quite a variety of textures and structures are encountered in a study of much material. No true glasses were found, but a rock of vitrophyric texture, in which the glassy groundmass made up most of its bulk, was seen (Fig. 16).

FIG. 16.—*Photomicrograph of vitrophyr occurring north of Cidra*
E. Feldspar phenocrysts altered to epidote. C. Chloritized glassy groundmass.

Another specimen shows a peculiar radial, felt-like structure much resembling that of a natural slag (Fig. 22). Microgranitoid texture is common among the larger intrusives. Rocks of granitoid texture are abundant and widespread, but none of the coarser granitoid rocks showed pronounced porphyritic texture.

COMPOSITION

The igneous rocks of the district are fairly uniform in composition. The predominant type is an andesitic, or the coarser-grained dioritic equivalent. The widespread occurrence of andesitic types is noticeable in the fragmental material constituting the ashes and tuff as well as in the igneous rocks *in situ*. Many of the tuffs are wholly made up of andesitic material. However, when one is afforded the opportunity of examining a variety of material, such as is to be seen in the boulder beds of any of the streams that drain a large area of the older series, one soon realizes that considerable variety in composition is represented. In examining petrographically the material brought from the district, the writer found almost every variety of the igneous rocks from acid to medium composition. Basic rocks, however, were uncommon; basalts and olivine basalts being rare, and typical gabbros or more basic rocks almost unknown.

As almost every square foot of the older series is intruded or modified by igneous rocks, it would obviously be impossible to attempt to describe each individual intrusive or to locate them geographically. Accordingly, they have been grouped on a basis of composition, and the more important members of each group will be briefly discussed. The gradations from one group into the next usually proceeds so uniformly and gradually that the introduction of several intermediate groups is unnecessary. A comprehensive classification of the igneous rocks of the district should include all of the following varieties:

Vitrophyrs	Trachytes
Rhyolites	Syenites
Granites	Latites or Trachy-andesites
Quartz latites and Rhyo-andesites	Monzonites
Quartz monzonites	Andesites
Granodiorites	Diorites
Dacites	Basalts
Quartz diorites	Olivine basalts

VITROPHYRS

These rocks are of rare occurrence in the San Juan district. On the trail between Aguas Buenas and Cidra, about a mile north of Cidra, there is a prominent outcrop of a rock which proved on microscopic examination to be a vesicular vitrophyr. Phenocrysts have for the most part been altered or completely weathered out, and the cavities since filled with epidote, chlorite, and quartz. The glassy groundmass is still fairly fresh, but there seems to be some indications of incipient devitrification. The rock shows a slightly fragmental structure and occasionally the outlines of former large crystals are to be seen, but these are believed to have been inclusions rather than original constituents of the rock (Fig. 16).

RHYOLITES

Rocks of rhyolitic composition are also quite rare. The best example was seen northeast of La Torrecilla in barrio Barrancas. This is a porphyritic rhyolite with phenocrysts of quartz, orthoclase, and mica in a fine-grained acidic groundmass. The whole rock has subsequently been highly sericitized (Fig. 16*a*). In the Bayamon Valley just east of Helechal Peak a number of acidic intrusives were found, among which were several rhyolite porphyries.

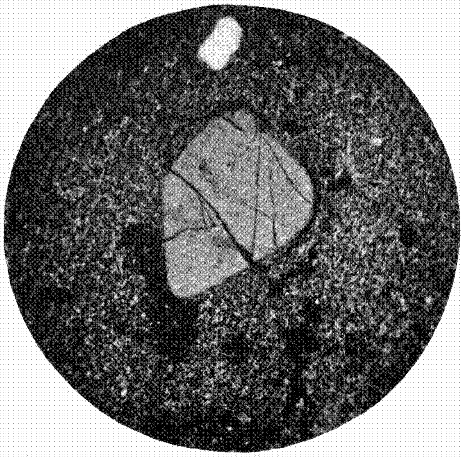


FIG. 16*a*.—*Rhyolite porphyry*

Large phenocryst of quartz in center, crossed nicols.

GRANITES

Granitic intrusives are widespread and fairly abundant. All of those studied microscopically proved to be rich in soda feldspar, or that variety known as soda granites. The large intrusive mass which covers an area of several square miles southwest of Morovis is of this composition. The rock is light-colored, with scattered patches of the darker ferromagnesian minerals, and coarsely crystalline in texture. It is composed chiefly of quartz, plagioclase, orthoclase, and hornblende, with scattered titanite.

magnetite, and apatite crystals. This intrusive is especially interesting in that it shows a well-developed poikilitic structure. The plagioclase, hornblende, and titanite crystals occur in the orthoclase, which shows no crystal outline. The orthoclase apparently crystallized last with the quartz, both now occurring as interstitial material (Fig. 17). Minute veinlets of secondary hornblende and actinolite occasionally traverse the rock for short distances. Minor copper impregnations were seen at several points, but these occurrences were of no economic importance. A

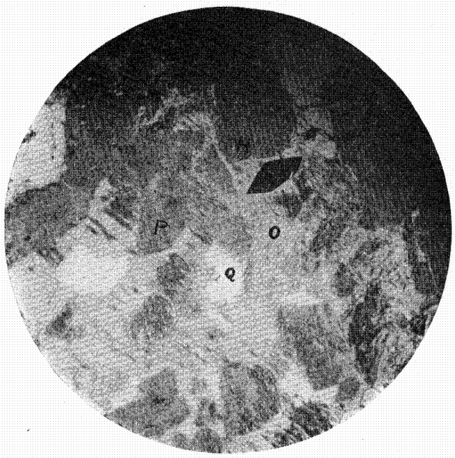


FIG. 17.—*Soda granite, showing poikilitic structure*

Phenocrysts of plagioclase, hornblende and titanite in orthoclase and quartz. P. Plagioclase. H. Hornblende. T. Titanite. O. Orthoclase. Q. Quartz.

smaller intrusive of similar composition was found on the mountain slope just south of Naranjito (Fig. 18).

QUARTZ LATITES AND RHYO-ANDESITES

In the felsitic rocks where the individual crystals that constitute the groundmass are too small to be accurately determined, the finer distinction in variety cannot be made. Accordingly, the quartz latite and rhyo-andesites, the felsitic equivalents of the quartz monzonite and granodiorites, respectively, are grouped together. Felsitic rocks of this composition are occasionally found. They consist chiefly of quartz and lime-soda feldspar with notable amounts of potash feldspar and subordinate ferromagnesian minerals. Such rocks are also known as dellenites.[8] A typical example of this group is to be found north of Aguas Buenas. The specimens collected consisted of phenocrysts of quartz, feldspar, predominantly the lime-soda variety, and mica, in a fine-grained groundmass.

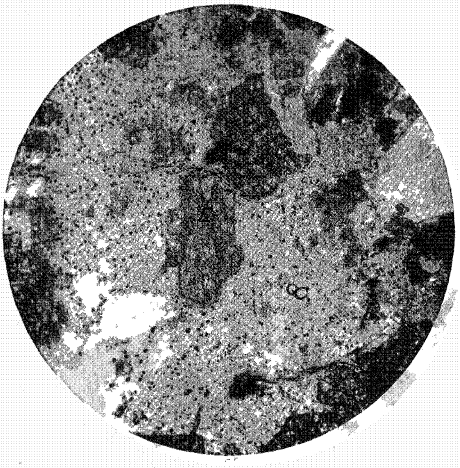


FIG. 18.—*Soda granite occurring south of Naranjito*

P. Plagioclase (oligoclase). Q. Quartz. M. Magnetite. S. Sericitized feldspar.

This rock occurs associated with other acidic rocks of almost the same composition, and is doubtless merely a differentiated phase of some larger intrusive.

QUARTZ MONZONITES

These are granitoid rocks consisting chiefly of quartz, medium plagioclase, with considerable orthoclase. With these may occur biotite, hornblende, or pyroxene. They are the closest associates of the granites and

[8] Brögger, 1895.

are often classed as such. They differ only slightly from the soda-granites already described, yet they serve to express a somewhat more alkaline step in the continuous series of intergrading varieties that is characteristic of the igneous rocks of the district. A small intrusive of this variety was found in the bed at the Bayamon River in barrio Sonadora. It is a massive granitoid rock of bluish color, made up of quartz plagioclase, orthoclase, and hornblende. The rock has subsequently been somewhat sericitized and carbonated.

GRANODIORITES

The granodiorites are granitoid rocks of nearly the same composition as the quartz monzonites. They contain less potash feldspar than the latter and more of the lime-soda varieties, that is, they are intermediate in composition between the quartz monzonites and quartz diorites. Southwest of Naranjito, in barrio Cedro Abajo, a fairly large intrusive of this composition was encountered. From a casual examination it would be classed as a granite, but under the microscope it is seen to consist chiefly of quartz and plagioclase (oligoclase) with subordinate orthoclase and hornblende and scattered crystals of magnetite, titanite, and apatite. This intrusive shows striking mineralization, which apparently took place in two stages; first, the introduction of additional magnetite, then sulphide solutions entered and deposited pyrite around the magnetite grains.

DACITES

Those rocks of andesitic composition which contain appreciable amounts of quartz are here grouped as dacites or quartz andesites. This variety is rare and only one typical example was found among the rocks studied, which occurred on the military road near La Muda. It is a porphyritic dacite, consisting essentially of phenocrysts of plagioclase (oligoclase), biotite, and quartz. All the constituents have been somewhat altered, especially the biotite, which has been replaced by chlorite, carbonates, and bleached mica. The intrusion has taken place through a series of coarse tuffs, and some of this material has been incorporated into the intrusive itself, giving it a fragmental structure.

QUARTZ DIORITES

The quartz diorites are more abundant than their felsitic equivalents, the dacites. Two miles southwest of Morovis an intrusion of this variety occurs in the large intrusion of soda-granite already described. Another sericite, chlorite, epidote, and calcite. Kaolin, iron oxides, and leucoxene also frequently occur in appreciable quantities. Since the latites are not distinguishable from the andesites in the field, no attempt will be made to list their occurrence. Many of them were there simply designated as andesites, and no specimens were collected for microscopic study (Fig. 21).

MONZONITES

The monzonites, or granitoid equivalents of the latites, are much less widely distributed. Many of the intrusives simply termed diorite in the

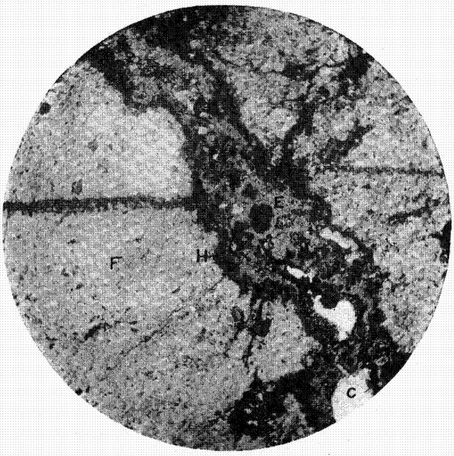


FIG. 21.—*Latite, showing veins filled with epidote and iron oxides*

F. Feldspars. E. Epidote. H. Hematite. C. Cavity.

field could probably have been referred to this group had they been examined microscopically. Two intrusives of this variety are to be found on the Comerio-Barranquitas road at K 35.5 and K 39.7. They are micrograntoid rocks, consisting of lath-shaped orthoclase and plagioclase crystals arranged in a coarse, felt-like aggregate with subordinate amounts of pyroxene and hornblende.

ANDESITES

The andesites are the most abundant as well as the most widespread of the igneous rocks. They are usually of porphyritic texture and assume all the structural forms that are represented in the district. The essential constituents are plagioclase of medium composition (oligoclase and andesine), and lesser amounts of orthoclase, pyroxene (usually diopside), and hornblende. Certain varieties of the andesite porphyries in which

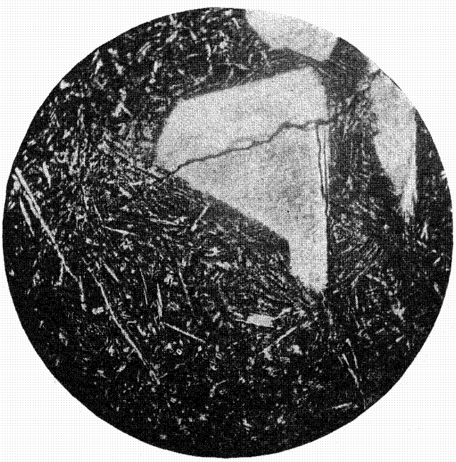


FIG. 22.—*An andesite porphyry with large phenocrysts of plagioclase surrounded by a groundmass, showing the structure of a natural slag*

the phenocrysts were chiefly feldspar showed a spotted appearance due to the white feldspar phenocrysts in a dark groundmass. Other varieties in which the phenocrysts were composed chiefly of the ferromagnesian minerals had a darker and more basic appearance. Diopside is much the most abundant of the ferromagnesian minerals; hornblende occurs infrequently, and biotite quite rarely. The present mineral constituents of many of the andesites are largely the result of secondary alteration. Some of them contain such large quantities of secondary carbonates that they effervesce slightly in cold dilute acid. Sericite, chlorite, kaolin, epidote, iron oxides, and quartz commonly occur and occasionally constitute a large percentage of the entire mass of the rock. A few of the more striking members of this group are herewith briefly described. At K 17 on the Comerio road a porphyritic hornblende andesite was found. Secondary alteration had greatly changed the original constituents of the rock. The original outlines of the hornblende phenocrysts could be clearly seen, though the hornblende itself had been changed into sericite, calcite, and chlorite. Another hornblende andesite was found at K 41 on

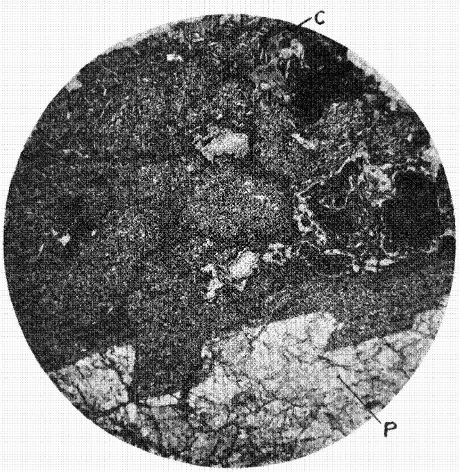


FIG. 23.—*Andesite porphyry impregnated with chrysocolla. Barrio Pasto*
P. Plagioclase. C. Chrysocolla.

the Military road, south of Caguas. On the Barros-Corozal trail an epidotized andesite porphyry was found. The rock consisted chiefly of epidote and plagioclase. Three distinct generations of crystals were shown. Another epidotized andesite is located just north of Aguas Buenas near the river Bairoa. This is an amygdaloidal andesite with epidote filling the cavities. On the Comerio road at K 5 an andesite porphyry with a remarkable radiating, felt-like groundmass was discovered. Its structure resembles very much that of a natural slag (Fig. 22).

One of the two largest intrusives in the district is an andesite porphyry. It occurs just south of the Orocovis River on the Morovis-Barros road, extending out of the district on the west. Large phenocrysts of light-colored feldspars in the dark groundmass gives the rock a spotted appearance. It is in this rock that the copper prospects of barrio Pasto occur. From microscopic examination it is seen that this rock also shows three generations of crystal growth. Large phenocrysts occur in a porphyritic matrix of smaller, lathe-shaped feldspars and a felsitic groundmass (Fig. 23).

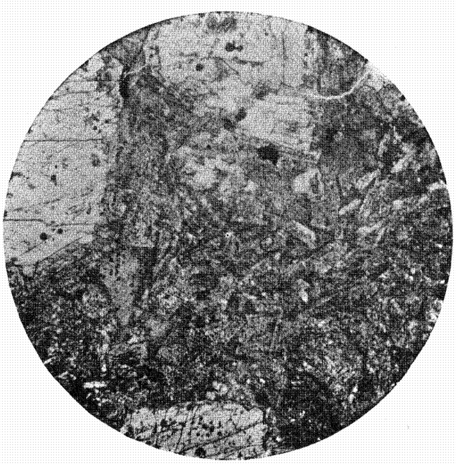


FIG. 24.—*Diorite porphyry with pyroxene phenocrysts in a groundmass of lath-shaped feldspars (plagioclase)*

DIORITES

Intrusives of dioritic composition are of frequent occurrence, though not so widespread as the andesites. They are as a rule dense, massive, dark bluish rocks often showing large phenocrysts of pyroxene. They consist chiefly of plagioclase feldspar and pyroxene, with subordinate amounts of orthoclase and hornblende. Diopside is much more abundant than augite. Many of the diorites show fragmental structure. Some of them have incorporated so much fragmental material that they may be mistaken for tuffs. The diorites are uniform in composition and general appearance, and when not modified by inclusions are readily recognized in the field (Fig. 24).

BASALTS

Many of the andesitic rocks might be mistaken for basalts by the casual observer, but typical basalts are decidedly rare. Basic varieties of ande-

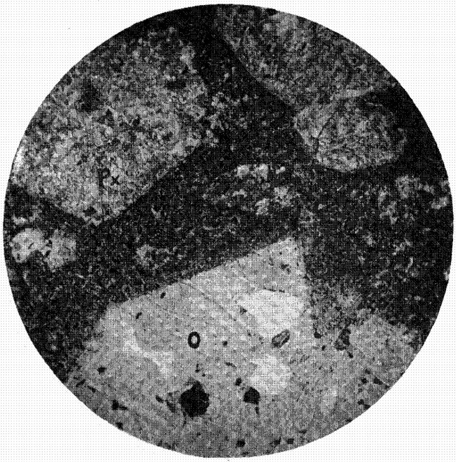


FIG. 25.—*Olivine basalt*

O. Altered olivine. Px. Pyroxene.

sites which have been called basalts are more common, but all of these rocks, though basaltic in appearance, show only the intermediate varieties of the plagioclase feldspars. At K 12, on the Comerio road, an amygdaloidal porphyritic rock of basaltic appearance intrudes the tuffs. It is composed of lath-shaped phenocrysts of plagioclase in a dark, basic groundmass of ferromagnesian minerals. The vesicular cavities have been filled with quartz and zeolite. While this rock has a typical basaltic appearance, the plagioclase shows low extinction angles (less than 10°).

which indicate that only the acidic varieties are present. Hence the rock should correctly be classed as a basic andesite.

OLIVINE BASALTS

Only one olivine basalt was found in the material collected for microscopic study. This was an intrusive body about two miles south of Corozal. It is of porphyritic texture, consisting of phenocrysts of olivine, and, to much less extent, plagioclase, in a groundmass composed chiefly of plagioclase and magnetite. The olivine was largely altered to serpentine and chlorite. The feldspars have likewise been so chloritized that their exact composition was indeterminable (Fig. 25).

No rocks of gabbroic or more basic composition were found in the district.

SUMMARY

No definite conclusions can yet be drawn as to the exact range in composition of the igneous rocks of the district or their relative abundance, for by no means all of the igneous bodies have yet been located. In the present survey all of the larger instrusives were located, and many of the smaller ones, where well exposed in stream beds and along the carreteras. There remains undiscovered a large number of minor igneous masses either covered by the residual soil or located between the traverses that were made. Sufficient material has been collected and studied, however, to give an accurate idea of the general range in composition and form of the igneous bodies. In the preceding pages minor differences and variations in composition have been unduly emphasized in order to give a correct idea of the relative range in composition, and the continuous gradation that exists between the more acid and basic varieties. The usage of many of the varietal terms that have been introduced here would be inadvisable for ordinary field work and general description.

The petrographic study of the igneous rocks of the San Juan district can be summarized as follows:

(1) The structural forms assumed by the igneous rocks of the district are of various sizes and shapes. The sills and stocks occur most commonly, while lava flows are rare.

(2) The igneous rocks are predominantly felsitic in texture. No relation of texture to size of the intrusive could be observed.

(3) The rocks of felsitic texture are almost invariably porphyritic. The porphyritic habit is sometimes poorly developed, but in some cases

the tendency towards development is so strong that three distinct generations of crystals have been formed.

(4) Fragmental inclusions are the rule rather than the exception in all the varieties of the igneous rocks. The fragments vary in size from large masses of the country rock to fine, tuffaceous and ashy material. Tuffaceous inclusions are often so abundant that the igneous rock assumes the appearance of a massive tuff.

(5) The large majority of the igneous rocks of the district are of andesitic composition, a fact which would seem to indicate that the source of the material was from a magma of approximately andesitic composition. Most of the fragmentary material composing the tuffs is also of andesitic composition. Acidic and basic variations of the predominant andesite or diorite are widespread. The acidic variations represented by the granite, rhyolite, and related rocks are more abundant than the basaltic varieties.

(6) After plotting the distribution of the intrusives, it was noticed that the rocks of related composition tended to group themselves in separate provinces. In the valley of the Bayamon River, southeast of Helechal Peak, there is a large group of acidic intrusives. A number of granitic intrusives are located in an east-west belt roughly following the inner lowland south of the towns of Morovis, Corozal, and Naranjito. In the southwestern portion of the district the igneous bodies were generally of andesitic composition.

(7) The igneous rocks showed extensive secondary alteration. Almost none was perfectly fresh. In some the alteration products constituted the bulk of the rock. Products of deep-seated as well as surface alteration were represented. The former included epidote, actinolite, tremolite, quartz, and some calcite. The latter type was represented by chlorite, sericite, kaolin, quartz, calcite, iron, oxide, and leucoxene.

(8) Evidence of regional metamorphism is wanting. Moreover, there is surprisingly little evidence of contact metamorphism. One rock consisting almost entirely of actinolite was found, which suggested contact effects. The abundance of epidote and diopside is suggestive, but the diopside is usually primary and the epidote products of ordinary alteration. No typical contact zones were found.

(9) Many of the intrusives showed more or less mineralization. Pyrite and magnetite were the usual products. Two intrusives were located which showed cupriferous mineralization.

STRUCTURAL FEATURES

Many of the larger structural features have been mentioned in connection with the formations involved. The most striking structural features are related to the igneous and fragmental rocks. The great series of interbedded tuffs and ashes, with occasional lava sheets and sills, which occupies most of the southwestern portion of the district, may be classified as a structural unit, forming the fundamental basal structure of the whole island. In this great volcanic series the minor igneous structures are numerous and complex. The interbedded sills, the flows, the dikes, the intrusives, all serve to increase the complexity of the series as a whole and incidentally cause a variety of minor structures.

Unconformities

The most striking unconformity in the district is that between the older and younger series. The almost horizontal limestones of the coastal plain resting upon the upturned beds and intrusives of the older series form a structural feature that will be noted by even the most casual observer. This unconformity represents the erosional interval in which the formations of the older series were uplifted, tilted, and finally reduced to low relief. It also marks the close of all volcanic and igneous activity. This erosional interval seems to have occurred either during late Eocene or early Oligocene time, an interval comprised between the Eocene beds of the older series and the overlying limestones of upper Oligocene age.

Above the unconformity there is another erosional interval represented. Though this interval is shown by no structural break, yet it represents a much greater period of time than that which transpired between the deposition of the older and younger series. This disconformity occurs between the Arecibo and the San Juan formations and represents an interval from upper Oligocene to Pleistocene time, during which the island was above water. During this time much of the erosion that has partially destroyed the Arecibo formation doubtless took place.

No direct evidence of an unconformity was found in the older series, but indirectly at least one important break was indicated. The discordance in strike of the limestone beds south of Aguas Buenas suggests either an unconformable or faulted relationship with the other formations of the series. The writer believes that these limestone beds lie unconformably below the other formations and have been exposed in this vicinity by more advanced erosion. The prominent conglomerate formation that strikes N. W.–S. E., crossing the Comerio road at K 12, indicates another break in the older series. To the southwest of this conglomerate the formations strike N. W.–S. E. with hardly an exception. Northeast of it outcrops are rarer. The shale beds for the most part appear to strike N. W.–S. E., but the sandstone at K 8 gives an exceptional strike of N. 65° E. Northeast of the conglomeratic Muda tuffs no strikes were obtainable from the few scattered outcrops. Berkey, however, noted that the shales on the Military road south of Rio Piedras strike E.–W., and the tuffs farther south strike N. 20° E.

The variations in strike over the northeastern portion of the district are at first very confusing, but when one considers that the material forming the sediments is of volcanic origin and was not derived from a single source, but probably from many vents, it seems surprising that any uniformity in strike would exist over an extended area. The volcanic material ejected from a number of vents would be concentrically deposited around each, forming a succession of local formations interfingering with the deposits from neighboring vents. Intense igneous activity has accompanied the deposition of all this tuffaceous material, and finally the whole complex thus formed was uplifted and folded by subsequent dynamic movements. The end-product of such a series of events would be a volcanic ash heap of great complexity, in which extended series of conformable beds would be the exception rather than the rule. Considering Porto Rico as a portion of such a mass, one can better interpret the many complex and erratic structures that are to be found as well as the local character of many of the formations which are so confusing to one who attempts a solution of the areal geology of a portion of the island.

Faulting

Indirect evidences of faulting are abundant, but in no case was the displacement itself visible nor the amount of movement determinable. Abrupt changes along the strike of certain formations indicate faulting on a large scale, but outcrops were too scattered to determine positively their presence. Evidence of faulting on a small scale is much more abundant. Along the Comerio road occasional shear and crush zones are visible, which apparently involve faults of some magnitude. The best examples occur at K 17 and K 21.5. In both cases, however, the complexity of the structure involved was so great that no accurate estimate of the amount of movement could be made.

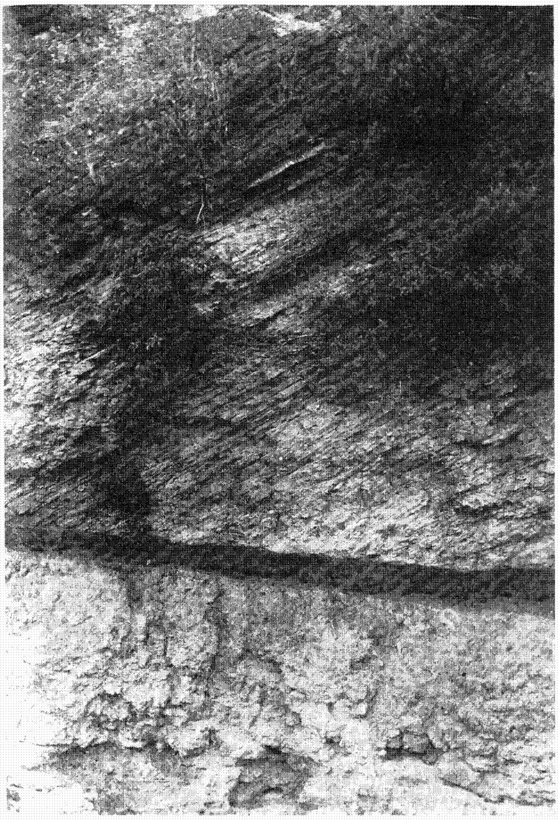


FIG. 26.—*Cross-bedded structure in the San Juan formation at Arecibo*

The horizontal marks crossing the inclined layers in the upper part of the picture are of supposedly secondary origin. Photographed by C. P. Berkey.

Folding

All of the sedimentary formations of the district show some folding or tilting. The limestones of the coastal plain have been only slightly tilted. Their maximum inclination is not over 10°, and no indications of folding or warping within the formations themselves could be discovered. The beds of the older series are characteristically highly tilted, and in many places well-developed folds are to be seen. The folding is on a small scale and is confined to certain less competent shales and ash beds. The fact that the sediments generally dip towards the sea on both sides of the island would suggest the possibility of a large anticline with the axis along the crest of the island. Minor folds are not uncommon in the shale series that forms the divide in the southern part of the district. Moreover, this shale series is anticlinal in its larger structure, with its crest just north of Barranquitas—a fact which gives additional weight to the theory of anticlinal structure for the older series as a whole.

Metamorphism

No evidence of regional metamorphism was found in the rocks of the older series. Evidence of contact metamorphism is also surprisingly scarce. The amphibolite already described is the only rock found that might safely be regarded as due to contact effects.

Minor Structures

Cross-bedding

The San Juan sandstone shows well-developed cross-bedding of the eolian type. Berkey (1915, p. 43) has described with some detail the double character of the cross-bedding where it is best exposed near Arecibo (Fig. 26).

Solifluction

The crumpling, due to the slumping of certain formations, either from external pressure or from the force of its own gravity, gives rise to what has been termed solifluction. This type of structure was noted in several of the thinly bedded ash formations, but it was best developed in the Juan Ascencio chert bed, which has been previously described (Fig. 11).

STRATIGRAPHICAL SUMMARY

The geological history of the island of Porto Rico has already been comprehensively summarized by Berkey (1915, p. 58). Little can be added to this from the data collected by the writer, except certain changes in the age relations of the formations. The geological history of the San Juan district or that of the whole island, for the former involves practically every step of the latter, still remains in great part uncertain. An accurate and detailed statement of it can only be hoped for as an end-product of the series of investigations that are now in progress. Each investigator, however, can contribute his share toward the final result. The writer, therefore, re-summarizes the historical statement of Berkey, making those modifications which he thinks are justified by subsequent investigation.

As stated above, the formations that compose the so-called "older series" were early recognized to be geologically young. While some of the shales and limestones have the appearance of being older than they really are, yet none of them is at all similar to the so-called "ancient rocks" of other regions. The age of the lowermost member of the older series is still undetermined except in the most general sort of way. The discovery of a Comanchic coral by Mr. Hodge in the shales south of Cidra indicates that these shales, which apparently form the base of the older series, are no older than the Comanchic age. Flanking these shales both to the north and south are the succeeding members of the older series, which are, as a whole, younger. Such a succession of the members of the older series would suggest a large anticline extending across the island along the belt surveyed by the writer and Mr. Hodge. Other portions of the island, however, do not support this theory, for a section from Arecibo to Ponce shows no indication of the anticline. The writer merely suggests it for the San Juan district and the district to the south, because the shales which form the crest of the island at Barranquitas are anticlinal in structure and are flanked on either side by younger formations. Whether the Barranquitas shales are regarded as the oldest formation of the older series or not, there still remains little reason for supposing that the base of the older series is older than Comanchic. Indeed, the whole of the older series might well have accumulated in a single geologic age, for all of its members give indications that their accumulation was, for the most part, a rapid process.

The deposition of the various members of the older series was accompanied by igneous activity on a very large scale. Great masses of volcanic ejectments were thrown forth to accumulate in fan-like deposits both above and below sea level. This was accompanied by periods of submergence during which the shaly and calcareous beds were deposited, and periods of emergence in which the recently formed sediments were uplifted and sometimes shattered by later volcanic outbursts. During the accumulation of the older series there seems to have been no great change in the nature of processes that took place. No change of sufficient magnitude occurred by which the series might be readily subdivided. It is true that changes in physical condition, such as would cause a shale or ash to accumulate instead of a tuff, frequently occurred—so frequently that these minor changes cannot be used as a basis for consistent subdivision. With the exception of the large conglomerate that crosses the greater part of the district from southeast to northwest, there is no formation which can be used as a definite division line. Other divisions are not even continuous across the San Juan district, and might never be recognized in the adjoining districts.

In early Eocene time this period of volcanic activity finally came to an end. Naturally, from the time of the first volcanic outbursts portions of the island had been dry land. Toward the end of the period of volcanic activity the lower portion of the older series must have been above sea level. This land-mass afforded the material for the late Cretaceous and early Eocene foraminiferal shales and limestones. It is probable, therefore, that much of the island had been reduced to a submature or mature stage of topographic development before the final cessation of volcanic activity. As such activity completely ceased, erosion continued and the entire island was reduced to a peneplane or to an old stage of topographic development. The development and extent of this peneplane have already been discussed. Until the whole island is examined with this point in mind it will be impossible to say to what extent it was developed. The period in which it culminated, however, was geologically short. Eocene formations are found beveled by the peneplane, and Oligocene strata lie above it.

As the erosion of the older series proceeded, sediments were deposited unconformably around the margins of the island as it existed then. In shallow water, and doubtless in the estuaries and bays of the coast of that time, were first deposited a series of shales. This phase of deposit was not well expressed in the San Juan district, but to the west it is represented by the San Sebastian and Lares shales. This earlier stage in the deposition of the younger series probably occurred before the interior had been reduced to an old stage of development. As erosion continued, clearer water conditions prevailed and the lower shaly beds of the Arecibo limestone were deposited. Later, after clear water conditions had become stable, the upper pure limestone and reef limestones were finally deposited.

At the beginning of Miocene time there was a marked emergence, and the early Tertiary limestones and shales were elevated to essentially their present position. This emergence was accompanied by warping, so that now these strata are inclined at an angle of about 6°. From that time until the present, these formations have been subjected to erosion, and in consequence the comparatively easily destroyed limestones and shales have been maturely dissected or almost completely removed.

Since this emergence there have been frequent minor movements, extending down to recent time—movements that have been rcorded in the marginal terraces by the occurrence of marine shells at considerable distances up the larger river valleys, and by the partial submergence and induration of the San Juan dune sand. The latest movement has apparently been one of slight emergence.

Berkey (1915, p. 60) summarizes the more important steps in the geologic history as follows:

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 of the formations of the San Juan district is the same as that formulated by Berkey (1915, p. 61) for the entire island, with certain minor modifications:

Recent alluvial deposits
    Submergence with marginal (playa) deposits
Younger series
    San Juan dune sand (Pleistocene?)
        Submergence with terrace cutting
        Post Arecibo emergence and erosion (Miocene)
    Arecibo formation (upper Oligocene)
    Lares shales, etc. (Lower Oligocene or upper Eocene) not expressed in San Juan district
    Marked unconformity

Older series
- Corozal and Muda limestones (Eocene)
- Foraminiferal shales and limestones (Unibon shale, shale at K 8, Comerio road) (Upper Cretaceous)
- Barranquitas shales and shaly limestones. Probably the base of older series (Comanchic ?)

MINERAL OCCURRENCES

Throughout Porto Rico there is evidence of widespread but apparently feeble mineralization, which has given rise to a variety of mineral deposits of small extent and uncertain importance. Mineralization in the San Juan district has produced even less results than in other portions of the island. Prospects occur in considerable variety, but no extensive deposit was found in this district. Up to the present time none of the mining ventures that have been promoted in the district has proved a success. This, however, has not been due wholly to the low quality and limited quantity of the ores encountered, but is due partly to the difficulties in transportation and the mining methods employed. Without the exercise of caution and economy in the development of small ore bodies such as are found in the district, success cannot be expected. Much money has already been wasted by attempting more elaborate methods than are warranted by the extent and quality of the ore occurrences.

The prospector is soon impressed by the extent of the mineralization in the igneous rocks of the older series. Numerous examples of mineralized igneous rocks have already been cited. An abundance of magnetite and pyrite are to be found in almost all the igneous rocks of the district, yet the resultant ore deposits are surprisingly small and unimportant. Native gold from quartzose zones and placers is the only metal that thus far has been produced in paying quantities. Indications of copper are abundant, but in only one locality does it occur in sufficient quantities to attract development. Non-metallic deposits of value are entirely wanting, except, perhaps, limestones for road metal or similar uses.

Gold

PLACERS

The principal gold placers of the island are located in the vicinity of Corozal. From the streams in this vicinity gold has been washed by the natives since the days of early Spanish occupancy. Tales of the great abundance of gold and the size of the nuggets found during those early days are widespread and form a favorable subject of conversation among the older native panners. No statistics are available, however, either to disprove or verify these statements. It cannot be denied that a large amount of gold has been panned out of the streams of this vicinity in past time. At present the work is slow and tedious and pays poorly even in the most favorable localities. The native panner stands up to his neck in a pool, which he has dug in the stream bed, and assiduously scrapes up the fine sand in a cocoanut shell, separating the larger pebbles by hand. If the pool is deep he dives to the bottom for the sand. If ten hours of this work nets him eighty cents he is fortunate, for the average daily washings do not exceed fifty cents. Indeed, the peon prefers steady farm labor at forty to fifty cents per day to the precarious living he can derive from the stream beds. During recent years about 100 ounces of gold are annually washed from the streams of the island, the larger part coming from the Corozal district.

Several years ago an unsuccessful attempt was made at hydraulic mining. A large dam was erected in the headwaters of the Corozal River and the water was conducted down by a 10-inch conduit to a point where the gravels were especially abundant in the same stream just above the town. Due to the difficulties in transportation, the cost of construction of the dam and conduit was very great, the material being brought some 20 miles from San Juan to Corozal by ox-cart and thence into the hills by pack. Unfortunately, the conduit proved inadequate to withstand the pressure of so large a head of water and soon went to pieces. The project was then abandoned for lack of funds and has never been reattempted.

Gold occurs not only in the Corozal and Negros Rivers, but is to be found in minute quantities in almost every stream of the district. It has been washed in paying quantities from the Plata, Mavilla, Naranjito, Unibon, and Orocovis Rivers, but its presence in these streams is so rare that no regular panning is practised.

AURIFEROUS QUARTZ MINES

South of Corozal, in the barrios Negros and Palos Blancos, some exploratory work has been done in an attempt to discover the lode or veins which might have been the source of the placer gold (see topographic map).

In the barrio Negros some of the old Spanish workings have been reopened in recent years, and two new shafts of shallow depth have been sunk in an attempt to discover a large vein. A so-called vein about three feet wide has been exposed. The country rock is highly weathered, but appears to be an andesitic tuff. On close examination the vein proves to be a silicified zone composed of many quartz veinlets and stringers, none of which is over a few inches in width. These veinlets carry the gold, and when bunched in large numbers are workable. Neither the quantity nor quality of the ore can be depended upon, for it is no longer workable when the quartz veinlets become scattered.

In the Palos Blancos mine the conditions are much the same, though this prospect has been more fully explored. The country rock is an andesitic tuff with associated intrusives. The silicified zone, or vein, is somewhat larger than in the other case, and has been followed by one tunnel some 180 feet. A fair grade ore could be concentrated, and one shipment was made to the States. Neither of the two prospects is now worked. The Palos Blancos mine might prove a success if properly developed and capitalized.

Platinum

Occasional particles of platinum are panned out with the gold from the placers near Corozal. The metal is called *plata* by the natives, who think it is silver. Although it sometimes occurs in quite appreciable quantities, the natives get nothing for it from the local buyers. The writer in purchasing the results of a day's labor from one of the native panners found that it contained, roughly, 20 per cent platinum; so in this particular case the platinum content, discarded by the native as valueless, was approximately as valuable as the gold, which locally brings only $12.00 an ounce. Such high percentages of platinum, however, are rare.

Copper

In the barrio Pasto, on the west central margin of the San Juan district, several copper prospects were visited and examined. These are the easternmost of a group of similar prospects that occur south of Ciales. The others, extending beyond the boundaries of the district, were not visited by the writer. The country rock is an andesitic porphyry, which has been described and figured on Fig. 22. This porphyry occurs as a large instrusive extending out of the district on the west. In this intrusive the ore occurs as impregnations along cracks and fissures. Several of the prospects in this vicinity have been partially explored. The principal one was examined by an American mining company and one shipment of several tons was sent to the States for smelting. In this prospect the principal vein, or impregnated zone, is about four feet wide. This had been followed about 30 feet into the hill. It is intersected by several other similar veins of smaller size. It is evident that the porphyry has been fractured and subsequently was mineralized. The copper-bearing waters have followed these fractures and deposited in them the copper minerals, impregnating the neighboring porphyry for distances varying from a few inches to several feet. At the juncture of two of these mineralized fracture quite a showing of copper is developed. In the specimens collected malachite, chrysocolla, and azurite appeared in the greatest abundance. Cuprite and chalcocite are rare at the surface, but may prove more abundant in depth. No idea as to the extent and quality of these occurrences can be had without further exploration. The ore bodies that have been unearthed in the ditches and tunnels of former exploratory endeavors have been subsequently concealed by infalling detritus and dense vegetation, so not even an approximate estimate could be made as to the quantity of ore readily accessible. The inaccessibility of this region has discouraged all attempts at the development of these prospects. The topography is exceedingly rugged and the distance from all means of transportation is considerable. At present the ore must be packed down to the valley of the Manati, from whence it can be carted to the main road. If the transportation facilities are eventually improved, these copper prospects may be successfully worked.

Lead

No occurrence of lead of economic value was found. A small quartz veinlet carrying galena was seen in barrio Magueyes, south of Corozal, but no other indications of the presence of this metal were found in the district.

Manganese

In the same locality a thin bed of psilomelane was seen. Its extent could not be determined, but it did not appear to be of enough importance to warrant exploration.

Road Metal

Road metal is abundant in all parts of the district. The Tertiary limestone is extensively used as such on all the roads that pass through the limestone belt. It is said that the purer beds of the limestone give a good quality of lime on burning, but the scarcity of fuel makes this industry impracticable. The tuffaceous sandstone at K 8, Comerio road, is quarried and used as road metal for the carretera for some distance.

In the interior the andesites and massive tuffs are used and, where accessible, the interior limestone beds are quarried for this purpose.

Building Stone

Many of the igneous rocks of the district that would make excellent building stones are not, and may never be, quarried, owing to the limited demand for such material and the difficulties of transportation. In San Juan, where the local demand is greater, the San Juan sandstone is used to some extent in the residential section, chiefly in building foundations, since it forms a pleasing contrast to the cement.

Guano

Bat guano is found in many of the caves. Large deposits have accumulated in the caves south of Aguas Buenas. These are locally used by the natives as fertilizer.

ILLUSTRATIONS

Cross-sections

Soon after the writer began the geologic study of the district, it became apparent that the structure of the older series was in greater part too complex to be shown in even moderate detail on a geologic map of small scale. It was decided then to supplement the map by a few more detailed cross-sections. Therefore, careful traverses were made across the district along definite lines, so that three cross-sections might be constructed showing to some degree the complexity of structure encountered (see Geologic Cross-sections, Plate IV). The data collected in each case have been projected upon a straight line. In this way the windings of the road or trail have been eliminated and the normal proportions and relative positions of the associated formations more clearly shown. The section through Bayamon and Comerio is the most complete and accurate because of the better and more continuous exposures. The other two sections are based upon occasional exposures and are therefore somewhat more generalized.

Maps

The difficulty of obtaining a map of sufficient accuracy on which the geology might be plotted was soon realized. Available maps, however well adapted they might be for other uses, proved to be so unsuited to this particular purpose that it became necessary to construct a large scale topographic map before beginning the study of the geology of the district. The accompanying map is the result. It was constructed by means of

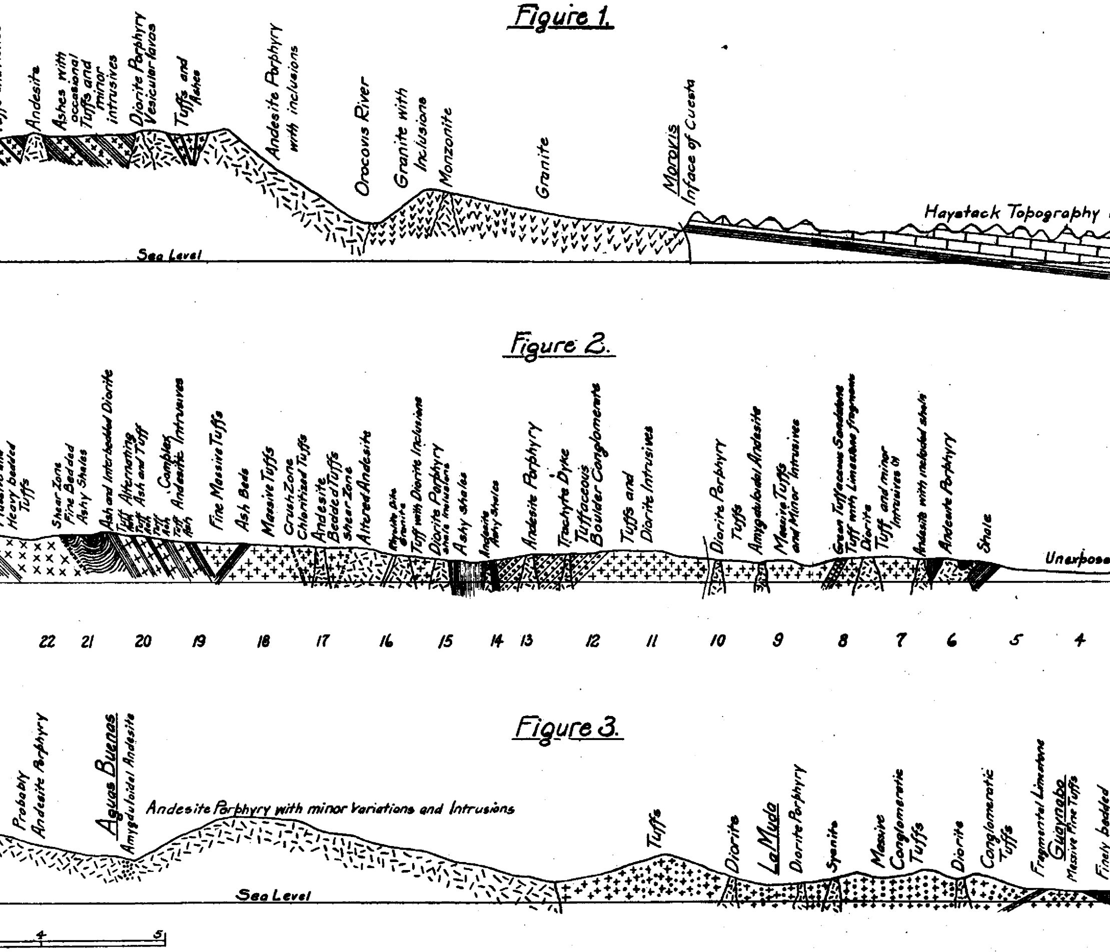


Figure 1 — North-South section from Vega Baja Playa, thru Vega Baja, Morovis and Barros

Figure 2 — Road Profile from San Juan, thru Bayamón and Comerio, to Barranquitas - Numerals indicate kilometer posts along the carretera)

Figure 3 — North-South section from San Juan, thru Guaynabo, La Muda and Aguas Buenas, to Cidra

Vertical scale 1" = 3000'

GEOLOGIC CROSS-SECTION

the plane-table and telescopic alidade, the contours being sketched in from aneroid readings. The main roads and streams are shown with some degree of accuracy, and a reasonably correct idea of the character of the topography can be had from the contours.

When one attempts to map an area of 500 square miles of country as complex geologically and topographically as Porto Rico, in a single summer, any great degree of accuracy is manifestly impossible. The subdivisions of the older series are necessarily somewhat arbitrary, for the members of the series, as a rule, do not maintain sufficient constancy to make close subdivision possible. Many of the division boundaries shown on the map are generalized or are compromises because there is a continuous gradation between some of the formations. Even the boundaries of the intrusives are obscure in much of the area. Some were located by single or widely separated exposures in districts of almost continuous soil cover. The dominant rock type is indicated, however, in each case and the approximate distribution and general trend and relative importance of the larger formational units are brought out by the different color patterns.

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