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Geology of the Coamo-Guayama District—*E. T. Hodge*

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THE GEOLOGY OF THE COAMO-GUAYAMA DISTRICT, PORTO RICO

By Edwin T. Hodge

CONTENTS

INTRODUCTION

Location and Area

This report covers an arbitrarily bounded area, which occupies the south central part of Porto Rico,[1] and will be called the Coamo-Guayama district. This district occupies about one-eighth of the 3668 square miles belonging to Porto Rico and measures 23 by 20 miles. Adjacent on the north is another area, the side lines of which are a continuation of those of the Coamo-Guayama district. It is called the San Juan district and has been described by D. R. Semmes.[2]

Purpose of Study

The purpose of the investigations made by Mr. Semmes and myself is to give a geological cross-section of a typical part of Porto Rico. In addition, I will describe in some detail the complex geological structure and the peculiar rock types of exceptional petrogenetic history; I will

[1] See Outline Map of Porto Rico, Volume I, Part I, p. 26.
[2] The Geology of the San Juan District, Volume I, Part I, pp. 33-110.

discuss the origin of the Coamo thermal springs, and attempt to present the data establishing the main events in the geological history of Porto Rico.

Acknowledgments and Previous Workers

The author is grateful for much assistance in the preparation of this report. The investigation was made possible by the generous support of the Porto Rican Government in co-operation with the New York Academy of Sciences. The rigors of tropical field-work were more than compensated by the uniform courtesy and exceptional hospitality of the citizens of Porto Rico. The author wishes to express his appreciation of the counsel and guidance of the professors of the Department of Geology, Columbia University, especially that of Dr. Charles P. Berkey. The laboratory investigation of this problem was conducted in the Geological Department of Columbia University.

Numerous travelers and scientific men have published observations on Porto Rico, among whom are the following: P. T. Cleve, Brig. Gen. G. W. Davis, W. Dinwiddie, M. K. Domensch, Amos K. Fiske, S. H. Hamilton, R. T. Hill, J. S. Newberry, H. C. B. Nitze, T. W. Vaughan, W. J. L. Wharton, H. M. Wilson and C. P. Berkey. With the exception of Berkey (1915, p. 69), none of the above more than briefly mention the Coamo-Guayama district. The reconnaissance study by Berkey cleared up the fundamental problems in this district, and the results of this work have been extensively used in prosecuting the present survey.

GEOGRAPHY

The distribution of the essential geographic features is shown on the Outline Map. The area includes the City of Guayama in its southeastern corner and the villages of Cidra, Aibonito, Cayey, Coamo and Salinas. A magnificent road enters at the northeastern corner and leads southwestward through Cayey, Aibonito and Coamo toward Ponce. At Cayey a branch road leads southeastward to Guayama. A narrow-gauge railroad and a wagon road traverse the coastal plain from west eastward to Guayama.

The area is divided into a northern mountainous part, which occupies about two-thirds, and a southern low coastal plain. The mountains are devoted to grazing and to coffee and tobacco culture. Large crops of sugar-cane are grown upon the coastal plain. The character of the drainage pattern is shown by the accompanying topographic map.

Because the island lies across the path of the prevailing trade winds, there is a great variation in rainfall in the various parts. The northern slope of the mountain ranges, where the moist trade winds are forced to rise, receives more than an abundance of rainfall. In the northwestern corner it is said to rain continuously week after week and the mountains at that season of the year are heavily clothed in mist. In contrast to this the southern coast, which is swept by winds deprived of their moisture, is extremely arid. Months frequently pass without a drop of rain falling, and during these periods all the vegetable life in areas not irrigated withers up and cattle must be driven to the interior. Because of the aridity an elaborate system of irrigation has been developed on the south coast, and to this all streams of the district contribute all or a part of their waters.

The harbors are poor and exposed. Aguirre is the best, but the approach to it is through a circuitous channel left by rapidly spreading mangrove swamps.

PHYSIOGRAPHY

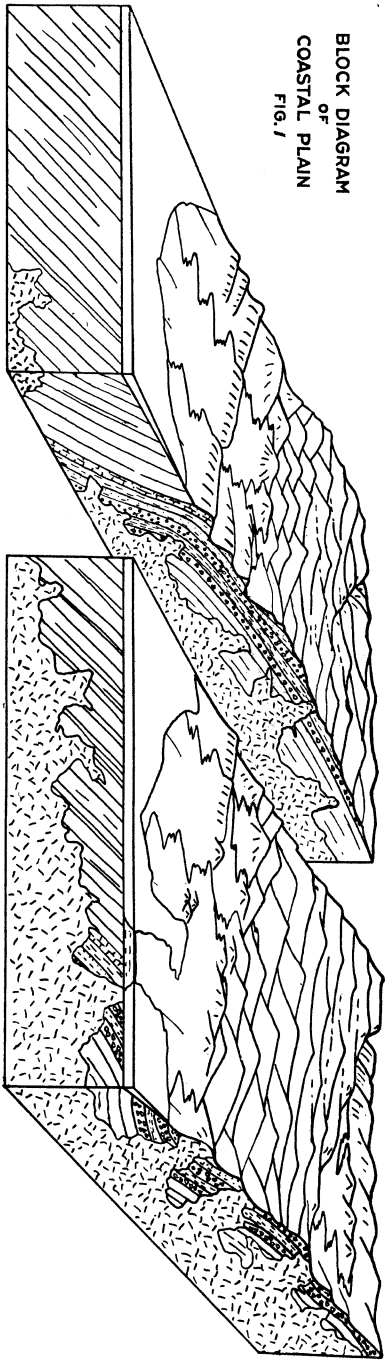
General Statement

Forming a southern border variable in width is a coastal plain which slopes gently upward from the shores of the Caribbean Sea to an elevation of about 300 feet. North of the plain is an old-land composed of a rugged mountainous interior with a main belt of mountains, known as the Sierra de Cayey, extending from the northwest corner of the district southeastward almost to the southeast corner. Because the old-land is dissected to maturity, broad sprawling spurs stretch southward and northward from the main range, and the mountains are not sharply separated from the plain, embayments of the latter extending northward between the spurs for many miles. Two major interior subsequent lowlands occur, one in the northeastern corner and the other forming a linear belt reaching northwest and southeast through the south central part of this district.

Coastal Plain

DISTRIBUTION AND GENERAL CHARACTER

The distribution of the coastal plain, which will first be described, is shown by figure 1. It has an average width of four miles. Guayama, Coqui and Salinas are located upon its inner margin. An embayment of the coastal plain into the mountains reaches a point where the Guamani River crosses the road, another reaches up the Salinas River to La Lapa, a third almost to Coamo and near the western border one extends almost to the Military Road.



BLOCK DIAGRAM
OF
COASTAL PLAIN
FIG. I

The coastal plain slopes gradually toward the sea. At Guayama the elevation is 200 feet and at Coamo Springs it is 240 feet. This gentle inclination is broken by mendip hills which rise like islands above its general level, by wave-cut and river-built terraces, and by meandering and slightly entrenched streams. The slope, the fine alluvial cover, and the generally undulating character of the plain make it admirably adapted for sugar culture.

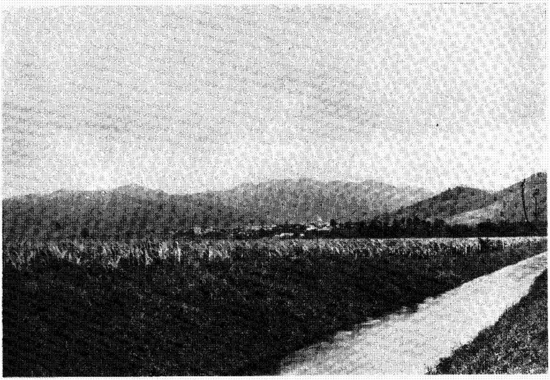


FIG. 2.—*Guayama upon the upper coastal terrace*

The arrows point respectively to the (1) lower and (2) upper terraces. Photographed by Professor Charles P. Berkey.

HILLS

The few mendip hills form prominent landmarks, such as the two large hills, 700 feet high, which lie just east of Guayama and are nearly surrounded by the coastal plain (Fig. 2). A group of low hills, the highest of which is 400 feet, occurs adjacent to the coast and west of Aguirre Harbor and are called Aguirre Hills. North of Aguirre Hills and west of Coqui is a low linear mound 300 feet high, known as Monte Sabater. There are two large hills occurring as detached portions of the inner mountains, one of which, north of Salinas, is 600 feet above sea-level and the other, just east of Coamo Reservoir, is 300 feet high. All of these are portions of the old-land protruding through the alluvial coastal plain.

Discontinuous linear swells of the coastal plain, 400 feet high, lie south of the mountainous tract and extend from Salinas River westward to the boundary of the district.

TERRACES AND SEA CLIFFS

Other features interrupting the general slope of the coastal plain are terraces and sea cliffs, of which two are well shown near Guayama, which is situated upon the highest of these terraces, 200 feet above the sea-level. The photograph (Fig. 2) shows very well the abrupt termination of the terrace against the Guayama Hills in a sea cliff. Ninety feet below, as indicated by the arrows, is the largest terrace, which descends by a gentle inclination to the sea.

Along the Rio Jueyes three sea cliffs are to be found. One occurs very near the coast, another a mile from the coast and the third, formed by the Cerro Raspado, occurs two and a half miles from the coast; the outer margin of the lower terrace is 35 feet high. The outer margin of the upper terrace is 100 feet higher than that of the lower. Traced eastward, both disappear before Salinas is reached, but both can be traced westward, though much dissected, to positions north of Santa Isabel. The upper terrace is well developed just south of Coamo Reservoir dam where its outer margin is about 160 feet above sea-level and rises to over 200 feet at Coamo Springs. The lower two terraces are much dissected. The southernmost part of the Aguirre Hills has a poorly developed sea cliff, which forms the nearest approximation to a clifted promontory found in this district.

COAST LINE

Aside from local irregularities the south shore of the Coamo-Guayama district has an angular pattern. Thus a wedge extends seaward to Pta. Equilarte; another to Pta. de Cayures; a third between Aguirre and Salinas; and a fourth south of Santa Isabel. Between each of these angular projections of land is an equally angular extension of the sea. This irregularity is due to drowning of the subsequent valleys which lie at angles to the coast line.

Mountains

DISTRIBUTION AND CHARACTER

The dominating range in Porto Rico is the Sierra de Cayey and it passes through this district from the northwest to the southeast corner. The Sierra de Cayey forms the divide for all the rivers in the Coamo-

Guayama district. Nowhere in this district is it cut through, but it has been maturely dissected, so that out from it to either side extend many sprawling ranges, some of which have been completely severed from the main range. Though its elevation in no place exceeds 4000 feet, nevertheless because of its ruggedness and heavy vegetable covering it is a most imposing and beautiful feature.

The Coamo Springs is a homoclinal range (Fig. 17) which extends from the west central border of this district, with a general southeastward trend, to Salinas Hill, just northwest of Salinas. Aguirre Hills are thought also to be related to the Coamo Springs Range and are so mapped in this report, though this relationship has not been proven. This correlation of the Aguirre Hills is based upon their alignment with the Cerro Raspado and upon the fact that they are formed of a limestone of similar character. The Coamo Springs Range rises as a solid, abrupt wall 500 to 1200 feet above the surrounding lowlands, having a steep northeastern slope and a gentler southwestern, with a width of about one-half mile. Its crest is notched by many wind-gaps and it is cut through by several large superimposed rivers, which serve to divide it into divisions as shown by the topographical map. South of this range lie many smaller and lower hills created by the erosion of subsequent valleys by tributaries of the Coamo and Descalabrado Rivers.

HEIGHT, RELIEF, DISSECTION

The average elevation of the Sierra de Cayey is 2500 feet in the eastern and 3000 feet in the western portions of this district. The relief of all the ranges is, perhaps, 1500 feet. The surface is dissected to early maturity and the texture in the interior is exceedingly fine. The slopes of the Porto Rican Mountains are always steep and deeply dissected. Thus slopes of 40° are common. The mountain sides are always cut by numerous gullies producing a very fine texture. Knife-edge crests are common and are barely wide enough to give footing to the small Porto Rican packhorses as they follow the trails upon them. The cause of these knife-edge crests is the character of the soil, which will stand up as vertical walls 5 to 10 feet for a year or more without caving. Such a soil does not creep readily after streams have cut the slopes, but remains standing upon the divides until finally carved away by running water. Headward portions of streams on opposite sides of divides, therefore, are not separated by a zone where soil flowage assists, but erode until they actually meet in a knife-edge divide.

CONCORDANT ELEVATIONS

The peneplane described by Berkey in his reconnaissance study of Porto Rico in 1914 is well shown in the Coamo-Guayama district. As one stands in the lowlands and looks up to the summits, it seems impossible to imagine any surface more broken or any slopes more steep. Viewed from a summit, the peaks blend into a solid mass with a remarkably level horizon line, regardless of the direction in which the distant peaks are

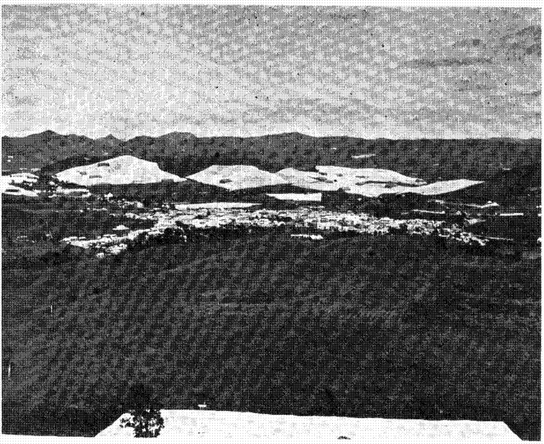


FIG. 3.—*Cayey in the Barranquitas-Cayey Lowland*
Photographed by Professor H. E. Crampton.

viewed. Not only are the mountains in the interior of nearly uniform height, but some of them have flat tops, which often afford sufficient space for a half dozen native huts. When one considers that the mountains are composed of rocks of almost infinite variety and exceedingly variable structure, their concordant elevation and the existence of an occasional flat area argue that the whole mass has been beveled by erosion to form a peneplane surface (Figs. 3 and 7).

Interior Valleys

There are two large subsequent valleys of greater importance than any other in this district. The Military Road from Ponce to Albonito follows a great lowland which continues eastward into the area under consideration. If one could remove the Coamo Springs Range, at the point where both the Military Road and the Rio Descalabrados find passage, this valley would continue eastward to the Coamo River. East of this passage or gap the valley is very large and open. It extends eastward from the great white hills of the Coamo Springs Range lying just outside the western boundary of this district to a mile beyond Coamo Springs. The southern boundary is formed by the wall-like Coamo Springs Range and the northern boundary is not sharp and distinct, but changes gradually from a flat lowland through many small hills to a large and low range. Beyond Coamo Springs and a group of low hills 400 feet above sea-level it continues eastward and finally merges into the valley of the Salinas. The floor is uniformly 300 feet in elevation.

The largest lowland, carved in soft tuffs and limestones, is found north of the Sierra de Cayey, in the northeastern part of this district. The shape is irregularly ovate, with the apex pointed toward Aibonito and the base widening northward so as to include Cidra. The principal outlet is north of Comerio, where the Rio de la Plata has cut a deep gorge in the highlands to the south. Another low pass or col lies beyond Las Cruces and it is taken advantage of by the Military Road between Cayey and San Juan. The floor is not flat, but is broken by numerous low hills composed of resistant rocks which rise as much as 300 feet above the general level and have a trend conformable with the lowland as a whole. The average elevation is 1500 feet above sea-level.

Drainage

RELATION OF STREAMS TO TREND OF VALLEYS AND MOUNTAINS

The larger streams do not lie in the larger valleys, nor are the major ranges parallel to the larger streams. This feature indicates a superimposed condition of the larger streams and the development of large subsequent valleys by their tributaries. A portion of the Rio de la Plata is an exception to this rule, for it descends from the northern slope of the Sierra de Cayey and flows northwestward across the floor of the Barranquitas-Cayey lowland to Comerio, where it turns northward and escapes through a narrow gorge. On the other hand, the Rio Descalabrados, the Coamo and the Rio Jueyes cut narrow water gaps through the Coamo Springs Range. Related to the gorges through the mountain are gaps through which streams do not always flow; for instance, the Cerro Raspado is cut at its eastern extremity by a deep notch through which a road leading northwestward from Salinas passes to the lowlands lying behind the range.

The width of the stream valleys is directly related to the character of the rock over which they flow. Where the streams flow across lowlands, their valleys are wide; where they flow through ranges their valleys are narrow. There are also minor variations in width which apparently are due to variations in the character of the rock over which the stream flows. Some of the streams flow over broad, flat-bottomed, loam-covered valleys for perhaps a maximum distance of half a mile and then cut deep gorges beyond which they may develop plunge pools. This condition is repeated many times in the length of every stream. It is only possible to give a few illustrations of the innumerable cases. For instance, three miles north of the Rio Jueyes Water Gap the Rio Jueyes cuts a gorge not more than 10 or 15 feet wide, while just beyond this gorge a valley one-quarter mile wide and over 3000 feet long opens up. Just beyond the open valley occurs another constriction and then another wide valley. In the gorges the stream flows on bare rock and through the wide valleys upon thick beds of silts and pebbles.

ENTRENCHED STREAM TERRACES

Near the inner margins of the coastal plain all the streams are more or less entrenched. Thus the Coamo River, near Coamo Springs, cuts vertically downward into alluvium (Figs. 1 and 23). Other streams are similarly incised, but to a less extent; the degree of incision seems to decrease eastward.

The streams which show the best entrenchments also show the best terraces; thus, on the Rio de Coamo three excellent terraces are developed. All the larger streams are provided with terraces, but the smaller streams lack them. The largest number of terraces cut, one below the other, is three, and these are found near the Baños de Coamo. The terraces are always local, yet the higher terraces are sometimes very wide, as, north of the Coamo Reservoir, along the whole lower half of the Descalabrados, the Jueyes and the Rio de La Lapa.

COASTAL STREAMS

Streams which flow across the coastal plain are modified in various ways. Many of the streams meander, others wither away and practically disappear; the Salinas is an excellent example of this latter phenomenon.

Long before the coastal plain proper is reached this stream takes on a braided appearance and by the time it has gone a short distance beyond Salinas it disappears in the soft porous alluvium. Some streams, of which the Cimarrono is the best example, exist only on the coastal plain.

CAPTURE

The Salinas wind gap mentioned above is a good example of recent capture. At one time a stream must have flowed through this gap to the Caribbean Sea; indeed, a small brook is developed there now in very wet weather. Water-worn gravels occupy this gap. Apparently a subsequent branch of the Rio Jueyes has captured the headward portion of the stream which formerly occupied the gap.

GENERAL GEOLOGY

Difficulties in Obtaining Data

Geological data are not easily obtained in the Coamo-Guayama district. Contrary to a generally prevailing belief, the larger part of Porto Rico is not readily accessible. Aside from the excellent roads which pass through the Coamo-Guayama district, travel in the mountainous interior is over miserable trails where one must often hew his way with a machete. In addition to the difficulties of penetrating the thick tropical growth, there are the difficulties resulting from the heavy mantle of soil. Outcrops are so rare that in field-work it was necessary to wade the streams and examine the rocks laid bare in the stream bed. Exposures in the streams, in the cuts along the Military Road, and the occasional outcrops at the crest of the mountains form the chief sources of the information contained in this report.

General Physical Character of the Rocks

The greater proportion of the rocks of the Coamo-Guayama district are of sedimentary origin and consist of tuffs, agglomerates, shales derived from volcanic ash, conglomerates, limestones and cherts. The tuffs and conglomerates are decidedly massive and the determination of their dip and strike is impossible. The conglomerates show little or no bedding. Occasional beds of limestones, shales and cherts furnish the only clews as to the geological structure of this terrain.

The types of rock derived from volcanic sources dominate and of these few have passed through more than one sedimentary cycle. For the most part, the sediments are loosely bound tuffs, ash shales, or calcareous tuffs. Despite the fact that the igneous rocks are quantitatively negligible, yet they are of great scientific interest because dikes, sills and flows occur in almost infinite number. If all the igneous outcrops which have been observed were plotted on the accompanying geological map, the entire surface would be dotted, and for that reason only a few of the major igneous bodies have been mapped.

Another factor adding to the complexity is the rapid alternation from one type of rock to another. For instance, in traversing a stream for a kilometer some fifty different and distinct occurrences of igneous and sedimentary rocks may be observed. In the few places where it was possible to trace a definite stratum laterally its character changed so completely that specimens collected a mile apart would not be recognized as belonging to the same bed. Occurring just as often as the above changeable transition is the pinching out of the strata because of their lenticular shape. It is, therefore, no exaggeration to say that the Coamo-Guayama district in particular and Porto Rico as a whole consists primarily of volcanic ash in many thousands of sedimentary beds, in part reworked and in part alternating with marine strata, all of which are cut through and through in a most varied manner by igneous rocks.

General Structure

The grouping together of such varied rocks into formations would not be such a difficult matter if the structure were simple and if it were possible to gather more complete data concerning the structure. Tropical vegetation and deep residual soil conceal the bedrock. It was the experience of the author and of several other geologists who have worked in Porto Rico that frequently in the course of a whole day's traverse only one dip and strike could be obtained which were considered reliable.

Such conditions explain why the structural relationship of the bedded rocks in the Coamo-Guayama district are not well understood.

In the western half of the district all of the dips recorded were to the south and varied between 20° and 55°. The fact, that the dips in the older series are not in all cases steeper than those of the younger, indicates local folds; nevertheless, because of insufficient outcrops, it was impossible to determine the detailed character of these local folds. Eastward, approaching the borders of a batholith which lies just beyond this area, more variable dips were noted. Aside from local irregularities, it appears that most of the northern half of this district is folded into a flat, broad syncline. The south limit of this syncline begins to develop at K. 12 on the road to Guayama. South of this point to K. 24 the rocks are folded

SHALES

The shales consist of bedded ashes and reworked tuffs. The former have suffered so little reworking that in thin sections their pyroclastic nature is easily made out. The latter have been so thoroughly disintegrated and sorted by water that the original character of their material is determined only by a few associated volcanic fragments. The perfection of the bedding is best developed in the younger rocks and most of the shales were accumulated near the shore, as is indicated by the presence of organic remains in them. Some of the shales are silicified and others are epidotized. The silicified shales are thought to be due to the organization of radiolaria and diatoms, and the epidotized shales to hydrothermal influences.

LIMESTONES

Between tuffs with a few organic remains and limestones with a few tuff fragments, there is every graduation and in like manner the limestones are related to the shales. Some of the tuffs, andesitic sills, and andesitic flows have so thoroughly altered to carbonate that they now consist of as much as 80 per cent carbonates and have usually been mistaken for limestones. The true organic limestones can be divided into two classes, those with no algal content and those containing algæ, and the latter are found only in the middle of the uppermost group of rocks. The other limestones are made up chiefly of foraminifera with some contributions made by pelecypod or gastropod forms. In all cases the bulk of the rock consists of reorganized calcite derived from organic remains.

Types of Igneous Rocks Present

Although the range of igneous rocks is wide (Figs. 24 to 40), the most common variety is augite andesite. The following list shows the range: rhyolite, granite, biotite granite, feldspathic andesite, granodiorite, augite andesite, hornblende andesite, diorite, hornblende diorite, hornblende-augite andesite, basic augite andesite, olivine-free basalt, and olivine basalt. Porphyritic rocks are uncommon and granitoid types extremely rare. The massive rocks appear usually in small dikes and flows; especially vesicular varieties were only observed in a few places. As pointed out above, the tuffs, volcanic breccias, and agglomerates contain so many igneous types that in a thin section of a tuff as many as ten to fifteen varieties may be observed. These fragments consist of rhyolites, feldspathic andesites, augite andesites and olivine andesites, and of these, as in the larger masses, augite andesites greatly predominate. After the augite andesites, feldspathic andesites occur in greatest abundance, and are followed, in point of number, by the basic varieties. The fact that the same type of rock appears in tuffs, flows, dikes and sills strongly suggests that these formations are nearly contemporaneous and indicates that while tuffs and breccias were accumulating on the surface liquid matter was being injected into the basal portion of the pyroclastic and sedimentary series.

Hydrothermally Altered and Mineralized Rocks

Nearly all the rocks studied in the Coamo-Guayama district show some mineralization and many of the rocks are intensely hydrothermally altered.

Basis for an Attempted Division of the Rocks

The rocks of the Coamo-Guayama are very hard to classify into series because of the variety of outcrops, complexity of the structure, extreme variability of rock types, and absence of fossils. The few fossils which have been observed are of no assistance in making correlations within this district, although they are of value in giving a clew as to the general age of the strata. The only practicable method of making correlations, which is not free from possibilities of error, consisted in noting the outcrops with their occasional dips and strikes; then, with a knowledge of the general structure, the hand specimens were compared and the outcrops of the same kind connected. Because of the similarity of the type, the divisions, except in a very few cases, between one series and another, are simply arbitrary lines, which attempt to separate sedimentary rocks of one general dominant character from those of another. While the correlations within the district are lithological, the ages of the various series rests upon a firmer foundation. Thus the structural data is sufficient to work out the succession and so determine which are the older and which are the younger. Again, there is some evidence of unconformities indicating diastrophic breaks of magnitude, and it may be fair to correlate these breaks with similar ones occurring at the same time in other parts of the world. Finally, there are fossils which indicate rather closely the age of the particular stratum in which they occur. Thus, with a known sequence of rocks, broken by a few unconformities, and with an occasional stratum, the age of which is more or less definitely known, it is possible to divide the rocks into major series.

The following series of sedimentary rocks, named after type localities from the northeast to the southwest, have been established:

Rio de la Plata series.
  Mostly tuffs with a few agglomerates, shales and limestones.
Barranquitas-Cayey series.
  Mostly shales with much limestone and a little tuff.
Sierra de Cayey series.
  Mostly conglomerates with a little tuff and some shale.
Guayama series.
  A complex series, mostly of shale, but with much chert, some tuff, limestone and conglomerate.
Rio Jueyes series.
  A complex series, mostly limestone, but with much shale and some tuffs and conglomerates.
Coamo Springs series.
  A heavy bedded limestone.
Rio Descalabrados series.
  A thick series of shales with a little limestone and chert.
Arecibo formation.
  Mostly limestone.
Santa Isabel series.
  Mostly alluvia.

And the following intrusive series:

Early intrusives.
Batholithic rocks.
Later intrusives.

In many cases the above divisions are areal and descriptive rather than distinctly stratigraphical.

Rio de la Plata Series

The rocks comprising the Rio de la Plata series are named from the river whose headwaters flow across them for many miles. The series is composed chiefly of tuffs with a few agglomerates and several lenses of limestone. The tuffs weather rapidly and are easily eroded. Into them the Rio de la Plata has eroded a great lowland (Fig. 3). The formations composing this group form a broad belt which occupies the northeastern portion of the district, and structurally forms the flat crest of an anticline. The strike of the rocks is generally N. 40° W. The northern limit of this series is presumed to lie outside of the Coamo-Guayama district. No definite line can be indicated at its upper contact because the variety of rocks characteristic of the group changes by an insensible graduation into those classed as the Barranquitas-Cayey series.

TUFFS

Tuffs make up the greater part of this group and are, as a rule, unstratified. They vary from cream yellow to red, are frequently mottled, and weather easily to a sticky clay soil. The structural details of some occurring at K. 65 on the Military Road, west of Cayey, are shown in figure 4. Microscopically they are chiefly lithic tuffs. The fragments are either augite andesites or augite-olivine andesites. The augite occurs as fresh, fractured, embayed zonal crystals frequently surrounded by

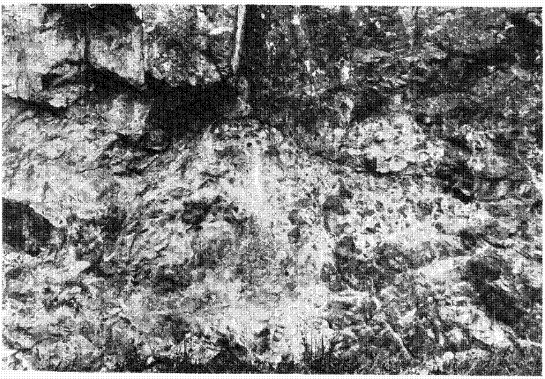


FIG. 4.—*Tuff beds*
Photographed by Professor Charles P. Berkey.

borders of magnetite grains. Augite, as phenocrysts, comprises about 10 per cent of these tuffs. The feldspars, which are of the oligoclase-andesine variety, are frequently embayed by the groundmass and largely altered to chlorite and calcite and comprise about 50 per cent of these tuffs. A few olivine crystals were present, but are now entirely altered to serpentine, magnetite, limonite and iddingsite. The groundmass is composed entirely of alteration products, such as calcite and limonite and a little pyrite. The lack of bedding and the angular character of the fragments indicate that these tuffs accumulated directly from volcanic eruption without any process of reworking.

LIMESTONES

Two beds of limestones have been observed. One begins just south of Cidra and outcrops every two or three miles till just south of Comerio. It is a dense, light gray, fine-grained rock. The microscope proves it to be composed of numerous flat fragments of pelecypods and gastropods. The shells are triturated and oriented, showing that they have been wave-rolled and finally deposited in a bedded condition. Among the foraminiferal forms observed were:

Textularia gibbosa, d'Orbigny.
Textularia conica, d'Orbigny.
Textularia tiochus, d'Orbigny.
Plecanium (*Textularia*) *speyeri* (Reuss)?
Operculine sp.
Orbitoides papyracea.
Orbitoides faujastii, Sowerby.

The shells make up about 60 per cent of the rock and the matrix is composed of crystalline calcite, recrystallized from the shell fragments and their detritus. A second small lens of limestone, of essentially the same character, occurs about three miles due south of Cidra.

AGGLOMERATES

Thin beds of rock, composed of angular or rounded andesite or of augite andesite prophyry boulders varying in diameter between 1 to 6 inches, appear frequently as lenses in the tuffs. Where the boulders are angular they are undoubtedly agglomerates and where rounded they exhibit the effects of transportation, probably in mud flows. The matrix of both types is always tuffaceous.

Barranquitas-Cayey Series

The rocks of the Barranquitas-Cayey series are respectively named from the two villages situated upon them, in the northeast corner and in the eastern margin of the Coamo-Guayama district. The series extends from the north central part of this area southeastward to the east central border and forms a belt averaging about three and one-half miles across the outcrop. This group consists chiefly of shales and shaly limestones with numerous limestone lenses and an occasional bed of tuff and conglomerates. The anticlinal structure of the Rio de la Plata series changes in its southern margin to an equally flat syncline. This syncline continues southward and gives the structure to the Barranquitas-Cayey series. The dip of the southern limb of the syncline increases in steepness to the southward until, near the upper contact with the Sierra de Cayey series, the dip amounts to 30° to 40° N. The strike of N. 40° W. in the western part changes to almost due east in the east-central part. Subordinate to the major structures are several faint anticlinal flexures, especially in the northwest near Comerio. The thickness is between 2000 and 3000 feet. The lower part grades into the Rio de la Plata series and the upper portion forms a sharp contact with the Sierra de Cayey series.

SHALES

The shales grade on the one hand into massive tuffs and on the other into pure limestones. The majority are calcareous and the change from

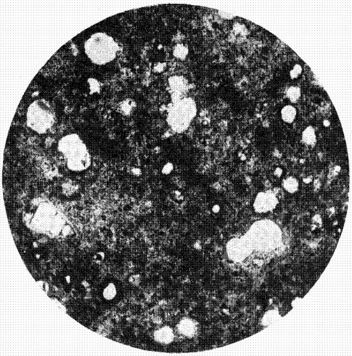


FIG. 5.—*Lithocampe sp. in shales of the Barranquitas-Cayey series*

argillaceous shales to calcareous is very gradual. Some of the shales are siliceous, as, for instance, several of the gray members which extend uninterruptedly from Barranquitas to Aibonito. The color varies from light gray and green to a very dark gray, almost black. The bedding averages two to three inches. The rocks break very easily into rhombs about five inches long. The siliceous varieties under the microscope prove to be very dense, streaky shale, containing about 20 per cent of tiny spherical areas, averaging 2 mm. in diameter; a few of these are filled with silt and most of them are empty, but in one was found a radiolarian belonging to the genus *Lithocampe,* so that it is reasonable to suppose that they are all due to foraminifera which have been dissolved out (Fig. 5). The chalcedonic cement of the rock may have been derived by recrystallization of the siliceous *Lithocampe* shells. Some of these shales are intensively mineralized by pyrite which has come in along bedding planes and has metasomatically replaced the shales.

LIMESTONES

Beds of limestones occur frequently among the shales, and of these three are of special importance. A series of interbedded lenses occur near the base of the series and outcrop frequently along the road from Cayey to Aibonito. They are black or dark gray in color and very dense, and when examined microscopically are found to consist of innumerable round bodies about 3 mm. in diameter, which are varieties of radiolarians and diatoms. The diatoms are:

Paralia (*Melosira*) *sulcata,* Ehr.
Conscenodiscus elegans, Grev?

And the radiolarians are:

Porodiscus concentrica (*Flustrella concentrica,* Ehr.) (Fig. 41).
Lithocampe sp. (?) (Fig. 5).

The tiny shell bodies are all stratified and about 30 per cent of them have been recrystallized to form an interlocking crystalline of cement calcite. Occurring in streaks and parallel with the bedding in these rocks is about 5 per cent of carbonaceous matter. There are also many angular crystals of augite and feldspar which are altered to calcite. It is evident that these limestones were formed either in the neritic zone or upon land by a gradual accumulation of foraminiferal, diatom, and radiolarian shells which had drifted landward and that, as they accumulated, wind-borne pyroclastic fragments were dropped among the shells and so added to the limestone. These limestones are, therefore, recrystallized tuffaceous shell limestones.

Another limestone occurs near the middle of the formation two and one-half miles south of Cayey. This limestone varies from a dirty gray to a dull purple in color, and the microscope shows it to be composed of shell fragments. The fragments are bounded by curves which are not in harmony with the organic structure and which indicate that the components have been rounded by erosion. This wear was developed under oxidizing conditions, as is shown by the heavy hematitic stain bordering each fragment and the entire absence of this stain in the interstitial cement which is pure calcite of secondary origin. The rock also contains some introduced sulphides. Apparently shells were blown from the strand inland and accumulated in beds. *En route* they were worn and oxidized and subsequently they were cemented by calcite, introduced probably by the agency of rain waters (Fig. 6).

Another heavy belt of limestones, "The Mountain limestones" of R. T. Hill, occurs close to the upper contact of this group and extends in a belt from about one mile west to six miles east of the Military Road. It is estimated to be a thousand feet thick.

The relationship between the shales and the limestones is very intimate. The former accumulated as estuarine, delta, or mud-flat deposits,

FIG. 6.—*Shells worn, oxidized, and cemented together to form one of the limestones of the Barranquitas-Cayey series*

the latter either just beyond them in the neritic zone or upon them where shells were wind-drifted inland a short distance. The shales contain many marine organisms and the limestones much terrestrial material.

TUFFS

The western two-thirds of the Barranquitas-Cayey series is chiefly shales, but in the eastern portion a tuffaceous phase develops until, at the eastern border and beyond, the series is composed of tuffs with a few agglomerates. A similar gradation exists between the tuffs and limestones or shales. Some are very fine grained and would be called shales in the field but for an occasional grain indicating a pyroclastic origin. The tuffs vary from the texture of ashes to volcanic breccias and coarse agglomerates. The color is black, dark gray or olive green; where fine grained, and, as the texture becomes coarser, the color becomes mottled because of the fragments, which may be black, gray, green, dark purple or dull red. Many of the lava flows contain tuffaceous material which may amount to as much as 40 per cent. Under the microscope the tuffs prove to be divisible into two classes, crystal tuffs and lithic tuffs. The crystal tuffs (Fig. 12) have the composition of an augite andesite porphyry and contain, taking the average, about 20 per cent augite, 40 per cent andesine feldspar, 20 per cent magnetite and 20 per cent of secondary products.

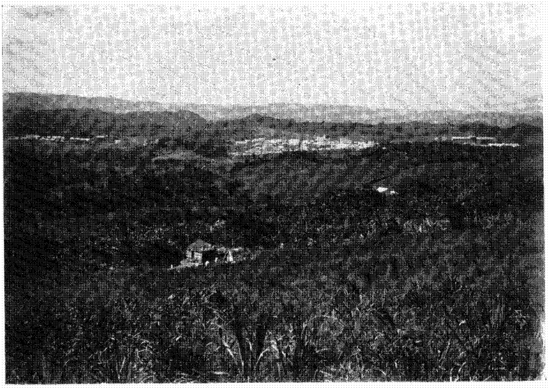


FIG. 7.—*Topography of the Barranquitas-Cayey Lowland*
Photographed by Professor Charles P. Berkey.

Sometimes they show a faintly streaked character, as if they were deposited under some sedimentary control. The augite is fresh, fractured, and pale green. The feldspars are highly altered, usually to chlorite and some epidote, which have, by their development, created the binding material of the rock. At times there are small pseudovesicular spaces filled with zeolites, probably natrolite. These spaces are about 1 mm. in size and are probably produced by infiltration and metasomatic replacement by zeolites.

In composition the lithic tuffs (Fig. 13) are rather simple. They are usually composed of feldspathic andesites or augite andesites. The textural types, however, are numerous and as many as fifteen may be present in one thin section. They vary from glasses to felsites of many textures and structures.

PHYSIOGRAPHIC EFFECT

The shales of the Barranquitas-Cayey are more resistant to weathering than the Rio de la Plata group. The spurs which extend out from the Sierra de Cayey are carved in them. Other hills occur in the lowland, such as the Cerro Gardo and Cerro Rabanal; their occurrence is due to the presence of more resistant shales. The topography thus produced is illustrated in figure 3. In this picture the greater part of the foreground, extending beyond the village of Aibonito, is occupied by the Barranquitas-Cayey group and beyond the first crest is the lowland cut into the Barranquitas-Cayey series.

GENESIS

The composition of the formations and their succession gives some clew as to their origin. Apparently at the time that the Barranquitas-Cayey series was being formed a volcanic center existed to the northeast and furnished the larger part of the material of the strata. In its immediate vicinity the sediments were mostly pyroclastic in origin. Farther away the volcanic ejecta were reworked and deposited close to the shore of the Caribbean Sea. The offshore zone was almost outside of volcanic influences and in it strata of biogenic origin with slight addition of pyroclastic material were chiefly accumulated. Compared with the Rio de la Plata series, which was formed during a period of intense vulcanism, in which there were a few quiescent intervals sufficient for a slight invasion of the sea, the Barranquitas-Cayey series is formed largely of reworked material indicating distant or less violent vulcanism.

Sierra de Cayey Series

DISTRIBUTION

The rocks of this series are mostly conglomerates, with a few tuffs, and are found cropping out along the crest of the Sierra de Cayey Mountains, after which they are named. The road from Barranquitas to Barros, beyond K. 16, follows the lower contact of the Sierra de Cayey series with the underlying Barranquitas-Cayey series. The bends of this road, which swing northward, are upon the shales of the Barranquitas-Cayey series; those which swing southward expose the conglomerates of the Sierra de Cayey series. The Military Road between K. 85 and K. 88 crosses the Sierra de Cayey Range through a wind gap carved in this conglomerate.

The conglomerate is well shown north of La Lapa, where the Rio Cayey cuts a narrow gorge, and again where the Jajome cuts through it west of Jajome bajo. The conglomerate phase is not dominant in all parts of this series. In the eastern portion tuff occurs instead of the conglomerate and for this reason the Cayey-Guayama Road between K. 15 and K. 21 shows comparatively few exposures of conglomerates. This transition from conglomerates to tuff is excellently shown along the trail, which leads from K. 21 westward to Barrio del Carmen.

STRUCTURE

The synclinal structure found in the Barranquitas-Cayey series changes to anticlinal in the area of the rocks of the Sierra de Cayey series. Thus,

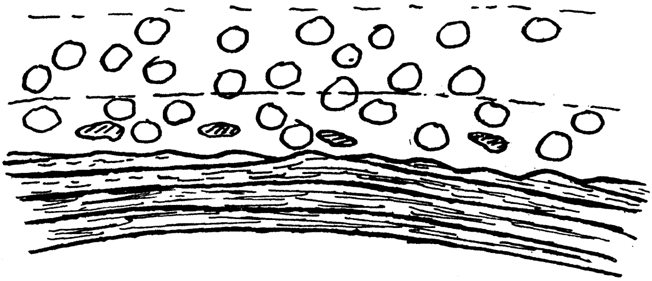


FIG. 8.—*Character of the unconformity between the Barranquitas-Cayey and the Sierra de Cayey series*

a flat anticline exists between kilometer 15 and kilometer 24.5. Going westward the strata begin to dip uniformly southward at angles between 30° and 40° and the strike varies between N. 40° to 60° W. A break of importance occurs at the base of this series, as indicated by the great conglomerate beds in the Sierra de Cayey group and by a distinct unconformity visible at two places. Thus between K. 86 and K. 87, on the Military Road west of Aibonito, the basal conglomerate of the Sierra de Cayey group rests upon the eroded surface of the underlying shales and contains pebbles of these shales (Fig. 8). Dips taken along this section show the shales to be gently folded and the conglomerate to lie upon the truncated portion of a faint anticlinal fold. Again, just west of where the Rio de Cuyon changes from a southward-flowing to an eastward-flowing stream, the heavy conglomerate lies upon a truncated portion of an anticlinal fold in the underlying shales. The upper contact is gradational with the overlying series. The formation is estimated to be between 3000 and 4000 feet.

COMPOSITION AND CORRELATION

The series is composed almost entirely of conglomerate with a few assorted beds of tuff. The basal portion lies unconformably upon the older formations, as shown by evidences both of erosion and folding before the conglomerate beds were deposited; and the upper portion changes by a gradual gradation into shales. Beds of shale begin to appear at infrequent intervals in the conglomerate, and then become more frequent, until shales finally constitute the entire group. Beginning where the shale beds predominate, another series, called the Guayama, is established.

CONGLOMERATE

The pebbles and boulders vary greatly in size, from a tenth of an inch up to seven feet. The largest boulders observed were exposed in the gorge of the Cuyon, and at that place boulders a foot and larger were very common. Most of the pebbles and boulders are very well rounded. The torrential bedding of the finer materials and the orientation of the rounded boulders indicate stream control at the time of deposition. The pebbles are mostly andesites or porphyritic augite andesites. The dikes and sills which cut through this conglomerate are of a coarser nature than the pebbles and some of them are of quite different composition.

The matrix for the pebbles is of two types. One type is water-sorted sandy material derived from tuffs or massive igneous rocks. Under the microscope this matrix proves to be composed of angular, sorted, and laminated grains chiefly of feldspar. These are bound together by secondary products in the following proportions:

	Per cent
Carbonaceous matter	5
Calcite	20
Chlorite	20

In part, however, the matrix is igneous, as in the case of a locality east of Barros where there are many conglomerate beds, some of which have an undoubted igneous matrix, and again southwest of Aibonito, especially in K. 86, where the conglomerates have an igneous matrix, and still again at the Cuyon gorge and westward along the Cuyon. The best exhibition of the igneous matrix is seen along the Rio de Cuyon, where for more than a mile the stream bed is formed by the water-polished surface of a conglomerate with a green andesitic cementing material. Structural features, such as bedding of the conglomerate, were not disturbed by the invasion of the igneous matrix, which must have entered the conglomerate in the form of an extremely fluid magma (Fig. 9).

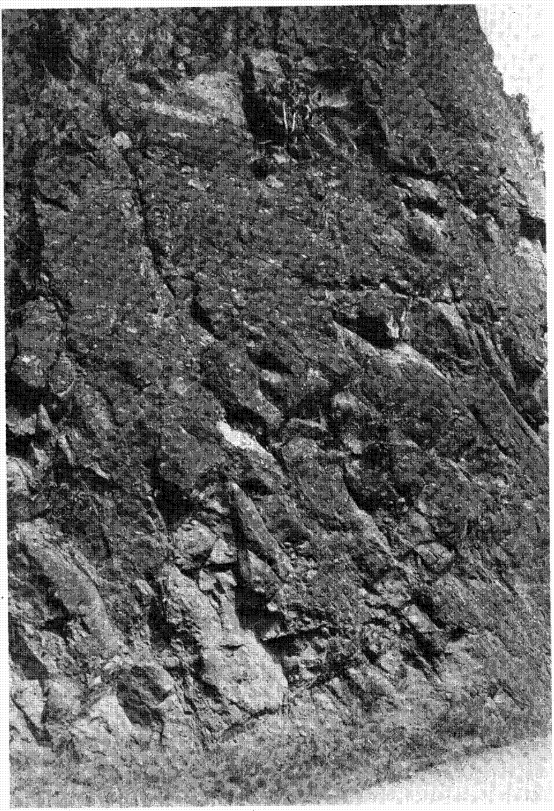


FIG. 9.—*Conglomerate with an igneous matrix*
Photographed by Professor Charles P. Berkey.

Study of the microscopic character of the igneous matrix shows it to be a massive rock of hiatal fabric. The oligoclase phenocrysts are turbid and lath-shaped, averaging from 8 mm. to 14 mm. and comprise over 40 per cent of the rock. Tabular, almost equant, pale green, and exceedingly fresh augites frequently occur as chadocrysts in the feldspar; and magnetite occurs in skeletal grains. The minerals of the groundmass are all less than .01 mm. in size and frequently they are all altered to chlorite; when not replaced they are oligoclase and augite.

Dr. Charles P. Berkey (1915, p. 23), speaking of these conglomerates as seen by him on the Military Road, southwest of Aibonito, says:

There must be a total thickness of strata, including shales and interbedded tuffs with occasional small limestones, of perhaps several thousand feet. In all parts of the formation where conglomerate is developed, the pebbles represent the same kind of rocks as were encountered in the tuffs and intrusive masses. Actual representatives of previously solidified bedded material or indurated ash and shales are very rare, but in one case at least a pebble was observed that was judged to represent a fragment from an older silicified tuff. As a matter of fact, the materials are practically all of simple igneous character and the matrix in most parts of the formation is very abundant, or even predominant, the particles of which are of the same igneous material. The distribution of material and the range of composition leads one to believe that this conglomerate represents a special state or condition whereby materials of essentially tuffaceous origin were, immediately after their volcanic eruption, worn, rounded, somewhat assorted and bedded and mixed with related material. The fact that the conglomerate beds, which follow to great thickness, are prevailingly of simple structural habit, as compared with the calcareous shales, ash and tuff series immediately below, suggests that there may be a break here of larger consequence than is observed in other parts of the pre-Tertiary or older series.

The development of so extensive a series of conglomerates doubtless does represent a considerable change in physical conditions, compared to those controlling the simpler deposits which preceded and followed them.

PHYSIOGRAPHIC EFFECTS

The conglomerates of the Sierra de Cayey play an important part in the formation of the Sierra de Cayey Mountains. Where the conglomerate beds are most numerous the mountains are higher and in straighter lines, and where the conglomerates are replaced by tuffs the mountains become less definite and more scattered as, for instance, in the eastern portions of this district. The Sierra de Cayey Range may be due to several causes, such as the erosion back of a tilted fault block, but its present relief is no doubt due to the resistance of the conglomerate. Streams which cut across the series do so at right angles and with narrow cañons such as those of the Cuyon and Jajome. The roads which pass over the mountains choose abandoned cañons or wind-gaps.

GENESIS

Because of the presence of heavy beds of rounded boulders, the origin of the Sierra de Cayey series is thought to be due to the rapid erosion of uplifted mountains and to the deposition upon their flanks of great alluvial fans. The materials of this group were not necessarily derived from the beds immediately below, because the strata beneath are not deeply eroded. Their site of deposition may have been a slope of small grade and they may have been deposited after transportation from loci of erosion a great many miles to the northward. While they were being accumulated it is possible that volcanoes were active a short distance to the east and threw out great quantities of tuffaceous rock. Under such conditions the strata on the east would have been predominately tuffaceous, and this view is supported by the fact that the tuffs, in the earlier portion of the series, contain a great number of associated volcanic flows.

The boulders found in the Sierra de Cayey series were, no doubt, formed in streams with gradients no steeper than those of the streams in Porto Rico at the present time. In the bed of the Salinas, for example, large boulders are to be found today. The fact that these boulders are found just north of Salinas, and far from their source, indicates the enormous transporting power of small streams, if favored by occasional torrents. These boulders could not have been formed by wave attack because the waves of an advancing sea will grind into silt any boulders broken off unless they happen to fall into deep water and beyond surf action. Other features which argue against a marine origin are the great petrographic variety, the discontinuity along the strike of the beds, the absence of marine fossils, and the absence of a marine succession characteristic of an overlap.

Guayama Series

GENERAL STATEMENT

Lying above the Sierra de Cayey series is the Guayama series, the strata of which are named after the City of Guayama, located upon them in the southeastern corner of the district. The average distance across their outcrop is about four miles. The series is the most complex of all those studied in this district, for it consists of shales, limestones, conglomerates, sandstones, tuffs, volcanic breccia, agglomerates and cherts. Of these, shales are by far the most important. Lenses of limestones are numerous and there are distinct and separate beds of conglomerate.

In the western part of the Coamo-Guayama district the strata apparently all dip southward between 30° to 40°. To the east a syncline is formed between K. 24.5 and Guayama. The lower contact is gradational with the Sierra de Cayey series. If an unconformity exists between the Guayama series and the Rio Jueyes above, it was not observed in the limited time devoted to this study. Moreover, it cannot be said that the rocks differ as radically from the overlying group as do the other series. The total thickness is about 2500 feet.

SHALES

The shales constitute about 75 per cent of the rock in the group, but their continuity is broken near the middle of the group by numerous large lenses of conglomerates. Many of the shales are limy and in places they pass over into true limestones, a condition which is particularly true near the top of the group and a short distance above the bottom of the group. In the western portion of the district shales replace both conglomerates and limestones. In the central part they have the least development and toward Guayama they are replaced, in part, by tuffs. The physical character and mineralogical composition of these shales is varied. For the most part they show excellent closely spaced bedding. Where the bedding is best developed fracture cleavage is also shown best and causes them to break up into small two-inch rhomboid blocks. The color varies from very dark to light gray. These shales were water-sorted and deposited under water, as is shown by their streaked appearance, which is brought out in a decided manner upon weathered surfaces. All of the material composing these shales is volcanic and it is common to find every graduation between massive tuffs and bedded shales. Hence most of the shales should, perhaps, be called finely bedded ashes. The true character of these shales is best shown by their microstructure. The fragments range between .05 mm. and .01 mm., and occasionally larger angular fragments, of clear undecomposed oligoclase or andesine feldspar without orientation, occur which look as if they had been dropped into soft silts after having been carried by the wind. Some of the larger fragments are rounded. Feldspathic material constitutes 60 per cent, carbonaceous material 20 per cent, secondary chlorite and calcite, derived in part from the feldspars and in some shales in part from organic material, make up the remaining 20 per cent, and some secondary chalcedony is present at times.

A few of these rocks contain spherical voids arranged in lines parallel to the bedding, some of which contain *Orbitolites* sp. (?) (Fig. 10), but which, for the most part, are filled with secondary chlorite and calcite. Some of these shales, especially near the top of this series, are hard and dense, due in part to the baking influence of intrusions and in part due to introduced silica and epidote, but which in larger part is due to reorganization of organic siliceous remains.

CHERTS

The cherts are of varied colors, a condition which is dependent upon their genesis. For instance, those due to baking or reorganization are

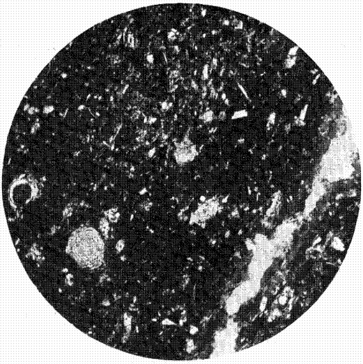


FIG. 10.—*Ash shales containing Orbitolites*

gray in color like the softer shales, and those which contain much introduced material are either a blood red or dull green. Under the microscope the genesis of the red and green cherts show that at first the ordinary tuffaceous shale was impregnated by epidote giving rise to the green chert, and later some of these green cherts were fractured and specular hematite was introduced as veins which, in part or entirely, replaced the rock forming the red cherts. Subsequently both green and red cherts have been veined with white quartz.

The reorganized chert shows traces of the original shale, which is composed chiefly of feldspar with streaks of carbonaceous matter bound together by secondary chlorite and calcite. Tiny spherical holes arranged in lines parallel to the bedding are numerous, some of which contain calcite, others chalcedony, and in still others the two minerals are intergrown. The occurrence of calcite and quartz intergrown indicates a contemporaneous deposition, which is chemically possible, since both are soluble in an alkaline solution. Fortunately not all of these areas are filled with reorganized minerals, but a few are filled with siliceous radiolaria or calcareous foraminiferal remains, some of which show only partial reorganization. This appears to indicate that the silicification is due to the migration of silica from reorganized radiolaria. These rocks also

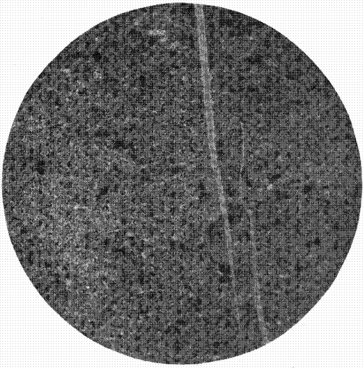


FIG. 11.—*Chert with desiccation fractures*

show micro-desiccation fractures, some of which are cemented by migrated chalcedony (Fig. 11).

TUFFS

Although the tuffs occur largely in the eastern exposure of this group, yet thin beds frequently occur among the shales, limestones, and conglomerate formations. This is to be expected in view of the fact that the shales are only reworked phases of a tuff series. The presence of the tuffs with the limestones indicates the periodic recurrence of intense volcanic activities. Purely pyroclastic types cannot be sharply divided into crystal and lithic tuffs, because the two types usually occur together. Lithic character, however, is the most common in which the rock fragments are all andesitic and extremely angular and show as many as ten textural varieties of rock in a single thin section. The fragments are bound together by secondary chlorite, hematite and calcite. The production of secondary calcite in many of these clastic rocks has proceeded to such an extent that they are commonly mistaken in the field for limestones.

The crystal tuffs are composed of about 40 per cent of highly altered plagioclase fragments, areas of palagonite frequently amounting to 5 per cent, and 55 per cent of secondary calcite (Fig. 12). The tuffs weather down to a red clayey soil from which all the calcite has been leached and in which no bedded structure is apparent. Spheroidal exfoliation is rather characteristic, not only of the tuffs in this group, but of all tuffs

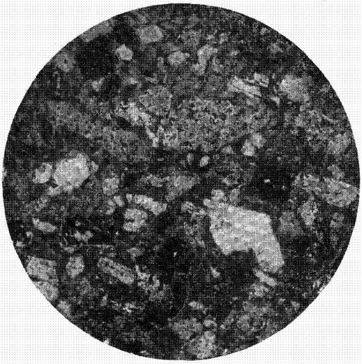


FIG. 12.—*Crystal tuff*

in the island. The Hoodoo structure, which frequently occurs, results from the sticky, compact nature of the tuff soil and from the presence of small rock fragments, which serve as protecting caps to the soil below them and prevent the vertically falling tropical rains from eroding away the underlying tuff soil. The result is a multitude of pinnacles three to six inches high covering the whole face of an exposed tuff formation. The formation of the Hoodoo structure is due in part to the same factor which develops the knife-edge ridges—that is, to the compact, sticky, difficultly eroded nature of the soil.

Not all of the tuffs are massive; some are faintly bedded. The latter are in some types composed of rather coarse, 7 to 10 mm. equigranular, rounded lithic fragments, which are usually oxidized upon the periphery.

Such fragments indicate a period of water sorting and rounding, followed by a period of oxidation. The cementing material is introduced calcite. Corresponding to the lithic is a crystal type, which is composed of rounded feldspar grains with associated carbonaceous streaks and a cement of secondary calcite, chlorite and quartz. Such characters indicate a water sorted and rounded rock. Other varieties of the bedded tuffs are composed of extremely angular grains, which are sufficiently well sorted and oriented to produce a bedded structure. The bedded structure is probably due to wind, because moving air within the limits of the size of the fragments which it can carry is more sensitive to differences of specific gravity than water, and, in addition, wind possesses a greater range of velocity. Moreover, a grain is always subject to resorting by the wind until it is finally dropped into a body of water. Most crystal tuff fragments are elongated; hence, when a tuff fragment falls to ground, if perchance it strikes upon one end, the fragment will fall over and lie upon a prismatic face. The accumulation of tuff grains all lying upon prismatic faces will result in orientation of the constituents and a development of obscure bedding structure. The essential components of all the lithic tuffs are oligoclase-andesine feldspars (40 to 50 per cent) highly altered to calcite and chlorite; also clear, fresh, fractured, equant, pale green augites about 5 per cent, magnetite 5 per cent and a few lithic fragments. The secondary cement consists of calcite and chlorite 20 per cent.

Still another variety is formed from tuff fragments which fell in the sea and became incorporated in the accumulating organic remains, such as foraminifera. Among the organic remains occur from 10 to 30 per cent of crystal or tuff fragments, some of which are rounded and evidently water-carried and others are angular and must have been windborne, but in all specimens a few well rounded grains testify to the accumulation of the organic fragments close to the littoral zone.

LIMESTONES

Akin to both the tuffs and the shales are the limestone lenses, which are, as a rule, only a few feet thick, although a few exceed 100 feet in thickness. Since they extend along their strike rarely more than a mile, the geologist is constantly bewildered by the abruptness with which they pinch out. Most of the limestones are found near the top of the group, in the central part of the district, which may indicate a former embayment of the sea. In color they are light to dark gray and in texture fine grained, and the thin sections show that these limestones are composed of clastic organic fragments, chief of which are foraminifera.

CONGLOMERATES

The best development of a conglomerate occurs near the middle of the group in the central part of the district, though isolated conglomerate beds are found frequently in other parts of this group, as near K. 99 and K. 94 on the Military Road. The pebbles and boulders are usually subangular, though some well rounded ones are to be found. Very large boulders, three feet in diameter, were seen north of Santiago. The boulders are chiefly andesitic igneous rocks with rare limestone fragments. These conglomerates in part have an igneous matrix, as, for example, those near K. 99 on the Military Road and of some north of Santiago.

AGGLOMERATES

A few beds of agglomerate occur in the tuff.

PHYSIOGRAPHIC EFFECT

In detail these rocks are affected by erosion in quite a variable manner, but considered as a whole they are carved into great spurs which extend southwestward and southward from the main axis of the Sierra de Cayey. The Military Road from Coamo to Aibonito after crossing the Cuyon River near K. 93 follows one of these spurs up to the Aibonito Wind Gap or Pass; the road from Guayama to Cayey follows another of these spurs to the crest of the range. In the great lower valley of the Salinas River there are many ridges oriented with the structure, such as Monte Sabater, west of Coqui. South of the Guamani Canal, extending from the Salinas Valley to Guayama, is a group of hills 200 to 300 feet high, developed upon resistant strata belonging to the Guayama series.

GENESIS

The origin of the Guayama series is doubtless similar to that of the Sierra de Cayey. The rocks of this series may simply be the peripheral portion of the Sierra de Cayey alluvial fans. Another and more probable view is to consider the Guayama series as the reworked portions of the Sierra de Cayey fan. After the first impulse of rejuvenation in the Sierra de Cayey had spent itself, erosion of a moderate character developed upon a lower grade. Rocks of varied types developed synchronously, because many agencies were at work. While rivers were building up a conglomerate inland and delta deposits seaward, volcanoes were active, spreading far and wide pyroclastic material, and here and there lava was flowing down a mountain side. Repeated periods of intense volcanism followed by long periods of gentle volcanic activity developed heavy beds of tuff and agglomerate and added to all the other formations some ejected volcanic material. During the dry season tuffs, perhaps gathered in the stream beds, cut into the various alluvial fans in sufficient quantities to divert the streams from their original beds in the times of flood. These periodic diversions would have started great mud-flows down the mountain sides, causing pebbles and boulders to be swept along with the mud-flows, all becoming more or less rounded *en route*.

Periodic encroachments of the sea gave rise to marine lenses. To do this a very slight subsidence would have been sufficient because (1) the delta phase of the piedmont plain would not have extended much beyond the shore zone and (2) in tropical regions, as shown in Porto Rico at the present time, limestones are laid down not only in the neritic zone, but commonly in the zone between high and low tides, and also some are formed beyond the reach of the sea, such as deposits of tepetate.

Rio Jueyes Series

GENERAL CHARACTER

The Rio Jueyes series is named from the river which flows over their central exposures. The series extends in a broad belt with an outcrop 4 to 5 miles broad and reaches from the west central part of this area southeastward, passing beneath the sea south of Guayama. Its one outstanding difference from the Guayama series is the number of limestones contained within it. The limestones, however, do not exceed in volume or number the shales, tuffs, or conglomerate beds. Lenses of agglomerates and volcanic breccias are numerous.

STRUCTURE

The rocks of this series differ from adjacent series sufficiently to make them worthy of a separate grouping. Their upper contact is sharp and clean. In fact, in many places the point of the geological pick may be placed where the Rio Jueyes series ceases and the Coamo Springs limestone series begins. The beds generally dip S. 30°. The total thickness may be as much as 5000 feet.

LIMESTONES

Two types of limestones occur, the white algal limestones and the dark gray crystalline, fine grained, highly bedded limestones.

Limestones begin to occur in the lowest formations and in Santa Sabater Hill reach their best development. This is a long, narrow, homoclinal hill north of Central Aguirre, which rises as a mendip, or morro, through the thin coastal plain deposit. The limestone beds composing this hill are in themselves variable; some have a cream tinge, are porous, and have an evident organic structure; other beds are highly crystalline, fractured and cemented by white calcite. Interbedded with both limestones are thin beds of tuffs. Both develop a pitted and cavernous surface upon weathering. It is remarkable how this limestone, soft and porous as it is, stands up as a resistant ridge. Everywhere in Porto Rico the limestones are resistant to weathering. Some form great ridges like the Coamo Springs limestone described below, others remain only as gentle swells, but everywhere they rise above the shale or tuff beds.

In thin section the white limestones are seen to be made up largely of honey yellow or colorless crystalline calcite. Rounded outlines, but without identifiable structures, indicate the former presence of organic substances such as algæ, which are present in tiny fragments, and foraminifera, such as *Globigerina cretacea, Globigerina bulloides* and *Truncatulina lobatala,* all of which indicate a very early Tertiary age.

Other limestones are fine grained, showing light and dark shades of gray and buff, and occur as thin, discontinuous lenses. Some may be 100 feet thick, but all those whose thickness could be determined are only a few feet thick. Most of the lenses are found in the eastern half of that portion of this group which rises above the recent coastal plain deposits. One rather continuous series of lenses, traced from southwest of Guayama across the district, occurs south of La Lapa, south of Santiago on the Rio Jueyes, south of Coamo on the Coamo River and again on the Descalabrados River. The lenses always occur among the shales into which they grade. Megoscopic volcanic material is present in many of them.

Under the microscope they are seen to vary from a tuffaceous limestone to a tuff with many shells. The organic fragments are comminuted pelecypod and gastropod shells with numerous foraminiferal remains, and diatoms, such as *Miliolina seminulum* Linné? The foraminifera observed are:

Orbulina universa?
Orbitoïdes papracea (Boubee).
Textularia gibbosa, d'Orbigny.
Globigerina, d'Orbigny.
Numulites sp.?
Gaudryina sp.?
Polymorphina sp.?
Miliolina sp.?
Biloculina sp.?

The rodiolarians are chiefly *Porodiscus concentricus*. The organic remains have all been more or less recrystallized and no calcareous algal structure was noted. The tuffaceous material is usually very highly altered feldspar laths with occasional lithic fragments. The feldspars and lithic fragments alter to calcite and chlorite.

SHALES

The shales, like the limestones, are best developed just west of the Salinas River, where they are finely bedded, siliceous and occur as frequent layers among the argillaceous phases. The color varies from buff

FIG. 13.—*Lithic tuff*

to gray. In thin section they are seen to be made up of a streaked dense material, chiefly quartz and some carbonaceous material. Little spherical holes, which are arranged in lines parallel to the bedding, make up about 1 per cent of the rock. Most of the tiny cavities are vacant, a few have a calcite filling and an occasional one has a diatom or radiolarian in it, such as *Melospira arenaria*, Rab., and *Coscenodiscus marginarus*, and similar types.

TUFFS

Beds of tuffs are exceedingly common. Beds of limestone are often sharply divided by a thin layer of tuff; most of the conglomerates have a tuffaceous matrix and some of the shales grade into tuffs. The pyroclastic formations are best developed in the western portion of the group. As in the older group, the tuffs may be divided into the lithic and the crystal groups. The lithic tuffs are frequently very beautiful rocks, since they are composed of angular fine-grained rock fragments of extremely varied colors, such as black, red, green, brown and purple. An excellent exposure of this type is found in the stream bed east of Coamo. The rock types present in the lithic tuffs are always andesites and as many as ten different varieties based upon texture may be present in one thin section. The fragments are cemented by calcite and chlorite and some are well bedded (Fig. 13).

The crystal tuffs do not differ from those described in the older series. They consist of lath-shaped altered oligoclase andesine feldspars, clear, fresh, pale green, embayed and fractured augites and grains of magnetite, all cemented by secondary calcite, chlorite, limonite and some zoisite. These secondary products are all derived from the feldspar and a former volcanic dust matrix.

CONGLOMERATES AND AGGLOMERATES

In the Rio Jueyes series frequent beds of conglomerate and agglomerate occur. The beds are never thick nor continuous along the strike and as a rule they are formed of well rounded pebbles and boulders of andesite and andesite porphyry. An interesting formation occurs about two miles north of the Rio Jueyes Water Gap, which consists of numerous well rounded three-inch pebbles of limestone, dark gray in color and highly fractured, with the fractures cemented by calcite. Among the well rounded pebbles also occur frequent three to six inch angular agglomerates, all in a tuffaceous matrix. Beds of this conglomerate six feet thick alternate with two-foot beds of shale. Two factors alternated to produce this formation: near-by volcanic eruptions, which gave rise to the tuffs and agglomerates, and stream erosion, which produced the conglomerates. The great falls of volcanic debris, probably diverted to streams first from one side of the alluvial slope down which they were flowing, and then to the other, and in this way the alternating beds of shale, conglomerate and agglomerate were produced.

PHYSIOGRAPHIC EFFECT

In part the Rio Jueyes series partakes in the formation of the spurs extending from the south flank of the Sierra de Cayey, and in part assists in the formation of an independent landmass south of the Rio Cuyon and west of Salinas. A series of great subsequent valleys is carved out of the southern half of the western third of the Rio Jueyes rocks. The eastern half of the series lies beneath the Santa Isabel coastal plain deposits and, therefore, exposures are to be found at only infrequent intervals.

GENESIS

From the facts stated above it appears that the conditions of accumulation were much the same as in the previous period. Mountains composed of older strata were being dissected and out of them alluvial fans of deposition were formed. Those portions of the fans which dip into the Caribbean Sea gave rise to shales, while conglomerates were formed in the ever-shifting stream beds. Between the projecting prongs of the fan the embayed sea was the site of calcareous deposition, and so limestones accumulated at stratigraphic horizons equivalent to the shales. Volcanic vents, of which a large number have been found in this district, gave forth moderate amounts of tuff continuously and at times exceptionally large quantities of both tuff and agglomerate. The result was that a series made up of alluvial fans alternating with local lenses of marine limestone was formed.

Coamo Springs Limestone Series

This series is named from a thermal spring located in the Coamo River Water Gap. It extends as a homoclinal mountain from Central Aguirre northwestward to the Descalabrados River and thence to the Jacaguas Reservoir. The Central Aguirre Hills are thought to be part of the same formation, a conclusion based upon the close similarity of the rocks and the alignment of these hills with the general trend of the Coamo Springs Range. If these hills are formed from the Coamo Springs limestone, then this formation continues eastward beneath the Caribbean Sea. The total length is at least thirty miles and the thickness about 800 feet. This group is composed essentially of a single formation, a heavy bedded, steeply dipping limestone, which forms one of the most interesting petrographic types and erosional features in Porto Rico. In addition to limestone, however, there are many thin beds of tuff within the limestone, into which the limestone grades at its top and bottom. Near the top and bottom the tuff beds get thicker and more numerous until the limestone ceases entirely.

STRUCTURE

The limestones and associated tuff beds of the Coamo Springs group have been tilted to rather high angles and in places faulted. In the

Aguirre Hills the dip is 45° S., at Salinas Hill 45° S. and at Jueyes Water Gap there is a change in dip from the top, where it is 70° S., to the bottom, where it is 45° S., which indicates the south limb of an anticline. West of the Coamo River the dip varies between 35° S. and 50° S. and in the vicinity of the Rio Descalabrados anticlinal structure is well shown (Fig. 14). The good evidence of anticlinal structure to the east and west of the Coamo River Water Gap suggests that the structure at the gap is also anticlinal, even though it is not evident there because of the

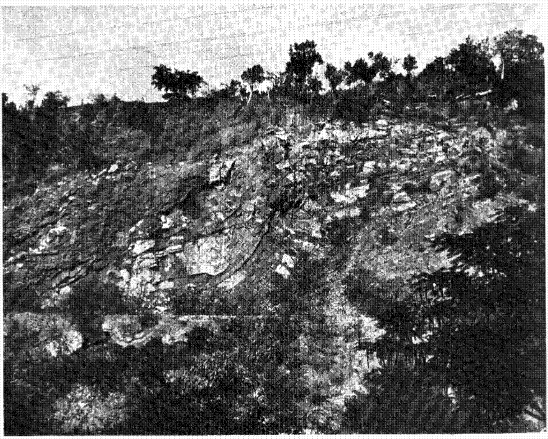


FIG. 14.—*Coamo Springs limestone exposed in the Descalabrados Gap*
Photographed by Professor H. E. Crampton.

massive character of the rocks. An anticlinal structure at this point would explain the great breadth of exposure of the limestone.

The whole range is arranged *en echelon*. The continuation on the westward side of the Rio de Coamo is almost a mile south of a line continued from the Cerro Pimentol westward, and in like manner the Cerro Gavia is broken in two places. These are features explainable only by faulting. The contacts of the Coamo Springs limestone series are the best marked of any rocks in the district.

LIMESTONE

The appearance of the limestone which forms this series is variable, yet certain features are so constant that the rock may be recognized at a glance and can be easily distinguished from all other limestones occurring in Porto Rico. The color varies from chalk white to cream or to pale lilac. The grain is very fine in most occurrences, but in part it is medium, and the size of the grain increases to the westward. Some of the rock is made up wholly of crystalline limestone, but for the most part it is mottled with organic and tuff fragments which are brown, soft and may easily be picked out with the point of a knife. The organic fragments

FIG. 15.—*Lithothamnion thallus in cross-section in the Coamo Springs limestone*

vary in size from 1 to 3 mm. and are cream-colored. Their organic character is apparent even in hand specimens, as shown by concentric zones in which a fine mesh structure can be seen. Other varieties have a fine-grained lilac-colored material stained with hematite, forming a matrix for the organic bodies. The thalli of the algæ of which this rock is largely composed are shown in figures 15, 16 and 18.

The microscopic character of this rock is most interesting. It is found to consist of at least three varieties of algæ-like structure. Some of these are undoubtedly of the red calcareous algæ type. Figure 16 shows one form that has a fucoid appearance, which is apparently the spore case of a thallus in longitudinal section, and 15 a thallus in cross-section. In addition to the algæ structure, foraminifera of several species are present, some of which are *Amphistegina* sp. (Fig. 19), *Discorbina globularis*, d'Orbigny, *Orbitoides* sp., *Globigerina* sp. (Fig. 42); ostracoids also occur, all of which testify to a Tertiary age. The interstitial substance is made up of interlocking calcite grains averaging .05 mm. in diameter, which have evidently been derived from the organic bodies (especially the algæ) by recrystallization. This is shown by the transition contact between the two and by the shadowy outlines of thalli in crystallized calcite. The organic structures have been highly fractured, broken and cemented by limonite before the induration of the rock took place. This suggests dry-land conditions. The tuffaceous matter consists of fractured crystals of the oligocene-andesine varieties. Chlorite areas are

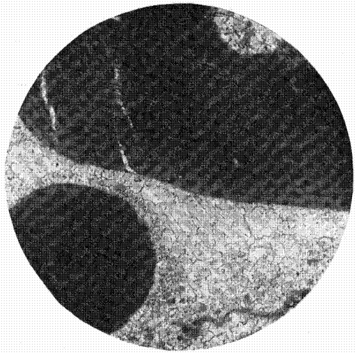


FIG. 16.—*Lithothamnion thallus in longitudinal section in Coamo Springs limestone*

also present, suggesting former pyroclastic grains. In some a bright green glauconitic-like substance occurs.

TUFFS

The tuffs have no features different from those described above.

PHYSIOGRAPHIC EFFECT

Because limestones are not eroded with ease in the tropics, the Coamo Springs limestone stands up as a ridge of southward-dipping rock.

Aguirre Hills are only a few hundred feet high (Fig. 17) and are separated from the rest of this homoclinal mountain by the broad valley of the Salinas River. Salinas Hill, the eastern extremity of the Cerro Raspado, rises to four hundred feet, and from this place the elevation increases till just east of Coamo Springs, where the elevation of the Cerro Pimentol is one thousand feet. Just west of Coamo Springs the elevation is again only six hundred feet, but it rises westward to over one thousand

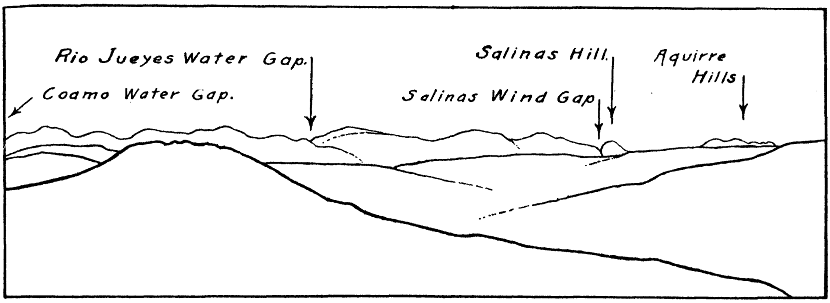


FIG. 17.—*Coamo Springs Range*

The sky-line is formed by the crest of the Coamo Springs Range. The middle portion of the sketch is occupied by the present coastal plain.

feet at Jacaquas Reservoir. To the north a great subsequent lowland has been carved, and to the south and east of the Coamo River the coastal terraces, carved in a later formation, reach to the foot of these mountains. Wind-gaps in its crest are common. In places the crest is double and in others triple, due to the intercalated and easily eroded beds of tuff.

GENESIS

Specimens selected either at random or by intent from various portions of the limestone formation universally show algal structure. In some parts, where only little shreds and fragments are to be found, the former presence of algæ is attested to by the faint outlines of their former thalli preserved in the recrystallized calcite. From top to bottom and throughout the entire length the formation was originally composed of about 40 per cent algæ—an estimation based upon the percentage found in the many thin sections studied. In some of the thin sections and hand specimens the ramifying branches of the former plants can still be seen, but for the most part the algæ are in fragments. The fragments are more or less rounded and, of course, this rounding is largely the result of surf-work, but in part it undoubtedly was due to terrestrial agencies—wind and flowing water—as shown by the oxidized borders of many of the worn algæ fragments. Some of the oxidized and other fragments possess fractures which, cemented by calcite, must have been formed at a time foraminifera occurring associated with it are also of shallow-water origin, or that foraminifera can be drifted shoreward and accumulated under shallow-water conditions. Since the foraminifera in the Coamo Springs limestone are identical or similar with those found in older and younger limestones, not containing algæ remains, it is probably safe to conclude that these limestones, too, were formed in shallow embayments of the southern coast. To accept this view assists in the explanation of the occurrence, character and relationship of the limestone lenses.

FIG. 19.—*Amphistegina in Coamo Springs limestone*

Calcareous algæ contain a great deal of magnesium carbonate. This is shown by the average of fourteen analyses (Högbom, 1894) of *Lithothamnion* selected from all parts of the world, which is calcium carbonate 80.29 per cent and magnesium carbonate 8.14 per cent.

In the processes of crystallization there may have been a residual enrichment due to the more soluble character of the calcium carbonate and a dolomitic limestone may have been formed. Algæ were undoubtedly the more dominant form of plant life in the earlier geological periods and the suggestion is offered that the dolomites of the early Paleozoic may have had their origin in this manner.

Rio Descalabrados Series

GENERAL CHARACTER

The series is named from the river which flows across them at their widest exposure. All the strata of the older series occurring above the Coamo Springs limestone belong to this series. It is largely covered by coastal plain deposits; hence outcrops are few and isolated and are found chiefly in a few road-cuts. West of the Coamo River a series of parallel hills rise through the coastal plain deposits and produce the exposures upon which this discussion is based. This group is composed of limestones, shales, cherts and tuffs.

STRUCTURE

The rocks all dip seaward at angles from 20° to 50° and the strike is uniformly N. 30°–50° W. Between the Coamo and Descalabrados Rivers the rocks are broken by a normal fault, which is thought to be the same fault that offsets the Coamo Springs limestone. The lower contact is sharply defined, but the upper contact is unknown because it lies beneath the Caribbean Sea. The thickness of this series is at least 3000 feet.

LIMESTONES

Three distinct limestones occur which resemble each other very closely in a petrographic way and which are separated from each other by thick beds of shales, cherts and tuffs. The variations which do occur are of a linear character—that is, they grade into each other from top to bottom or along the strike. The color is gray except where the limestones contain much included tuffaceous material, which gives them a green or yellow shade. The grain is medium or coarse crystalline where the rock is homogeneous, except where large quantities of tuffs are present which appear to have prevented complete recrystallization. The lowest limestone formation is the most impure and resembles the Coamo Springs limestone very much. This is especially true in that outcrop forming the hill to the east of the Coamo Springs Reservoir. All these rocks are highly fractured and cemented with calcite.

In this section these limestones are seen to be made of three types of material: organic, volcanic and recrystallized calcite. The organic material consists of algæ, which are most numerous in the bottom limestones. Foraminifera are common in all three formations, some of which are *Nummulites* sp., *Orbitoides* sp., *Biloculina* sp., *Miliolinas* sp. and *Globigerina* sp. The tuffaceous material consists of oligoclase—andesine feldspar altered to chlorite, calcite and limonite. Depending upon the abundance of one or the other of the secondary minerals, the color of the rock is olive green or a buff yellow. Grains of magnetite are common and a few pieces of devitrified palagonite occur. The binding of calcite has been developed from interstitial lime silt and from the larger organic remains. In many ways the origin of these limestones was identical with that of the Coamo Springs formation.

SHALES AND CHERTS

The shales and cherts form finely bedded deposits occurring between the limestones. Most are silicified, a few epidotized, and some are cal-

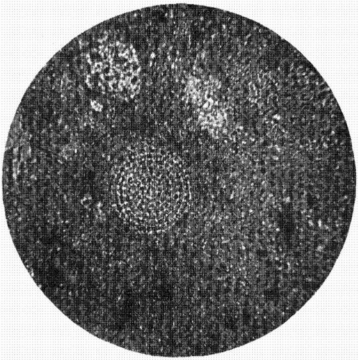


FIG. 20.—*Porodiscus concentricus in shale*

careous and others are argillaceous. The excellent bedding is an expression of a very fine lamination, microscopic in size which weathering brings out in relief. The colors are black, dark gray or green. Microscopically these shales and cherts are of a dense material the composition of which it is impossible to determine, but is probably a very fine secondary quartz with carbonaceous streaks, sericitic flakes and limonite bands. Most of these rocks contain small spherical holes arranged in lines, some of which cavities are filled with quartz, others with quartz and calcite and still others have radiolarian remains. As the radiolaria can be seen to alter secondary quartz, the calcite must be tertiary and introduced, probably, under thermal conditions. Some of the shales are fractured and the fractures cemented by epidote which develops outward from the fractures and in some entirely replace the rock. The silicification is thought to be due entirely to recrystallization of the radiolaria and diatoms, some of which are *Heliodiscus humboldti* Ehr. and *Porodiscus concentricus* Ehr. (Fig. 20) and diatoms of the type of *Melosira* sp. The highly bedded character of the shales belonging to this group is shown in figure 21.

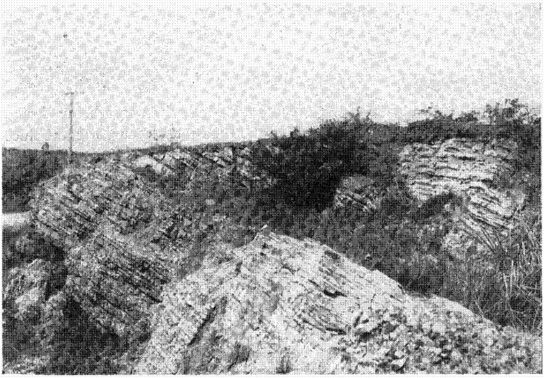


FIG. 21.—*Shales of the Rio Descalabrados series*
Photographed by Professor Charles P. Berkey.

PHYSIOGRAPHIC EFFECT

West of Central Aguirre the recent marine terrace is carved upon the upturned edges of Rio Descalabrados series. A few hills, due to the resistant limestone beds, are separated by a series of small subsequent valleys opening up toward the Coamo and the Descalabrados Rivers. These hills are divided into three parts by the Coamo and the Descalabrados. Of these the small limestone hill east of the Coamo Reservoir is the northeasternmost division. In addition to the three major divisions so formed, these hills are again divided by small resequent valleys.

GENESIS

The view is held that these shales are entirely of delta origin, which is indicated by the excellent bedding, the carbonaceous streaks and lenticular character of the beds. During the period at which this group was formed there was an intermittent subsidence, so that after delta shales had accumulated offshore limestones would develop. The subsidence was sufficiently graded so that before the limestones could reach a notable thickness a newly formed delta advanced seaward and covered them. A later subsidence gave opportunity for a new limestone deposit. This condition was repeated at least three times.

Arecibo Formation

This formation has been described by Berkey, the name being derived from a river on the north coast where the limestones occur in great thickness. The Arecibo caps a hill 100 meters in diameter in the southwestern corner of the Coamo-Guayama district. This formation once covered the district over a much greater area, as is shown by the erosional border lying just west of the district, by the isolated remnant of erosion above mentioned, and by the superimposed drainage.

Because of its importance in the interpretation of the geological history of this region an extended quotation from Berkey (1915, p. 50) is perhaps admissible:

> Both on the north side, for nearly the whole length of the island, and on the south side, over the western half, there is a bordering belt of limestone and associated beds that have been developed on an eroded surface which beveled across the more complex structures of the older series of formations that formerly made up the mass of the island. These limestone beds are several hundred feet in thickness and dip gently toward the sea. On the inner margin of their present extent toward the interior they are abruptly terminated in a very irregular line of modified cliff forms facing toward the prevailing smoother and lower ground for some distance toward the interior. In its best development, however, it is a typical cuesta, formed in the usual manner by the erosion of a formation representing a recently uplifted coastal series. The series of formations involved formerly extended inland very much farther than they do now. Only the outer margin remains from the erosional construction of a series of beds and reefs that in former times covered a large portion of the island. . . .
>
> In a large way this series forms a structural unit. Below it lie the older and more complicated igneous and sedimentary rocks. The break between these two represents the chief unconformity in the whole geological column. For a considerable distance an average dip of 30° to 36° was estimated and the total thickness represented, based upon the width of the belt, must be at least 3000

feet. As one goes eastward, a comparatively short distance they are almost entirely lacking. . . .

Between Guanica and Juana Diaz, wherever the inner margin of the Arecibo formation was seen, it was bounded by a fault which brings the upper beds abruptly against the older tuffs and shales of the pre-Tertiary. The formation furnishes an abundance of fossils. The lower portion of the lower beds on the south side of the island, as seen at Juana Diaz, seem to be the most promising for a determination of the age of the beds of the formation. . . .

The formation as a whole is essentially a structural unit. . . .

These rocks are separated from the older ones by a discordant unconformity or structural unconformity. This is shown by the manner in which these gently dipping Arecibo limestones rest on rocks tilted to high angles and by the fact that they rest on a peneplane surface.

The existence of this peneplane was first observed by Berkey, who says:

Beneath the limestone constituting the cuesta and representing the Tertiary series, there are, in numerous places, traces of a former plain that represented the results of erosion on rocks that had a complex structure. Occasional profiles of more distant ridges also show a sky-line that suggests the former existence of such a plain, and in favorable localities it can be traced directly to the foot of the limestone cuesta. Occasional traces are also seen on more mountainous tracts, especially at the west end of the island, near Rincon and in the vicinity of Mayaguez. It is the judgment of the writer that these all belong to a single base-leveling surface or marine-cut platform formed in the period just preceding the development of the Tertiary limestone series.

The peneplaned surface has been elevated and tilted. The elevation is 2500 feet in the eastern portion of the Coamo-Guayama district and 3000 feet in the western. It descends toward the north. Dissection has cut down far below the level of the peneplaned surface to the south, and so its former trend can only be inferred. Were it not for dissection the former peneplaned surface would attain at least another thousand feet at the southern coast.

That the Arecibo limestone once covered the entire district is shown by the superimposed condition of the major streams. In the above paragraphs the general strike of the stratified rocks is described as northwest and southeast, but the large streams, excepting the Rio de la Plata, flow southward. It might be argued that the original drainage was parallel to the structure and that coastal streams have worked back and captured them. Such problematical coastal streams would have received their initial supply of water from the most arid portion of the island, while the captured streams were supplied by the heavy daily rains of the interior. To capture under such conditions is impossible and the theory must be abandoned. The large streams have courses discordant with the structure. This is shown in most striking fashion by the Rio Descalabrados.

Coamo and Jueyes, which pass at angles of ninety degrees and comparatively narrow water gaps through the Coamo Range.

PHYSIOGRAPHIC EFFECT

One result of the superimposition of the drainage across the structure of the rock has been a numerous series of captures. A good illustration of a recent one is cited. A channel filled with pebbles lies between Salinas Hill and the Cerro Raspado. Back of this latter range a subsequent branch of the Rio Jueyes flows, and it seems evident that this latter stream has captured the headwaters of this nameless stream and diverted them eastward. As a result a wind-gap, which is so low that a wagon road passes through it, has been formed.

Santa Isabel Series

OCCURRENCE

This formation is named from a little village situated upon the coastal plain deposit in the southwestern part of the district. Deposits of the Santa Isabel series cover the southern border, extend as embayments up all the rivers flowing across the coastal plain, and occur as isolated patches along the various rivers.

GENERAL CHARACTER

For the most part this series is composed of a fine black alluvium of varying thickness. Thus, west of La Lapa the Rio Cerro shows 20 feet of bedded silts interlarded with boulder beds. North of Salinas Hill it is 25 feet, near the Baños de Coamo the river flows between vertical silt walls 50 feet high (Fig. 23), and at Guayama the silts are only a few feet thick.

All of the alluvium found in the valleys of this district cannot be classed as a coastal plain deposit (Fig. 2). Some is due to a local base-level created by a hard rock partially damming some stream. Streams dammed in this manner have aggraded their valleys with alluvia to considerable depths. Thus, three miles north of Rio Jueyes Water Gap is a deposit 25 to 30 feet thick composed of excellently bedded silts with an occasional lens of pebbles, and in this stream there are also alluvial beds at 660 feet elevation. Again, in the great Barranquitas-Cayey subsequent lowland is a deposit of silt 10 to 15 feet thick, due to a local base-level located just south of Comerio which is about 1500 feet above sea-level. Such deposits are classed with those of coastal plain because they have been formed in Recent times.

The coastal plain rests upon the upturned edges of a series of tuffs and shales and upon these planed surfaces wave-rounded boulders are frequently found, as shown in a cut of the road southeast of Guayama. Between and on the top of the Aguirre Hills such boulders occur in profusion and represent the time when the sea was awash with the tops of these hills. Some of these perfectly rounded boulders are of Arecibo limestone which must have been transported littorally a great many miles.

In the beds of many of the streams deposits of chalky white, porous limestone are being formed. These tepetate deposits form in the shallows of the intermittent streams, where the waters evaporate rapidly. They are also formed at points where the water cataracts over a small ledge and loses some of its carbon-dioxide content and is thus forced to precipitate its heavy load of calcium carbonate.

PHYSIOGRAPHIC EFFECT

When the coastal plain was in process of creation the streams previously developed upon the old land entered the sea at the inner margin of the present coastal plain. With the retreat of the sea the rivers flowed over this coastal plain and some of the streams, like the Coamo, sought out their old courses and became resurrected, while others, like the Descalabrados and the Rio de la Lapa, were not able to cut through the coastal plain upon which they meander to the sea. These streams meander upon reaching the coastal plain because they lose much of their water through the silts and gravels. This lost water, upon reaching the surface of the wave-cut terraces, seeps along the top of these terraces to the sea. This seepage furnishes the only zone of water to which wells may be driven in the whole Coamo-Guayama district.

Still another class of streams was created for the first time upon the gently inclined surface after the emergence of the coastal plain. The lower portion of the Guamani belongs to this classification and the Rio Cemarrona is another good example which by headward erosion has begun to eat into the old land behind the coastal plain.

The superimposition by the coastal plain of some streams has caused marked changes in drainage. Thus, the present course of the Guamani is either due to capture or to the superimposition of a stream which formerly flowed down the wide-open valley east of Guayama hills, but now flows down to a point marked by arrow (Fig. 22) and then turns abruptly westward through a narrow cleft in a spur of the mountains and then flows southwestward to the sea.

The terraces found at the lower end of the Coamo, and to a less extent associated with the other streams, are due to the dissection of the embayed portions of the coastal plain. The elevation of about 250 feet which brought the coastal plain to view revived all the streams. The reviving influence of uplift took place long enough ago that the effect is now active in the headward courses of such streams as the Rio de la Lapa. In the upper reaches of the streams degradation is cutting into the old complex of volcanic rock. Figure 23 shows how the Rio de Coamo has cut a young valley 50 feet deep into the alluvium accumulated when the Coamo stood at the highest level during recent times.

Most of the streams in this district have cut laterally faster than they cut downward. This lateral cutting flattens the floor of the valley. The

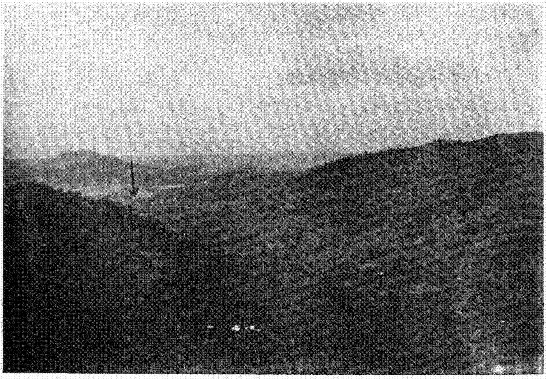


FIG. 22.—*Valley of the Guamani*
Photographed by Professor Charles P. Berkey.

cut continues to one side until the streams meets a resistant rock which reflects it to the opposite side, and a deflection in a stream once started continues until deflected again. Associated with lateral cutting is down-stream cutting. The combined effect is to produce a terrace. Slow uplift of streams which are provided with rocks in their banks to deflect them will cause a series of terraces to be cut one below the other. Ledges of rocks projecting into the stream are ideal for this purpose. The Rio de Coamo is deflected by the Coamo Springs limestone and as a result three terraces are formed. Continued uplift has caused these to be dissected by consequent streams into a dendritic pattern. The highest terrace of the

Coamo is dissected to a depth of 50 feet in this way—a testimony to the rapid rejuvenation which has taken place.

The coastal pattern appears to be due in part to the coastal deposits as shown by the present growth of the south coast. Offshore coral reefs are being built. Inside of these land-derived silts are accumulated until the water is shallow enough for mangrove bushes. These form veritable traps for sediment and the sea floor is rapidly transformed to dry land. All along the south shore this is an active process. If one could remove all

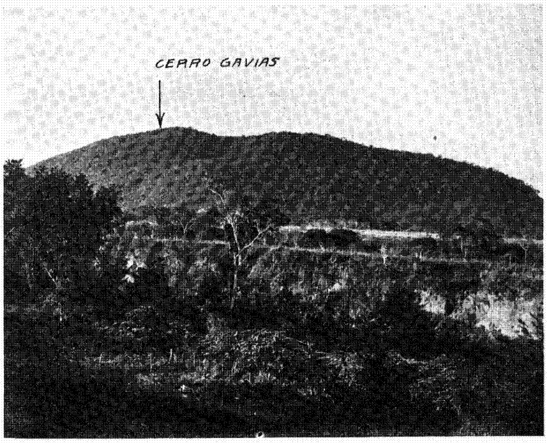


FIG. 23.—*Cerro Gavias, Coastal Terrace, Coamo River*
Photographed by Professor H. E. Crampton

this built land the angular character of the south coast would be very pronounced. The projections seem to have no relation to present streams; they are not deltas; in fact, they are composed of truncated rock covered with a thin veneer of coastal plain. A tentative theory is proposed—the southwest shore of each of these prongs has a trend practically parallel with the general structure of the region. Moreover, if the various resistant strata were continued to the sea they would in each case follow these projections. When the region was submerged, subsequent valleys were drowned and the ridges between were planed by the advancing sea. Then the uplift of 250 feet came, which was not sufficient to fully resuscitate the drowned portions which form the embayed portions between each projection. The combined results of drowning and marine planation have produced the angular coast lines.

GENESIS

The withdrawal of the sea to its present position exposed a series of terraces covered by a mantle of sediment. This mantle is called a coastal plain, though it is commonly misnamed playas (Grabau, 1913).

The coastal plain is a heavy black alluvial silt deposit and is looked upon as delta material deposited beyond the cutting edge of the advancing sea which carved the southern coastal terrace. After being deposited as deltas, littoral currents swept the material along shore and so spread a thin veneer over the whole wave-cut terrace. The mangrove bushes undoubtedly were an important factor in the formation of this coastal plain. Their ramifying branches caught the silts and caused the sea bottom to be rapidly brought to the surface. Thus part of the Central Aguirre Harbor near Pta. Carchones within the last five or six years has had a fringe of land built out from the shore over 200 meters and the mangrove belt has advanced seaward an equal distance.

Early Intrusives, Flows and Pyroclastics

OCCURRENCE

The earliest intrusive igneous rocks occur as innumerable dikes and sills cutting the older series and as occasional flows and as fragments in tuffs and volcanic breccias.

The rocks of this series will be discussed in two divisions. The first described will be the composition rock types, and the second the structural types.

COMPOSITION TYPES

The following composition types will be described: rhyolites, feldspathic andesites, augite andesites, olivine andesites, basic augite andesites, olivine-free basalts and olivine basalts.

Rhyolites.—Rhyolites are extremely rare and occur widely separated as thin flows. Most of the rhyolitic types were observed as occasional fragments in volcanic tuffs and breccia in the younger rocks of the older series.

The hand specimens are mostly aphanitic, though a few show quartz grains as large as 1 mm., and flowage structure is well developed. The color varies from gray, bluish-gray to buff and all are more or less mottled by iron stains.

In thin section a few of these rocks prove to be glasses. Patic substance varies from 75 to 90 per cent, which is colorless, shows excellent flow lines and contains many blebs and bubbles. In most of the thin sections the quartz cannot be certainly distinguished from the feldspars. In some, however, small .03 mm. euhedral quartz crystals occur. Tabular clear feldspar of the sanadine variety is the rule, but orthoclase and even albite are frequently found, which are usually kaolinized. Magnetite and titanite occur. Secondary minerals are limonite, kaolin, sericite and leucoxene. Some of these rocks are devitrified, as shown by the microaphantic but not isotropic groundmass, and these rocks are much affected by epidotization and carbonation.

Feldspathic Andesites.—The feldspathic andesite rocks occur as small dikes, as thin sheets or flows and as parts of volcanic tuffs and breccias throughout the entire district and cutting all the sedimentary formations of the older series. While their distribution is universal, they do not occur in equal abundance in all parts of the area. Thus, in the eastern part of the district they are about the only rocks to be found, but to the westward, andesites of other varieties increase in number until in the extreme western portion feldspathic andesites are found infrequently. In other words, feldspathic andesites are more numerous in the proximity of the granite batholith and appear to be diaschistic dikes.

These rocks, as found in the field, show grains which are rarely larger than 3 mm. and very few of them are aphanitic. Where glassy substance is present it is only found by microscopic study. Most of the rocks are hiatal—that is, show crystals of marked larger sizes—but few show a perfect gradation between the grains of various sizes. The minerals as a rule, have a tabular or prismatic habit and some have a true granular shape. Only phenocrysts of plagioclase appear, which are usually tabular, though at times they are prismatic. Rarely do the plagioclases occur in groups, but when they do, two or more are crossed like the letter *X*, and some are striated. The colors of these phenocrysts vary from pure white to pale green when fresh. The color of these rocks as a whole is decidedly light green, though darker green is common and other colors are gray and buff. Commonly the green color is not uniform, but within the pale green spots of much darker green occur. These types upon weathering simply get a darker green, though the feldspars at times take on a reddish color due to iron stains. Epidote areas are common and these begin to develop just about the feldspars. The rocks are frequently fractured and the fractures cemented with calcite or in some places by epidote. Some contain vesicles which are usually about 4 mm. long and filled with calcite, which is white or pink. Microscopic study shows the structures of these rocks to be extremely variable. Some are equigranular, others are decidedly hiatal, but most of them occupy positions between the two extremes. By far the largest number are seriate porphyroid. The larger grains rarely get above 3 mm. in size, the average larger crystals or phenocrysts are about 3 to 5 mm, and the smallest grains in the groundmass are .05 mm. The phenocrysts seldom make up more than 25 per cent of the rock; the average is 10 per cent. In some rocks the crystals have no definite arrangement, but in most the crystals in the

FIG. 24.—*Felspathic andesite*

groundmass have a true pilitic texture. Rarer types have diabase texture and extremely rare types have fine granular texture.

The feldspars present in greatest abundance are of the oligoclase-andesine variety. They are tabular to prismatic, dull, at times highly altered even to complete replacement, frequently embayed by the groundmass, and often containing inclusions of the groundmass. The twinning lines are irregular and uneven. Very commonly the feldspars are cumulophyric. The feldspars are extremely susceptible to alteration and in fact it is a rare thing to find a fresh one. The change to chlorite takes place readily and especially in the case of the smaller crystals. In this variety of andesite, where the groundmass is highly feldspathic, it is usually entirely altered to chlorite; hence the green color of all these rocks. The feldspars also alter very readily to calcite. In some this alteration has proceeded to such an extent that they are commonly mistaken for limestones. Other alterations affecting the feldspars are changes to secondary quartz, epidote, actinolite, and zeolites which are hydrothermal effects.

The feldspathic andesites are almost a single primary mineral type. The only other primary constituents are magnetite and apatite. The magnetite is often euhedral and averages 5 per cent in amount (Fig. 24). The fillings of the amygdules will be discussed under hydrothermal effects.

Augite Andesites.—Rocks of the augite andesite variety are very rare in the eastern portion of the Coamo-Guayama district. In the central part, compared to the feldspathic andesite, they occur as two to one and in the western third as three to one. They are not confined to rocks of any particular age, but occur as small dikes, sills and flows in rocks of all ages. Sills especially are abundant; augite andesites occur most profusely as components of the tuffs. The two best occurrences of columnar rock are of augite andesite, one of which occurs about three miles north of the La Lapa and the other on the Aibonito-Comerio Road at K. 40. The several occurrences of pahoehoe lava are of augite andesite. Augite andesites are found about the several volcanic centers and are especially abundant about the volcanic center east of La Lapa. The augite andesites therefore are by far the most abundant igneous rocks in the district and make up the major part of the pyroclastic sediments. The size of the grains in these rocks is characteristically small, usually below 3 mm. in their largest dimension, and a few of the rocks have components so small that their crystallized character cannot be determined with a hand lens. The few types which are in part glassy were only so determined by microscopic study. Over 80 per cent are porphyritic, and of these but a small portion are augite porphyries or with phenocrysts 5 mm. or larger. The fabric is most variable; some are decidedly hiatal—*i. e.,* composed of two types of grains differing greatly in size. In some the grains are of uniform size. In most of these rocks the grains are tabular or prismatic and have pilitic or diabasic texture. In a few rare types the texture is truly granular. In some of the rocks of this type only augite phenocrysts are to be observed. These are usually equant or equant-tabular, of dark-green color, and the augites are fresh and clear and more or less perfect in form. The feldspars when observed are usually tabular or tabular-equant, rarely prismatic, and frequently many are grouped together and commonly two or more feldspars are crossed like the letter *X*. Striations are rarely present. The color is sometimes white, usually gray or greenpredominating minerals present. Introduced zeolites, epidote, antinolite, and quartz are frequently seen.

The glassy varieties of the augite andesites occur only as portions of tuffs and volcanic breccias. In these the structure is decidedly porphyritic. Dark brown glass forms 70 per cent of the rock, which contains abundant vesicles and crystallites and shows a well-developed flow structure. The feldspars form 10 per cent of this rock and are tabular twinned, clear and are of the oligoclase-andesine variety. Augite up to 15 per cent occurs in small euhedral pale green, cleaved, fractured fresh grains. Apatite and titanite also occur. Leucoxene and chlorite are de-

FIG. 27.—*Glassy-augite andesite*

veloped in small amounts. These paloganites or augite andesite vitrophyres cannot be other than the former glassy scum formed on the surface of some lava-filled crater (Fig. 27).

Olivine Andesites.—Andesitic rocks containing olivine are not abundant, though several notable occurrences of them were observed. Thus north of La Lapa is a large exposure occupying the bed of the Rio de la Lapa for half a mile and in the vicinity of a volcanic center east of La Lapa they are common as dikes and they occur throughout the central and western half of the district as dikes, sills, flows, or as fragments in tuffs and volcanic breccia.

The hand specimens of these rocks look very much like the augite andesites, from which they differ only by the darker colors of the groundmass and the presence of olivine instead of augite crystals. The groundmass is gray, dirty green or chocolate and iron stains are very common. When the olivine is present it occurs as tiny 1 to 2 mm., euhedral crystals, but usually the olivine is altered and its former presence is shown by cavities of olivine shape filled with limonite.

The microfabric of these rocks is seriate intersertal to seriate porphyroid. Phenocrysts make up 37 per cent of the rock. The largest grains reach 3 mm. Since augite also occurs in these rocks they might be considered as basalts, but we place in this group all the rocks in which the quantity of the feldspars is three times the femag constituents. The

FIG. 28.—*Olivine andesite*

feldspars are oligoclase-andesine with some labradorite. As phenocrysts they do not exceed 5 per cent, but since they are extremely abundant in the groundmass their average percentage is 70. The oligoclase-andesine occurs in prismatic crystals with regular twinning lamellæ. They are altered to calcite and much stained by limonite. The augite is the usual pale green, fresh, twinned, cleaved, fractured, cumulophyric crystals with chadocrysts of magnetite and makes up 10 per cent of the rock. The olivine grains are small, about one or two mm. occurring only as phenocrysts. When fresh they are euhedral, but usually they are completely altered to serpentine, limonite and hematite. They are very cumulophysic and make up 5 per cent. Magnetite occurs as large irregular grains, frequently intergrown with augite, amounting to 5 per cent.

Hematite, limonite, serpentine, secondary magnetite are the alteration minerals (Fig. 28).

Basic Augite Andesites.—Only two occurrences of basic augite andesites were observed, both as dikes cutting the lower parts of the older series. The matrix of this rock is aphanitic and dark dull grayish green. Small 2 mm. dark green, almost black, equant augites and 5 mm. laths of pale green feldspar form the phenocrysts. The microscopic appearance of these rocks is very similar to the augite andesites described above, from which they differ in the greater percentage of femag minerals. Thus in the augite andesites the ratio of feldspars and femags runs 70

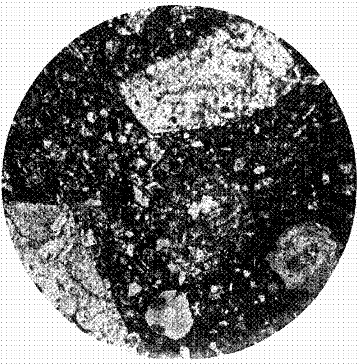


FIG. 29.—*Olivine free basalt*

to 30 and in these 65 to 35. The fabric is seriate porphyroid and the arrangement of the crystals is diabasic. Phenocrysts form about 40 per cent of the rock. The feldspars are of the andesine-labradorite variety. Some oligoclase also occurs. The feldspars are tabular, irregularly twinned and zonal, and contain inclusions of brown glass. They occur in groups and are strongly affected by chloritic alterations. As phenocrysts the feldspars form 30 per cent of the rock and the augite 13 per cent. The phenocrystic augites are tabular to equant, subhedral, fresh and cumulophysic. In the groundmass the feldspars are extremely prismatic, fresh and form 9 per cent. The augites of the groundmass form 14 per cent, are equant, fresh, highly cleaved, pale yellowish green, nonpleochroic and interstitial. Magnetite in large 4 mm. equant grains forms 8 per cent and a few grains of apatite occur. Chlorite developed along cleavage plains in the feldspar is the only secondary mineral. Some of these rocks are amygdaloidal with calcite fillings.

Olivine-free Basalts.—The only occurrence is a vesicular flow near a boss of granodiorites northeast of Coqui. Considered megascopically it is slightly porphyritic, with light to dark gray feldspars occurring in a dark gray matrix. Small amygdule areas filled with white calcite are present. The fabric of this rock is seriate porphyritic. Phenocrysts of feldspars 1 mm. in size occur in a consertal groundmass and are chiefly andesine-labradorite, which are tabular crystals made up of broad twins

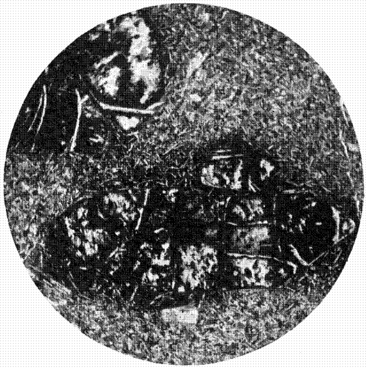


FIG. 30.—*Olivine basalt*

of variable width. As phenocrysts and as groundmass the feldspars make up 60 per cent of the rock. About 30 per cent of bytownite anorthite occurs, which is similar to the other feldspars except in extinction. Nearly 10 per cent of .05 mm. equant grain of augite are present. Calcite, chlorite and hematite occur as secondary minerals (Fig. 29).

Olivine Basalts.—The olivine basalts are found frequently among the tuffs or as flows, dikes or sills of the older series. The color of the matrix is very dark gray, purple or reddish. The phenocrysts are 3 mm., equant to tabular dark green augites, 5 mm. tabular, striated, light green feldspars, and rusty pits of olivine shape. Most of these rocks are either vesicular or amygdaloidal (Fig. 30). A study of the thin sections shows some of them to be basaltic vitrophyres which have a decidedly hiatal fabric. Phenocrysts make up 50 per cent of the rock. In part the groundmass is microaphanitic. The basic glass is grayish yellow, though in part it is greenish, probably due to chlorite alterations. The yellowish glass is crowded with tiny bubbles, globulites and perlitic cracks. The phenocrysts consist of large 1 mm. crystals of bytownite-anorthite, 10 per cent of andesine, and 10 per cent of labradorite. All the phenocrysts are tabular, broadly twinned and altered along twinning planes to chlorite. Clear, fresh equant pale green euhedral augites occur, amounting to 10 per cent. Olivine entirely altered to serpentine reaches 5 per cent and a few grains of magnetite are always present.

The holocrystalline types of olivine basalts have a seriate porphyritic fabric and possess phenocrysts, which make up 35 per cent of the rock. The feldspars which range from andesine to bytownite are tabular, broadly and irregularly twinned, dull, zonal, resorbed and at times completely altered to chlorite and carbonate. The augites are clear, equant to tabular, euhedral, pale green and cumulophyric. The euhedral olivine is dull or entirely altered to limonite, magnetite, chlorite and iddingsite (?), The groundmass is made up of "fern magnetite"—that is, magnetite crystals in parallel growth and untwinned laths of feldspar. In total the olivine makes up 12 per cent, augite 10 per cent, magnetite 15 per cent, and feldspar with secondary products the remainder of the rock.

SPECIAL STRUCTURAL TYPES

Some of the above-described composition types take on structures which deserve special mention. There are many occurrences in Porto Rico of volcanic flows filled with pyroclastic materials. These flows are either augite andesite or feldspathic andesites. Scattered throughout the igneous matrix are lithic fragments and sedimentary fragments. Some of these rocks are crowded with introduced fragments, as, for example, the beautiful rock exposed in the stream bed just east of Cayey. The fragments show little or no absorption, but they do show at times contact phenomena. Thus euhedral .05 mm. pale greenish-yellow garnets form rims around the feldspars and occur scattered irregularly throughout the groundmass (Fig. 31). Other examples of flows filled with breccia are found east of Coamo, just south of Cidra, near the northward bend of Rio de Cuyon and just west of Comerio. True flow breccias were found which belong to the augite andesite or feldspathic varieties. In thin section they are seen to be composed of angular fragments lying in irregular positions, in a matrix of the same composition. The best example was found south of Cidra (Fig. 32).

The most interesting types of compound rock are conglomerates with an igneous matrix, of which several fine examples were observed. An accessible occurrence is between K. 86 and K. 78 on the Military Road; another is found where the Rio de Cuyon turns westward, but the very best extends in the bed of the Rio Jajome for nearly a mile in the Jajome Gorge. Others were observed north of La Lapa, and southwest of Comerio, and east of Barros. These formations show typical conglomerate structure. Pebbles and boulders occur in layers, semi-oriented, and between them the finer pebbles show torrential bedding. Viewed from a distance, the igneous character of the matrix would not be suspected

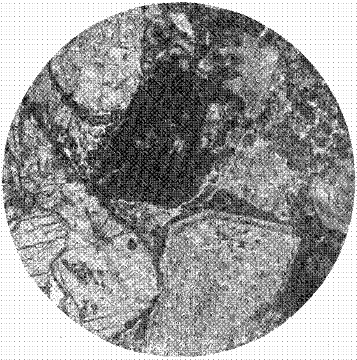


FIG. 31.—*Lava flow containing pyroclasts of calcite which are surrounded by garnets*

(Fig. 9). Critical pieces selected and examined microscopically show good igneous structure (Fig. 33). This structure might have been developed by metamorphism, but this is disproved by the unmetamorphosal character of the under or over lying beds. Moreover, the same conglomerate traced along the strike changes to formations with a sedimentary matrix. The matrix is undoubtedly primary igneous rock and was locally introduced, which would be possible in several ways. A valley filled with conglomerate boulders or a fan of conglomerates might have had a flow of lava pass over it. This lava would sink into and fill the interstices and so cement the borders. In view of the perfect sedimentary matrix of the same conglomerate beds elsewhere, it is unlikely that the portion with a conglomerate matrix was free of tuff or interstitial silt matter, will be seen that near the end of every flow there must exist a position where the columns will be bent, as shown in the figure.

GENESIS

All the rocks described above are considered early differentiates of the batholith which is exposed in the eastern end of the island and which extends westward beneath the Coamo-Guayama district. If all the types could be averaged the composition would probably be that of an augite andesite, a rock which may be considered to represent the composition of the magma reservoir from which they were derived. Since the sediments in the Coamo-Guayama district were derived from rocks of the same composition, the view cannot be held that the composition of the underlying

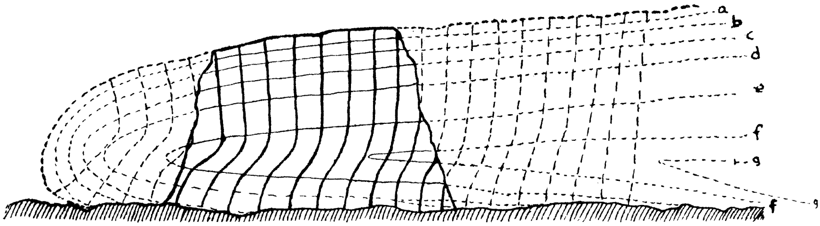


FIG. 34.—*Relation of isothermal surfaces to andesitic columns*

magma was due to their assimilation. The composition was either primarily augite andesite or made so by assimilation of rocks not exposed in this terrain.

BATHOLITHIC ROCKS

OCCURRENCE

The greater portion of the batholithic rocks lie beyond the limits of this district and enter it only as a somewhat detached mass occupying the hills just west of Guayama.

GENERAL CHARACTER

The general character is described by Berkey (1915, p. 28):

The most prominent type of intrusive mass is that seen in the southeast portion of the island, including the district about Huamacao and Yabucoa and Las Piedras and Juncos. Whether or not this is all one mass belonging to a single intrusion has not been determined. The variety of composition seen in the different samples, taken at different points, is consistent with the presence of more than one intrusive unit; but it is also possible and quite as likely that the variety observed is wholly due to magmatic differentiation. The southerly portion of this mass, especially that near Yabucoa, is represented by a very coarse, very quartzose and almost pegmatitic granite. Farther to the north, in the vicinity of Las Piedras Juncos, the rock has the appearance of a syenite. Although a part of the rock does show the composition of a true syenite, by far the greater number of specimens collected on this expedition show the presence of quartz in sufficient amount to make the rock a granite. It would appear, therefore, that this occurrence in the southeast portion of the island is essentially a granite mass and that it is of unusually large size, reaching practically from the coast at Maunabo to Caguas. The distance across this mass is, therefore, not less than about 12 miles north and south. In all probability it is not of quite so great an extent east and west, but these boundaries are unknown.

The portion adjacent to this district is not coarse enough to be a true granite. Micropegmatitic structure is characteristic. Traced toward the Coamo-Guayama district it becomes dioritic in composition and the grain becomes finer until at Guayama the extreme border is an andesite in composition and texture.

Hornblende Granite.—Hornblende granite is the only type which enters the Coamo-Guayama district. The hand specimen appearance is mottled, due to grains which are of equal size and irregular form. Areas of dark green hornblende 1 to 3 mm. in size are separated by larger areas of quartz and feldspar. The feldspar is either white, pale pink, or pale green. Under the microscope this rock is holocrystalline and equigranular. The average size of the component crystals is 2 mm., which is almost too small for a granite. The rock consists of 30 per cent orthoclase intergrown micrographically with quartz. Feldspar of the albite-oligoclase variety occurs to 20 per cent. The feldspars are faintly kaolinized. Quartz occurs as part of the microscopic intergrowth and as euhedral grains. The latter contain numerous lines of bubble inclusions. Quartz makes up 40 per cent of the rock. The hornblende occurs in prismatic crystals, is cumulophyric and makes up 5 per cent of the rock. The hornblende is in part bleached and in part altered to epidote and chlorite. Other primary constituents are titaniferous magnetite altered to leucoxene and apatite. Some limonite stains occur and the rock is highly altered in part to epidote, and needles of actinolite (Fig. 35).

GENESIS

Whether the batholith is a satellite or the peripheral portion of the primitive batholith, it must represent the residuum left after the separation of the augite andesites and basalts. Whether it is injected without solution or whether it is invaded by dissolving the country does not matter, for in the latter case it would only assimilate a small portion of the rocks, eliminated as intrusions and extrusions in an earlier period. Such assimilation would increase its basicity but little; it would return to a stage in its magmatic history a little previous to its present one. Because the apophyses of this batholith are of intermediate composition and quantitatively small, to return all apophyses to the batholith would increase slightly its basicity; therefore, at the time of its injection the composition of this batholith was probably grandioritic or monzonitic. Hence, if in turn we add the large number of augite andesites and the few basaltic

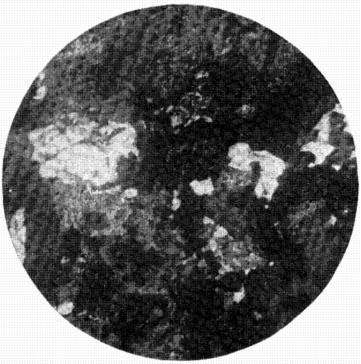


FIG. 35.—*Hornblende granite*

types, the composition of the primitive magma is obtained, which would be dioritic.

LATER INTRUSIVE ROCKS

OCCURRENCE

Rocks of this series occur as large intrusive dikes and stocks throughout this district. They bear undoubtedly a diaschistic relation to the batholith. The composition range in this group is from biotite granodiorite to hornblende andesite, which is a greater range than exists between the extreme of the earlier intrusives.

Biotite Granodiorite.—Just north of where the Rio de Cuyon turns and flows westward is a boss of granodiorite which cuts the Barranquitas-

Cayey series. A group of hills east of Coqui is formed by a boss of this rock, the marginal phase of which is diorite and near its base a dike of augite andesite and a flow of vesicular olivine-free basalt are found (Fig. 36). Megascopically the rock consists of 2 to 5 mm. masses of dark green biotite and occasional specks of hornblende or pyroxene in a white to light green field of feldspar. In some varieties the quartz is not apparent in the hand specimen. In thin section the rock is equigranular and made up of grains which average 5 mm. in size. Oligoclase in dull, tabular, subhedral, twinned crystals amounts to 55 per cent. Some of the oligoclase is twinned according to both the albite and Carlsbad laws. The biotite

FIG. 36.—*Biotite granodiorite*

occurs in brown and green cumulophyric intergrown patches amounting to 15 per cent. Much of the biotite has gone over into the chlorite. The first occurrence mentioned above has 5 per cent of clear, colorless augite, the second a small area of green hornblende. In the former the quartz occurs in interstitial material, in the latter as multiform grains with many strings of inclusions. In both, quartz is present to about 20 per cent. Equant grains of magnetite and prismoids of apatite and zircon occur. Sericite is secondary and epidote an introduced mineral.

Hornblende Diorite.—Rocks of this type occur throughout the older series as bosses or thick intrusions. They are more common than their finer-grained equivalents, the hornblende andesites, suggesting a genetic relation existing between depth and the occurrence of hornblende. As observed in the field the size of the grain ranges between 2 mm. to 5 and 6 cm., the average being 3 mm. With few exceptions the rocks are composed of grains of equal size and these are thoroughly intergrown. In some, however, the hornblende crystals get very large; a few have been observed which were 6 cm. long. The hornblendes are decidedly prismatic, black and fresh. The feldspars are tabular, rarely striated, and vary in color between white and pale green. Generally the hornblendes occur as interstitial matter between the feldspars. A few grains of magnetite are common. The microscope shows the essential structure of these rocks to be seriate homeoid, and composed of grains averaging 1 mm. in size. About 50 per cent of this rock is made up of tabular 1 mm. euhe-

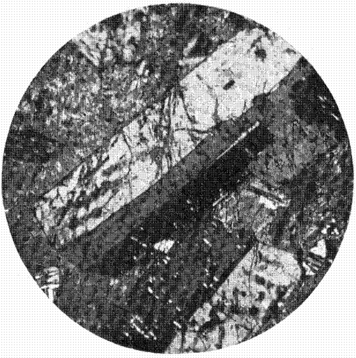


FIG. 37.—*Hornblende diorite*

dral, broadly twinned crystals of andesine. Most of these andesines are fresh and clear, though a few are slightly altered to chlorite and zeolites. A few crystals of labradorite, less of orthoclase and many of oligoclase occur. The hornblende is pale green, subhedral, and pleochroic, occurs interstitially and cumulophyrically, and contains chadocrysts of feldspar. Around the borders of the hornblendes are large numbers of magnetite grains. The hornblendes have very ragged borders and the magnetites occur within the shadowy former border of the crystals. Apparently the magnetites are left as a residuum after the dissolving away of the hornblende borders. Hornblende makes up 25 per cent of the rock. About the border of the hornblendes and occurring apparently as recrystallization substances are tiny augite and calcite crystals. Magnetite occurs in large areas with chadocrysts of feldspar. Apatite also occurs as a primary mineral. The feldspars are altering to calcite, sericite and secondary quartz (Fig. 37).

Hornblende-Augite Diorite.—Just south of La Lapa several dikes of this variety of rock were observed. Considering the large number of augite andesites, it is remarkable that no augite diorites were found; or, to view the matter from another point, the large number of hornblende diorites is in striking contrast with the very few hornblende andesites. In hand specimens the hornblende augite andesites are made up of holocrystalline, equigranular, intergrown 3 mm. areas of dark green hornblende with smaller white feldspar areas. Under the microscope this rock

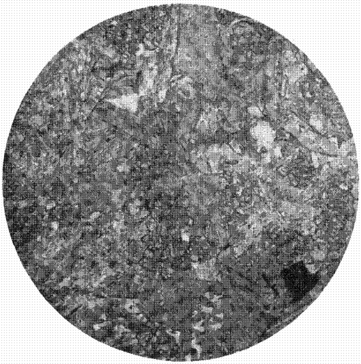


FIG. 38.—*Hornblende-augite diorite*

appears seriate porphyroid with the largest grains reaching .05 mm. The feldspars are chiefly andesine with some oligoclase and make up about 50 per cent of the rock. The hornblende is all altered to chlorite and in and near the chloritic areas, still retaining the hornblende shape, are small crystals of augite. Some of these augites are cumulophyric. The augite therefore appears to have been derived from the hornblende. Long 1.5 mm. needles of apatite occur. The feldspars are zeolitized and secondary quartz is present (Fig. 38).

Hornblende Andesite.—Hornblende andesites occur as thick dikes. A fine one is exposed on the Aibonito-Coamo Military Road, between K. 97 and K. 98, and several dikes occur south of the Coamo Reservoir dam.

In all occurrences the rocks are coarse, almost hornblende diorites. No specimens were observed in the volcanic tuffs. Hand specimens show grains which may approach 4 mm.; the average is about 1 mm. except in a rare occurrence which has a divitrified groundmass. The fabric is, as a rule, hiatal, with large phenocrysts of plagioclase and hornblende occurring in the groundmass, which may be light or dark green, gray, pale blue or dull gray. The plagioclase crystals are tabular, rarely striated and sometimes crossed. The hornblendes are black, shiny, and highly prismatic.

Under the microscope the fabric is usually found to be seriate porphyroid, though a few may be seriate porphyritic. The larger crystals, com-

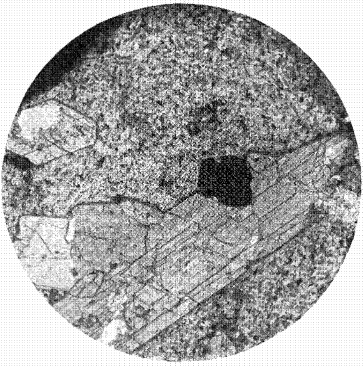


FIG. 39.—*Hornblende andesite*

monly in the case of hornblende, reach 5 mm. in size and the feldspars 3 mm. The crystals of the groundmass may be so small that the texture is microcrypto-crystalline, as in the case of one hornblende andesite with a divitrified matrix. The most common texture is diabasic. The phenocrysts are hornblendes and feldspars. The hornblendes are euhedral to subhedral, prismatic, dark green, usually cumulophyric, and highly altered to chlorite and epidote. Some contain chadocrysts of magnetite, which commonly shows octahedral parting. Magnetite amounting to 5 per cent also frequently occurs secondarily as a product of reorganization about the ragged borders of the hornblendes. The feldspars are of the oligoclase-andesine variety, with the emphasis on the andesine, and average 16 per cent. One or two per cent of orthoclase occurs at times and an occasional crystal of plagioclase. The feldspars are irregularly twinned and zonal. Their shape is tabular, as phenocrysts, or prismatic in the groundmass. The phenocrystic feldspars are commonly cumulophyric, crossed and highly altered to chlorite and calcite. Magnetite occurs in equant crystals up to 5 per cent. Other primary minerals are apatite, pyrite and ilmenite. The groundmass is composed of feldspars and magnetite and generally is entirely altered. The ratio of groundmass to phenocrysts is 66 to 34. Other secondary minerals are zoisite and leucoxene (Fig. 39).

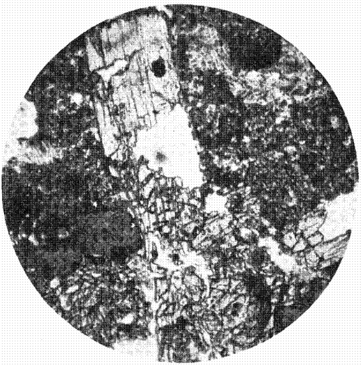


FIG. 40.—*Hornblende-augite andesite*

Hornblende-Augite Andesite.—Dikes of this rock occur among the augite andesites and are particularly common near La Lapa and north of the Baños de Coamo. These rocks in hand specimen show 3 mm. phenocrysts of hornblende. These are set in a light green matrix of feldspar laths. In thin section they are seriate-intersertal. Augite crystals form the largest phenocrysts, amounting to 10 per cent. They are pale green, clear, fractured, and cleaved; the hornblendes are prismatic and green and are altering rapidly to chlorite. The hornblende occurs both as phenocrysts and throughout the groundmass as shreds. The total amount of hornblende is 10 per cent. Oligoclase-andesine in euhedral, zonal-twinned, prismatic, dull crystals make up 60 per cent. Magnetite and apatite occur (Fig. 40).

GENESIS

The rocks discussed above are thought to be diaschistic dikes given off by a batholithic mass which underlies the Coamo-Guayama district. The range in composition is greater than in the earlier intrusives, which is due to the fact that a batholith which ascends to higher levels will show greater differentiation than at lower levels. This is due to the greater time for differentiation and the wider range in temperatures and pressures. The larger intrusives are more acid; the largest observed were of biotite granodiorite and the smallest were of hornblende andesite—that is, the nearer the intrusives approach in size to the batholic rocks the more acid becomes their composition, or the nearer the diaschistic dikes are eroded to the batholith the more their composition approaches that of batholith. The succession of these various intrusives was not determined. Among the older andesites were a few hornblende andesites. The hornblende diorites are always thick dikes and much more common than hornblende andesite. No augite diorites were found, but a few hornblende-augite diorites were observed. In all these, as described above, the augite is reorganized from the hornblende, and the hornblende often shows reorganization to magnetite and secondary augite. Such facts show that hornblende as a mineral is genetically related to higher temperatures and pressures, and augite to lower temperatures and pressures.

Conclusions as to the Ages of the Various Series

SEDIMENTARY ROCKS

In the above paragraphs two pronounced unconformities have been described. One exists between the Baranquitas-Cayey and the Sierra de Cayey series, beneath which some fossils were found and which give a clew as to the ages of the older rocks. A short distance below this unconformable contact two calyxes of a coral were found in a limestone which have been identified as *Cladophyllia furcifera*. Ordinarily this form is considered a typical index fossil for the Edwards division of the Fredericksburg group of the Comanche in the Gulf region. Its presence here should indicate that the rocks are at least of Comanche age. Below the limestone occurs a thin bed of bog iron ore and in it were some leaves. Dr. Edward W. Berry and Dr. F. H. Knowlton identified these leaves as follows:

Nelsonia, an old Mesozoic order of cycads.
Protorhipis, a fern with same range as above.
Another species of Mesozoic fern.
A dicotyledon.

The above authorities stated that these plants were not critical for the Comanche, but that they tended to support the evidence of the corals—at least they indicate Mesozoic age. In addition to the above, at several horizons some radioliaria, foraminifera and diatoms were found[3] as follows:

Textularia gibbosa, d'Orbigny.
Textularia conica, d'Orbigny.
Textularia triochus, d'Orbigny.
Pleocanium (*Textularia*) *speyeri* (Reuss).
Operculina sp.
Orbitoides papyracea, fragments.
Orbitoides faujasii, Sowerby, fragments.
Paralia (*Melosira*) *sulcata,* Ehr.
Coscinodiscus elegans grev?
Parodiscus concentrica (*Flustrella concentrica,* Ehr).
Lithocampe with seven joints and flatly compressed edges (Fig. 5).
Orbulina universa, d'Orbigny?

Textularia gibosa is a form well developed in the Miocene and early Tertiary and *Textularia conica,* d'Orbigny, is common today in the coral reefs of Porto Rico. However, *Textularia,* as a whole, is characteristic of the Lower and Upper Cretaceous; *Operculina* and *Orbitoides* occur also in the Cretaceous. Radiolarian forms, though very numerous in the Miocene, are well known to occur far back in the geological scale and *Orbulina universa* is common in the Upper and Lower Cretaceous. Thus while some have great range, yet in view of the fact that the most common form, *Textularia,* is generally Comanche or Cretaceous, it is probably safe to say that these smaller creatures also support a Comanche age for this system. I conclude, therefore, that the above rocks are Comanche in age.

Immediately above the Sierra de Cayey and Barranquitas-Cayey contact the only fossils found were several *Orbitolites* forms, which signify but little. About two miles north of the Rio Jueyes Water Gap and close to the Rio Jueyes River, in a very calcerous tuff, was found one specimen of *Venericardia alticosta.*[4] In the Gulf States this is considered an index fossil for the Jacksonian and Claibornian formations of the Upper Eocene. But some fossils which are indices of certain horizons in one place are often found to belong to beds of older age in other regions. This may prove to be the case with *Venericardia alticosta.*

Large numbers of foraminifera, radiolarians and diatoms were found in these rocks. In all cases the minute organisms were only discovered in thin sections and for that reason their determination in many cases was

[3] Identified by Rufus M. Bagg.
[4] Identified by Prof. A. W. Grabau.

found impossible. Sufficient were determined to testify very strongly to an Eocene age for these rocks.

The types observed follow:[5]

Foraminifera:

Orbitoidea papyracea (Boubee).
Textularia gibbosa, d'Orbigny.
Globigerina bulloidea, d'Orbigny.
Truncatulina lobatula (W. and J.).
Meliolina seminulum, Linné?
Textularia sp.
Gandryina sp.
Polymorphina sp.
Miliolina sp.
Biloculine sp.
Numulites sp.
Orbitoides sp.
Amphistegina sp.? (Fig. 19).
Discorbina globularis, d'Orbigny.
Globigernia sp.? (Fig. 42).
Ostracods sp.?
Heliodiscus humboldti, Ehr?
Porodiscus concentricus, Ehr? (Figs. 20 and 41).

Diatoms:

Melospira arenaria, Rab.
Coscenodiscus marginatus.
Melosira sp.

Among the above fossils *Porodiscus concentricus* is of *early* Tertiary age (Fig. 41), as is *Amphistegina* (Fig. 19). As a whole, this group of minute forms and *Venericardia* indicates Tertiary and some point directly to the Eocene. Apparently the Eocenic is in the older series. That this is so is further shown by the age of the next succeeding group of rocks.

The Eocene age of the uppermost rocks of the older series has some bearing on the problematical presence of the Cretaceous. For, in view of the universal presence of Cretaceous rocks in the islands of the West Indies which have been studied, it seems fair to assume Cretaceous rocks in the Coamo-Guayama district. There may be an unconformity between the Eocene and Cretaceous (?) which was not found in the limited time devoted to this study.

The next great break is the discordant unconformity separating the Rio Descalabrados formation and what little remains of the Arecibo in the Coamo-Guayama district. The age of the Arecibo is rather definitely fixed. Fossils were collected from it on the north coast by Mr. R. D.

[5] Identified by Rufus M. Bagg.

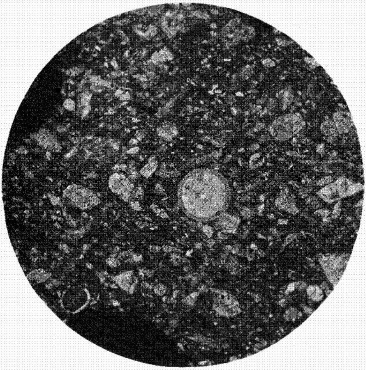


FIG. 41.—*Porodiscus concentricus in tuffaceous shale*

FIG. 42.—*Globigerina and algæ in the Coamo Springs limestone*

Semmes and from it in the south coast by Prof. Charles P. Berkey. Both collections were identified by Dr. W. H. Dall. On the north coast were found:

Metis trinitaria (Dall), an index of the Bowden formation, Upper Oligocene of Jamaica.
Pecten sp.
Haminea sp. Very abundant.
Cypraea sp. Abundant.
Amauropsis sp.
Conus sp.
Ampulina sp.
Strombus sp.
Orbicella aff. cavernosa (Linné).
Fringed coral, not determinable, but similar to those found in Oligocene of Antiga, Anguilla and Cuba. Dr. Dall considers this an Upper Oligocene fauna.
Metis trinitaria, which is typically Upper Oligocene, is stated by Mr. R. D. Semmes to occur at the base, as well as in the upper portions of this formation.

Professor Berkey collected his fossils west of the mouth of the Descalabrados River, just outside of the area under discussion, and west of Ponce. Care was taken to gather them from the base of the Arecibo limestone, which is the younger series of Berkey.

These were identified as:

Lucina sp.
Lucina sp., much like forms from the Chattahoochee.
Pecten sp., like *Pecten thetidis* (Sowerby).
Fasciolaria.
Amauropsis ocalina, similar to forms in the Ocala limestone of the Gulf States.

Mr. R. T. Hill (1899) states that the Arecibo limestone is in part equivalent to the Arecibo on the north coast and though largely Pleistocene, the lower strata may be as old as Oligocene. Of the older series Hill (1899*a*) says: "The rocks of the central mountain region are Cretaceous and possibly of early Eocene age; at least no evidence tending to establish other dates has been as yet discovered." Since these limestones of Upper Oligocene age lie upon a peneplaned surface, they indicate that the Eocene exists either in the great unconformity or is to be found in the older series. The presence of *Venericardia* and the large number of Tertiary foraminifera diatoms and radiolaria seems to suggest that the latter is the case.

If the age of these formations is correctly determined, then a great break lies between the Eocene and the Oligocene in Porto Rico. The character of the Eocene-Oligocene contact in North America is poorly understood. A summary (Cooke, 1916) of the views taken regarding the contact in the area where it is best known shows that the various authorities differ by as much as a whole geological period. Could this divergency of view be explained by the existence of an unrecognized unconformity?

The Santa Isabel formation is undoubtedly recent in age. Fossils collected from railway cuts and from terraces south of Coamo Springs were compared with specimens washed up on the south shore of the island and for every fossil species an identical one could be found among the types still living. The stratified character of the fossil horizons, the presence of corals and sponges, and the total absence of human artifacts led to the conclusion that the fossils found were deposited by natural agencies and that their presence indicates an elevation of very Recent origin.

IGNEOUS ROCKS

The igneous rocks appear to be divisible into three age groups. In the first group they occur mostly as dikes, flows, sills and volcanic fragments of which augite andesites were found in greatest number. This is shown by their dominance in the early tuffs, by their presence as flows in the older series, where they occur as intrusions, and by their comparative rarity in the vicinity of the granite batholith. Types such as basic augite andesites, olivine-free basalts and olivine basalts, in so far as these rocks occur, are to be found under similar conditions. Feldspathic andesites are to be found in the older tuffs, but in view of the great number bearing a peripheral relation to the granite batholith, it is more reasonable to postulate a later period at which a great many of the intrusive feldspathic andesites developed.

The second group is younger. The granite batholith cuts Comanche and Cretaceous sediments and probably, though it cannot be proved, cuts Eocene sediments. The point which is important is that the igneous rocks classed in the first group occur as component parts in sediments which are cut by this granite batholith. The top of this batholith is truncated by the peneplane developed in Porto Rico and the invasion of the batholith is, therefore, antecedent to the peneplane.

The direct evidence that a third stage exists are the dioritic and hornblende andesite dikes which cut the batholith at various places, notably north of Virella. Throughout the Coamo-Guayama district biotite granodiorites, hornblende diorites, and hornblende-augite diorites occur. These are so different in character from the rocks known to belong to the first stage and so like those which cut the batholith that the inference is that they are genetically related to the granite batholith and later in age. The feldspathic andesites are best developed close to the batholith, and seem to be, therefore, apophyses of it. Not all the augite andesites can be proved to belong to the first stage. Some of them may have been given off in the third stage.

SUMMARY OF AGE RELATIONS

The following tabulation summarizes the age relationship of the various rocks:

The Older Series.	Rio de la Plata series Barranquitas-Cayey series	Comanche.
	Sierra de Cayey series Guayama series Early intrusives Rio Jueyes series Coamo Springs series Rio Descalabrados series Batholithic rocks Later intrusives	Cretaceous to Eocene.
The Younger Series.	Arecibo formation Santa Isabel formation	Oligocene to Recent.

HISTORICAL SUMMARY

Under the heading of "genesis" and elsewhere, the geological history of the Coamo-Guayama district has been described in detail. Here only a summary of the more salient events will be given.

Early Period to End of Comanchic Time

The very existence of Porto Rico is dependent upon a volcanic past. This much can be said from the character of the sediments which are of pyrogenic materials, slightly reworked or not reworked at all. That the island has been built up from the ocean bed by the accumulation solely of volcanic debris is to be doubted. The more probable view is that the vulcanism which produced the sediments was only a superficial expression of the major organic forces which elevated the whole West Indian region in early Comanchic (?) time. The embryo Porto Rico may even have stood above sea-level when the first volcanic activity began. The practical absence of glassy types in oldest known pyroclastic rocks, or, for that matter, in any of the rocks, seem to indicate relatively slow cooling, which would not take place in the cold water of the profound ocean depths.

The earliest record in the Coamo-Guayama district shows intense vulcanism. The materials ejected or poured out had little or no reworking. Quiescent periods occurred during which the sea advanced over former sites of deposition, as is shown by the several beds of limestone which are free of tuff fragments. During the latter portion of this era vulcanism apparently decreased, for the uppermost rocks are reworked tuffs and ashes.

Cretaceous and Eocene

The deposits accumulated in previous times of intense volcanic activity were reworked and redeposited during this period. The Sierra de Cayey period was one of sudden and pronounced uplift. The uplift, which was either that of a broad arch or a fault block, revived all of the streams, and the result was the creation of great alluvial fans which sloped down from the mountain toward the south. This uplift was probably not very great. A small change of elevation will cause decided erosion. At the time under consideration the elevation was probably not much greater than at the present time. The essential factor in rejuvenated erosion is that at times the stream becomes torrential and carries down a mixed load of boulders and silts, followed by a period when the stream is incapable of removing the boulders, but can separate out from among them the finer material. Thus in the present flood-plain deposits and in the course of the Salinas River large boulders occur in great profusion, many of which are as large as any occurring in the older measures. The same conditions are exhibited on the Coamo River and several streams on the south coast.

The alluvial fan condition, initiated by the Sierra de Cayey period, continued through the Eocene. After the first impulse of rejuvenation had worn itself out, the streams eroded and transported finer materials on a reduced grade. Periodic outbursts of vulcanism developed tuffaceous measures. Slight oscillations of the Porto Rico block permitted the sea to advance inland for periods long enough to develop thin limestone beds. As a whole, however, the data testify to a very little diastrophic movement. Most of the limestones were formed in embayments between great alluvial fans and developed synchronously with shales brought down by rivers or tuff intermittently thrown out by volcanoes. As the island was gradually worn lower and lower, the batholith underlying the Coamo-Guayama district, except in the southeastern corner where it outcrops, was gradually working its way upward. Long before the end of the

Eocene the upper portion of the batholith had come so close to the surface that it froze and was partly eroded. At the close of the Eocene the general baseleveling, which had been in progress since the end of the Comanche, eventually reached its highest degree of perfection in a peneplane and the land surface became so low that the sea was enabled to advance over it.

Oligocene

At the time of the marine transgression vulcanism must have been absent; otherwise the basal portion of the coastal deposits would contain much volcanic débris and the limestone would contain many tuffaceous inclusions. Neither of these conditions are conspicuous enough to have been observed; on the contrary, the base of the coastal plain deposit is a carbonaceous shale. This carbonaceous basal shale indicates that the sea advanced rapidly over an area pretty well worn down. If the sea had transgressed slowly a perfect sorting of materials would have ensued from marine-planed old rock and this would have given conglomerates, sandstones and shales. But if there existed a peneplane, covered with a deep residual soil and supporting a heavy growth of tropical vegetation and the sea advanced rapidly, then only a carbonaceous shale, followed by limestone deposits, would have been formed. The result of the overlapping sea was the deposition of a heavy limestone formation.

Miocene to Pleistocene

The first event after the deposition of the limestones was uplift. Berkey (1915, p. 40) writes as follows:

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

The next event was the removal of the Arecibo and dissection of the underlying older series. So completely has this been performed in the Coamo-Guayama district that only one outlying hill remains of the Coastal Plain limestone deposits. Dissection has continued to the present time and brought the district to a state of maturity and has been accompanied by stream adjustments, but without equal success, for the streams are about as imperfectly adjusted as possible.

Pleistocene (?) and Recent

Judging purely by analogy, Porto Rico suffered first a major uplift in the Pleistocene (?). This first movement, intended to satisfy internal earth stresses, probably not only compensated these stresses, but over-reached its mark and produced others of an opposite nature. To relieve these latter stresses, oscillatory movements of the island are now taking place. The frequent earthquakes throughout the West Indies are part of this phenomenon. One effect has been to cause a recent elevation of the island. But before this recent uplift took place the island remained stationary for a considerable period, during which the Caribbean carved a platform far into the island. Thus west of the Coamo-Guayama district a terrace is cut into the Arecibo Oligocene limestones. However, the total cutting in the whole island was so little that nine-tenths of it still remains mountainous. When the sea had finally finished its carving the shore stood much farther inland than at present and the site of the Guayama was beneath the sea and those of Salinas and Santa Isabel were between 50 and 60 fathoms deep. The surface of the Caribbean was nearly awash with the tops of the Aguirre Hills, Salinas Hill and Monte Sebater. Great bays were formed in the valley of the rivers, one of which extended up Guamani to about K. 24, another reached La Lapa in the vicinity of Salinas, a third reached as far north along the Rio de Coamo as the Baños de Coamo, and the great subsequent lowland behind the Coamo Springs limestone range was a salt marsh. Those hills which stood as islands during the sea's farthest advance, or as reefs 25 feet or more above the sea bottom, became surrounded on all sides by the coastal plain and some sediments now all eroded away may have been deposited upon them. The isolated hill southwest of Coamo Reservoir, the low hills southwest of Salinas Hill, Salinas Hill itself, Monte Sabater and Aguirre Hills and the hills near Melonia Reservoir are now islands in the coastal plain technically called mendips or morros. The high hills east of Guayama were at one time mendips, but erosion of the coastal plain to the north has converted them into peninsulas extending into a coastal plain.

After the sea had advanced as far inland as described above, uplift occurred in two successive stages. The result was the formation of two terraces. The second uplift followed closely upon the first, because the sea-cliff cut is small and the size of the lower terrace is much the larger.

VULCANISM

Volcanic centers are typical features of the Coamo-Guayama region and of many other parts of Porto Rico. In this district volcanic vents were observed in the following places: South of the Coamo Reservoir, about a mile south of the Rio Descalabrado Water Gap, between K. 98 and K. 99, and between K. 87 and K. 88 on the Military Road, several on the Rio de Cuyon east of the bridge on the Military Road crossing it at K. 93 and a very large and complex one east of La Lapa. The one, south of Coamo Dam on the Military Road, can be seen in cross-section. There the strata are cut by numerous intrusions, mostly of a dioritic character; the sedimentary beds have been shoved, crowded, broken and thrown out of their former attitudes and the intrusive dikes contain large irregular fragments of the sediment, which are hydrothermally altered. Tuff accumulations occur irregularly between the sediments and the dikes. On the Descalabrado, where a volcanic vent is to be seen in plan, the same features are shown and in addition the rocks are highly fractured and cemented by epidote and calcite. The center east of La Lapa shows an old vent, now filled with coarse volcanic breccia, with much tuff and introduced epidote and calcite. Surrounding this vent, within an area of about two miles square, are hundreds of augite andesite intrusives and flows and less numerous dikes and flows of feldspathic andesite and a few hornblende diorites. These numerous intrusives, cutting shales, which are intensely altered hydrothermally, form a complex the structure of which is impossible to decipher. In the bed of the Cuyon a limestone formation is broken through by a vent, which is filled with limestone fragments, andesite tuff and augite andesite lava. With the one exception, between K. 87 and K. 88, all vents cut Eocenic sediments. Older ones undoubtedly existed, but their presence has now been effectively concealed and the only conclusion to be drawn from the location is that vulcanism continued into post-Eocenic time. Of course all the superficial physiographic features produced by vulcanism were wiped away by the post-Eocenic peneplanation.

HYDROTHERMAL EFFECTS

Mention has been made of the highly fractured character of all the Porto Rican rocks. These fractures are usually cemented by introduced minerals. Some rocks, in addition, show metasomatic replacement and a few others are almost entirely replaced. Whether the minerals are simply introduced or in part replaced, all are considered hydrothermal. There is direct evidence in some of the addition of water; in others only certain constituents have been dissolved away, apparently by water, and in many the state of the minerals indicates only the presence of some agent, such as water, which facilitated chemical reorganization without the introduction or subtraction of any component.

The following types of hydrothermal alteration will be considered:

(1) Those in which one or more of calcite, quartz, chlorite and epidote were developed.
(2) Those in which zeolites, calcite and chlorite were formed.
(3) Those in which epidote, quartz, chlorite and actinolite, one or more, were introduced.
(4) Those in which hematite and quartz were introduced.

FIG. 43.—*Chlorite developing from feldspars which are associated with fresh augites*

(1) Weathered surfaces of Porto Rican rocks show partial or complete alteration of the femag minerals, especially of the pyroxenes. This is in striking contrast with the clear, fresh, unaltered condition of the same minerals within the body of the rock where weathering influences have not reached. Feldspars, on the other hand, even in the most durable, firm and unweathered rocks, are generally altered. Feldspars are commonly entirely replaced in parts of the rocks far beyond any influence of weathering. Thus in a prospect on the slopes of the Luquillo Mountain where a shaft had been sunk 50 feet below the weathered zone, the feldspars were all altered. The feldspars are universally dull and lusterless and even if exposed on weathered surfaces they are never much more

altered than in the interior of unweathered rocks. The above facts lead to the conclusion that the alteration of the feldspars is related to some internal agency.

Many of the feldspars show little patches within them of calcitic alterations; others are replaced by pseudomorphs of calcite. The feldspathic groundmasses alter easily, frequently and completely to calcite. The feldspars are all calcic and only the addition of CO_2 is required to alter them. Almost every rock shows carbonate and some are altered so completely that, in the case of sills or flows, they are easily mistaken for limestones. This alteration is not confined to igneous rocks, but is found in

FIG. 44.—*Epidote replacing feldspars*

sediments which contain calcium-bearing minerals. It is not an exaggeration to say that 20 per cent of all the rocks in the Coamo-Guayama district are altered to carbonate. For such an intensive alteration CO_2-bearing water solutions must have been coming up from the depths in great volumes and for long periods of time. The calcite so formed does not always remain in place, but migrates to other rocks or is dissolved out of the rocks entirely. Thus the deposits of tepatate, frequently observed in the stream beds, result from the precipitation of the dissolved calcite and apparently the streams are carrying concentrated solutions of concentrated calcium carbonate to the sea.

Hardly less common than the calcite is chlorite. The first place that chlorite develops is along cleavages or twinning planes in the feldspars.

Where well developed it is always in association with the feldspars and shows direct evidence of being genetically related to the feldspars. In the rocks where chlorite is best developed the ferromagnesium mineral augite will be clear, fresh and unaltered (Fig. 43). In the case of chlorite we must grant the introduction of magnesium. Probably water solutions of magnesium carbonate reacted with the feldspars to form $CaCO_3$ and the hydrous magnesium aluminium silicates. The calcite and chlorite are, as a rule, intimately associated as if this were the case. Secondary quartz would be released by such a reaction, and fine-grained secondary quartz is, therefore, very common in these rocks. Epidote at times re-

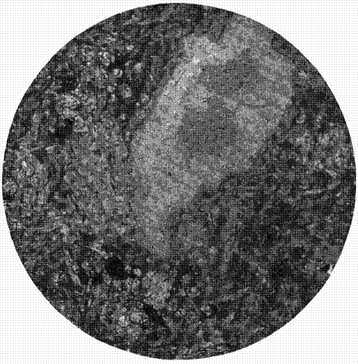


FIG. 45.—*Minerals named in order from the center outwards: stained antigorite, stilbite, laumontite, and calcite*

places the feldspars and occurs alone or in association with the above minerals. It can be formed from the calcite feldspars directly by hydration (Fig. 44). (See figure 45.)

The phenomena discussed in the above paragraph are principally those of reorganization plus slight additions of magnesium, CO_2 and H_2O. Hot water, however, was the stimulant which occasioned the reorganization.

(2) Closely related to the above alterations are the zeolites. Strange to say, the zeolites were not found filling amydaloidal cavities nor are the zeolites common and they always occur intimately associated with chlorite. Around the periphery of these zeolite-chlorite areas is, commonly, a border of calcite. The shape and the association with more or less altered

feldspars is such as to prove a direct development from the calcic feldspars. Reorganization, stimulated by thermal waters, bearing in addition to magnesium carbonates, also potassium carbonates, would produce chlorite, zeolites, and calcite from calcic feldspars. It appears that of the secondary minerals formed calcite was the most mobile, for it traveled to the periphery of the groups of secondary minerals so formed or even farther (Fig. 45).

(3) The greater portion of the hydrothermal rocks contain the quartz, epidote, chlorite, actinolite and zeolites, one or more, in either vesicular cavities or fractures and the boundaries of these cavities show little or no

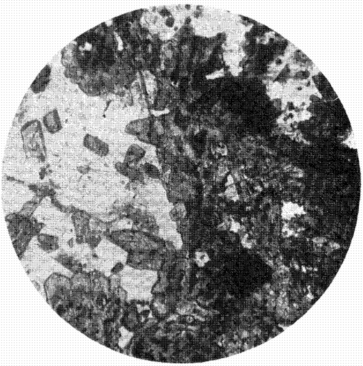


FIG. 46.—*Intimate mixture of quartz, epidote, and actinolite*

replacement (Fig. 46). In a few cases the replacement has proceeded to such an extent that the whole body of the rock is a mass of epidote. Though epidote was not the first mineral to come in, it was in many rocks the only one and quantitatively it plays the major rôle. In the types of rock described above epidote can be definitely proved to have developed originally from the feldspars by reorganization (Figs. 44 and 47). Some of the epidote so developed may have migrated and filled the veinlets and vesicles in the rocks of this type. If so, the epidote in some of its occurrences came in from distant, deep-seated sources, for it occurs in veins or in vesicles in rocks which are strictly fresh and unaltered in all other particulars. Moreover, its intimate association with actinolite of undoubted introduction argues very strongly for a deep-seated source (Fig. 46). It is difficult to explain the complete replacement unless introduction was under intense hydrothermal conditions.

All the minerals did not necessarily come in a definite succession. In some rocks (Fig. 46) quartz, epidote and actinolite seem to have come in almost simultaneously. Where the succession is best shown the order is quartz, epidote, chlorite, actinolite and zeolites. In a few rocks epidote occurs on the walls of veins which have a quartz filling, showing epidote to have been introduced first, but the balance of the evidence indicates that quartz began to develop first and continued to come in with the later minerals.

FIG. 47.—*Quartz and epidote replacing feldspar*

Actinolite occurs as isolated needles, as needles penetrating quartz, and as radiating growths and the occurrence of actinolite in such relationships is generally regarded as sure proof of igneous emanations. The actinolite is not stable, but readily hydrates and converts to chlorite. It is metasomatic only in so far as it penetrates quartz—a phenomenon very common in rocks altered by igneous emanations.

An interesting feature, rather common, is the association of zeolites with the actinolite frequently in intimate intergrowth. If the actinolite is an igneous emanation, then the zeolites must also have been introduced by thermal waters at high temperature. Another feature is the extreme development of secondary quartz. Shales are converted entirely to cherts by the quartz. The association of the quartz with the other minerals of this group proves it to be hydrothermally introduced and not the result of reorganization of radiolarian and diatom shells, as is the case in some of the sediments. The sediments show the calcareous shells of foraminifera replaced by secondary quartz. In other rocks calcite of hydrothermal origin plainly replaces the quartz. Evidently inert calcite can be replaced by hydrothermal quartz, but when both calcite and quartz are hydrothermal the quartz has a greater solution pressure and is readily replaced by calcite. In the andesite secondary quartz will develop in aureoles and then by reorganization take on the trapezohedral form. When first observed the writer considered such rocks to be quartz andesites. Further

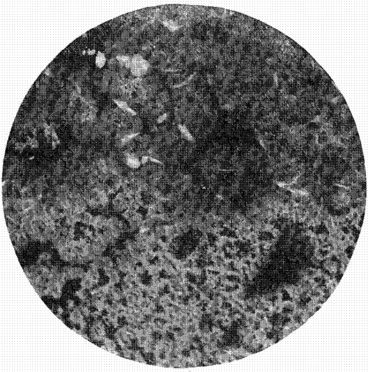


FIG. 48.—*Spherulitic growths of specular hematite and chalcedony*

study shows that the quartz is all secondary. It is possible that many of the quartz andesites described in the literature were of this origin.

(4) The fourth type deals with some effects which are interesting because they show a hydrothermal introduction of hematite and because of the possibilities involved if the process were carried to completion. Shales are silicified by spherulitic growths of chalcedony. The growth of these chalcedonic fibers was spherical and nearly equal in all directions and the growth was frequently interrupted, probably due to the intermittant supply of feeding solutions. Synchronously with the growth of the chalcedony spherulites, specular hematite was introduced. It was deposited interstitially, chiefly between the spherules, and when the spheru-

lites were not-growing formed a hematitic shell about them. After a period of continued growth of the spherules, another shell of hematite developed, and repetition of this process formed bodies of spherically radiating fibers of chalcedony containing within them and around them concentric shells of specular hematite. After the cessation of chalcedonic growth hematite continued to be introduced and in some cases has metasomatically replaced the fibers of spherules. Where this has taken place bodies formed of a succession of concentric shells of hematite separated by radiating fibers of hematite are cemented together by hematite—that is to say, a typical oölitic structure is formed. The oölitic structure is emphasized in thin sections by the hydration of parts of the shells to limonite (Fig. 48). The petrogenesis of this rock was not worked out until too late to collect critical samples. It is thought, however, that the continuation of this process to completion in a large shale bed should produce a rock that could not be distinguished from oölitic iron ores. Or, to go even further, why could not some of our oölitic iron ores have been produced by hydrothermal action?

The phenomena described in the above two paragraphs are developed best in the vicinity of old volcanic centers. The two best occurrences were found about a volcanic center near the Quintana thermal spring, north of Ponce, and about the La Lapa volcanic center.

MINERALIZATION

Mineralization is a feature considered to be genetically related to the hydrothermal effects and is just as common. Nearly all the rock of the Coamo-Guayama district contains introduced sulphides, mostly pyrite, though chalcopyritic pyrite is frequently present, as shown by the copper carbonate stains on the rocks.

THE COAMO THERMAL SPRINGS

Location and Purpose of Study

The Baños de Coamo is a thermal spring located just north of the Coamo Water Gap and issues through a bed of conglomerate and tuff, which rises as a boss of rock through alluvium (Fig. 49). The point at which the spring opens is about 50 feet above the beds of the nearby Coamo River. Practically no deposits are being formed by its waters. The thermal and mineral properties of the water have for many hundreds of years been regarded as possessing medicinal properties and it is from this fact that it has received the name Baños de Coamo. The origin of its waters is the subject of discussion in this section.

Occurrence of Springs and Wells

Reconnaissance studies over the greater part of the island by the writer and observations made by several geologists over all of Porto Rico indicate that, with this one exception, no springs of any kind are to be found in the older series of rocks. There are many seepages at the

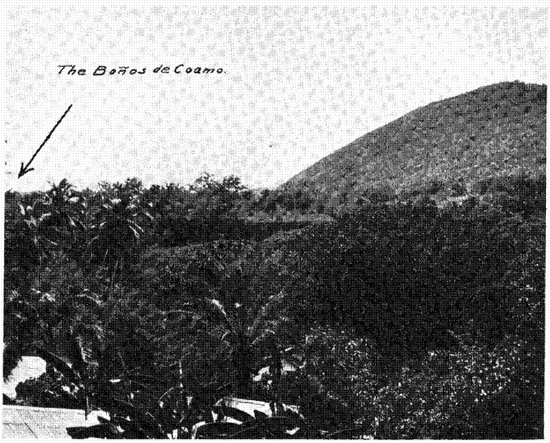


Fig. 49.—*Coamo Springs*
Photographed by Professor H. E. Crampton.

bottoms of the débris-filled gullies in the interior mountains after heavy rains. These cannot be considered springs and do not affect our discussion. Not only are springs absent from the older series, but wells sunk into them have never been successful. In the younger series, however, springs do occur at times, and wells are occasionally located. The cause of this relationship is simple. The rainfall upon the interior mountains, formed of the older rocks, does not sink into them, but follows superficial courses down their flanks until the waters meet the cuesta edge of the coastal plain deposits, under which a small part of the water seeps. The waters working between the coastal plain deposits and the bed-rock of the older series give rise to springs or wells. Thus the best wells in the Arecibo formation have been found near thin coastal margins and the best wells in the Santa Isabel alluvium are found adjacent to streams. Does it not appear significant that in the older series there is only one spring and that a thermal spring?

Location Near a Fault

The direct location of the spring is probably due to a fault which strikes north very close to the Coamo River. Berkey (1915, p. 39) describes another fault which may continue into this district, and if it does extend eastward in the same direction it would lie very close to the Coamo Springs:

> The most prominent fault, in its effect upon present features, is the one now marking the inner margin of the "younger series" of chalky limestones and shales constituting the coastal belt along the south side of the island from Juana Diaz past Ponce at a short distance to the north, crossing the Ponce-Arecibo Road at K. 4.8 and thence westward crossing the Ponce-Penuelas Road at K. 10. . . . It must be of very late Tertiary age, because the chalky Ponce beds are abruptly cut off by it. The older rocks of the pre-Tertiary are lifted with respect to the "younger series" forming the present coastal margin wherever this fault has been seen. . . . What becomes of it at either end is not yet determined, but it is believed to extend much farther in both directions.

Source of Water

The Coamo Springs may obtain their waters from one or more of six sources, as follows:

(1) Meteoric,
(2) Connate,
(3) Entrapped,
(4) Strayed magmatic,
(5) Secondary magmatic,
(6) Primary magmatic.

(1) Meteoric waters are the waters of rainfall which have descended to sufficient depths to become heated and have then ascended again to the surface.

(2) Connate waters are sea waters which became entangled with marine sediments at the time of deposition and remained locked up in these sediments after the coastal plains had been uplifted and more or less consolidated. The best known example of this is found in the copper mines of Michigan (Lane, 1908).

(3) Entrapped waters are waters of any type which were formerly following some underground channel and as a result of faulting, intrusion of a dike, or the occurrence of some similar event were cut off from an avenue of escape and prevented from reaching the surface. Waters at Butte may belong to this category (Lindgren, 1913).

(4) Strayed magmatic waters are those given off from a magma for the first time and which follow channels not leading to the surface, and so have remained stored underground until tapped by a fault, a valley, or by mining. Such waters, depending upon the length of their sojourn, may develop a composition reflecting the country rock through which they have passed. Some of the waters of the Comstock Lode may be of this type.

(5) Secondary magmatic waters are waters of any type which, as a result of assimilation of rocks containing them by an invading magma or as a result of diffusion into the magma from the country rock, have become incorporated into the magma and have been subsequently given off from the magma.

(6) Finally waters, which were part of the earth's interior magmatic reservoir, may be given off and reach the surface for the first time. Such waters are primarily juvenile.

Where there are so many sources or combinations of sources from which a spring could obtain its waters, it is difficult to decide which is the more probable source.

Possibility of a Meteoric Source

SEASONAL RAINS AND VARIABILITY

The meteoric origin will first be considered. If the waters are meteoric or derived from the rainfall, they should show some relationship to the seasonal rains of Porto Rico. That the rains are seasonal is shown by the following record of a typical station, the Toro Negro station near Juana Diaz.[6]

		Inches
1911.	September	8.60
	October	21.63
	November	6.25
	December	18.14
		53.62

[6] From the records of the Porto Rican Irrigation Service.

1912.	January	2.82
	February	2.07
	March	3.38
	April	7.50
	May	1.89
	June	1.51
	July	9.46
	August	8.81
		37.44
1912.	September	14.71
	October	25.67
	November	15.06
	December	2.59
		57.83
1913.	January	2.54
	February	2.91
	March	5.06
	April	9.97
	May	8.44
	June	4.03
	July	2.18
	August	3.04
		38.17
1913.	September	13.35
	October	11.80
	November	5.80
	December	2.59
		33.54

This is a typical station as regards variability of rainfall, and it shows that during the four months nearly twice as much water falls as during the eight arid months. Yet despite this great difference in precipitation the Coamo thermal spring shows no noticeable change in volume year after year. Legend tells us that at the time of Columbus it gave forth more water than at the present time, but within the last two generations the flow has been just the same as it is today.

The southern coast of Porto Rico is arid and it is within this belt that the Coamo-Guayama district lies. In 1897-98 for a period of 13 months not a drop of rain fell in Guayama (Wilson, 1899), but the thermal spring, a few miles distant, did not show the slightest variability in its discharge.

FLOODS AND UNDERGROUND CIRCULATION

After one of Porto Rico's torrential rains the streams rise rapidly to floods sufficient to carry boulders, but within a few hours after the cessation of rainfall the streams quickly fall and within twenty-four hours the beds are dry. This phenomenon is particularly noticeable on the south side, where rains are infrequent. On the north side daily rains occur and the larger streams receive new contributions of water before the previous day's rain has been entirely carried away. Nevertheless, upon the tributary streams, which are more sensitive to daily deluges, the intermittent character of the stream is striking. It would appear that if there was an underground circulation some of the rainfall would be delayed underground to feed the streams a day or two after heavy rain. Mr. F. H. Newell, the hydrographer of the Porto Rican Irrigation Service, stated to me that "the discharge figures show a peculiar condition to exist. They show that almost as much water runs off of the various drainage basins as enters them by rainfall." This does not seem to be an anomaly. It only proves that practically none of the rainfall enters an underground circulation. That rainfall cannot enter a subsurface circulation is not to be wondered at, in view of the character of the soil, which is an extremely unctuous, tenacious, sticky, red, heavy clay. In the interior of the island, where the rainfall is heaviest, this impervious clay is as much as 50 feet thick in places. It adheres to almost vertical slopes despite rains of intense character. Any channels of circulation open at the surface would quickly become sealed by this clay.

The arguments presented above will appear to most readers as quite unnecessary, in view of the fact that meteoric waters to become heated would have to descend beyond a thousand feet or more. The accumulated evidence is now overwhelming in proving that deep rocks are dry rocks (Lindgren, 1913; Kemp, 1903).

TEMPERATURE

The temperature of Coamo Springs is 44° C. Cold meteoric waters would have to descend to over 3000 feet to reach a ground temperature as high as 44° C., unless, perhaps, they came within the influence of volcanic rocks of very recent origin.

LOCATION NEAR A VOLCANIC CENTER

Just south of the Coamo Springs Reservoir dam an old volcanic center is shown in cross-section and in the vicinity of Coamo Springs former post-Eocenic volcanic centers are very common. There is one between the springs and Coamo, another on the Rio des Descalabrados, and to the eastward, in the Jueyes drainage system, are several more volcanic complexes. This spring is thus intimately related to volcanic centers. The close proximity of this spring to young volcanic centers must have a genetic significance. How recently these volcanoes were active is not known. No evidence of the volcanoes cutting the Arecibo rocks has been found. The volcanoes are at least post-Eocene and may perhaps be post-Oligocene.

CONSTANCY OF COMPOSITION

The following table gives the results of four chemical analyses.[7] Number 4 is the analysis made for this study. I am inclined to regard analysis number 3 to be devoid of accuracy and there is much doubt about the other two. Neglecting number 3 and considering only $CaCO_3$, $MgSO_4$ and SiO_2, there seems to be a rather constant value for them all—that is to say, the figures are of the same magnitude. In a limited way analyses numbers 1, 2 and 4 argue for a constant composition over a period of many years.

	I	II	III	IV
HCl	00.84	00.852	.....	.....
H_2SO_4	44.08	36.710	.....	.....
H_2CO_3	27.88	33.433	0.76	.....
NH_4Cl	.....	.....	.....	11.31
Na_2CO_3	.....	.....	2.07	.....
Na_2NO_3	.....	.....	.....	00.38
$NaNO_3$	.....	.....	.....	06.93
Na_2SiO_3	.....	.....	4.79	.....
Na_2SO_4	.....	.....	30.98	.....
$NaCl$	.....	.....	13.60	07.72
KCl	.....	.....	0.02	02.43
$LiCl$	.....	.....	.....	00.34
$CaCO_3$	00.20	00.390	.....	00.01
$CaSO_4$	00.41	00.413	47.12	63.90
$MgCO_3$	20.07	21.460	.....	.....
$MgSO_4$	00.84	00.846	.....	00.63
$FeCO_3$	.....	.....	.....	02.38
Fe_2HCO_3	.....	.....	0.66	00.26
$FeSO_4$	04.59	04.801	.....	.....
SiO_2	01.09	01.095	.....	03.71
	100.00	100.00	100.00	100.00

[7] I. J. J. Heller, 1847.
II. Señor Gunenez, 1899. t° 45.3; average temperature of air near springs, 27.3; and constant sulphurous odor; sp. gr., 1.233.
III. 1.6855 grains per mile made at the agricultural station of Mayaguez.
IV. Louis Hernandez, 1916. t° 44° 1.59970 grains per mille.

River waters are solutions of calcium and sodium carbonates and silica. It is an axiomatic fact that river waters reflect the composition of the rock over which they flow, and one should expect spring water which has traveled through such rocks to have a similar composition. These analyses show that this is not the case.

The location of Coamo Springs, their constant flow, the temperature, composition, constancy of their composition and the physical character of the rocks of the older series all argue against the direct meteoric origin for their waters.

Possibility of Connate, Entrapped and Strayed Magmatic Waters

The presence of a new loci of heat, such as an intrusive magma or a volcanic center (and it is to be remembered that a batholith underlies this district), would stimulate entrapped or connate waters and rejuvenate strayed magmatic waters and cause them to rise to the surface and there form springs. Apparently the only way these waters could be distinguished one from another would be by their composition. Lindgren (1913), speaking of connate waters, says that "the presence of bromide is almost characteristic; traces of iodine and boron are often found." These critical elements are lacking in the Coamo Springs waters.

There are some features concerning the composition of the Coamo Springs waters which show their dissimilarity to entrapped meteoric or connate waters. As they issue at the surface they are mostly solutions of calcium sulphate. Their present composition is undoubtedly due to reaction of sulphuric acid with the very calcareous rocks through which the waters pass. Acid waters of meteoric origin are always low in sodium, potassium and lithium, three elements which occur in notable quantities in these waters, and, on the other hand, these alkalies are very common in waters of volcanic origin (Clark, 1916). The ammonia radiçle, which is also peculiar to volcanic waters, is strikingly high in the Coamo Springs waters. If the assumption is made that the sulphuric acid has resulted from the oxidation of hydrogen sulphide, then the composition of the Coamo Springs water at depth is an alkaline solution of sodium, potassium, and lithium chlorides, ammonia hydroxide and hydrogen sulphide gas. Such a composition is, indeed, unlike any entrapped meteoric or connate water! The composition indicates that the Coamo Springs waters are neither connate nor entrapped meteoric waters, but it does not disprove them to be entrapped magmatic waters. Moreover, strayed magmatic would have a composition identical with entrapped magmatic waters, or, for that matter, secondary magmatic waters. Strayed magmatic waters or entrapped magmatic waters could be rejuvenated so that they ascended to the surface and there formed springs. The waters of Coamo Springs may have such an origin.

Possibilities of Secondary and Primary Magmatic Waters

Two other possibilities of origin that remain to be considered are secondary and primary magmatic waters. Waters contained in rocks invaded by a magma are considered by some writers to be able to enter a magma either by assimilation of the country rock or by diffusion from the country rock into the magma. After the waters had entered the magma their composition would have become changed, so that they could not be distinguished from primary magmatic waters. The problem, then, resolves itself into a consideration of the possibilities of diffusion and of assimilation.

ASSIMILATION

Even the most enthusiastic exponents of magmatic assimilation admit that the process of assimilation does not take place in the zone of flowage, and we need only consider in this zone absorption by diffusion.

DIFFUSION

In order to diffuse, water must be present in the rock adjacent to the magma and it must be available. Rocks in the zone of flowage do not have more than 0.5 per cent by volume of pore space. The pore spaces that do exist are closed and completely separated from one another by crystalline substance. There is absolutely no evidence, experimental or geological, that gases can diffuse through solid crystals. A minute passage must always be present. Granting that a little water exists in these pores (though the experience of deep mines and bore-holes is quite to the contrary), would it in any manner be able to create fractures or develop cleavages through which it could pass to the magma? Of course the water in the pores adjacent to the intrusive magma would be absorbed, but the quantity would be infinitesimal. Adjacent to the magma the temperature is 1000° C. or higher. From the walls of the magma outward the conductivity of the rock is so low that within a few feet the temperature is lowered to 500 degrees, and from that diminishes rapidly outward. There is about the upper surface of the magma a zone 10 feet thick at most which has a temperature sufficient to raise water above its critical point of 364.3° C., and throughout this zone all the water stored in the pores is in the vapor phase. In this state and brought in contact with solutions of minerals composing the magma, water will rapidly diffuse and become incorporated into the magma.

There are two factors which would prevent this diffusion taking place: one is the cubical expansion of the minerals upon heating, and the other is the immense outward pressure of the gases contained within the magma. The minerals of the rocks next to the intruded magma would expand, when heated, in all directions. If the pores were empty they would be closed. If the pores contained water vapor, this vapor would either be compressed or forced to move along some plane of weakness. If the water vapor moved in any direction it would necessarily move outward and away from the magma, because in that direction the temperature would be lower and the cubical expansion less. Any fractures present or separation along cleavage planes would be closed tight and the pressure forcing them tight would be *greatest near the magma* and less far away. Thus the magma in the zone of flowage hermetically seals itself on the outside by a layer of rock, ten feet or more wide, through which gases cannot pass and out of which water vapor, if it must escape, will be compelled to travel away from the magma.

All authorities on igneous rocks, such as A. Harker, A. Lacroix, Joseph P. Iddings, R. A. Daly and numerous others, ascribe to magmas enormous quantities of gases, such as water, carbon dioxide, boron, fluorine, chlorine, and others in lesser amounts. Whether these gases are able to free themselves from the magma in the zone of flowage or not, the tendency is there and the outward pressure of these gases is sufficient if released to drive outward and away from the magma any water which might exist. These gases probably do not escape in the anamorphic zone because of the hermetical zone surrounding the magma, as discussed in the above paragraph. As magmas approach the upper limits of the anamorphic zone and the outward pressure of the dissolved gases becomes greater, due to crystallization, it is probable that these gases may open up veins for themselves, but in so doing the velocity of their outward movement would not permit any water contained in rock pores to diffuse toward the magma.

Assimilation or Diffusion in Katamorphic Zone

In the katamorphic zone of the earth's crust, where fractures may exist and pore spaces are larger, cubical expansion of the minerals, due to the heating by the uprising magma, will not be sufficient to form a hermetic shell. Any water which by some unexplained manner may get down a thousand or two thousand feet, if brought in contact with a magma, would diffuse into it. Smaller cavities and fractures close to the magma will be closed, but larger fractures will be filled by injected masses of rock. The peripheral portions of these injected igneous rocks will allow diffusion into them of water vapor, but the area of the terminal portions exposed to diffusion will be small and allow of no contribution directly to the magma. If these injected bodies succeed in completely surrounding a block of rock and this block sinks into the magma, because of greater relative density, or if a slab of rock is loosened by shattering, any water contained will be incorporated.

The speed of marginal shattering or block dissection will be a slow process and will always be preceded by an outward radiation of heat from the magma. The heat will convert the water to steam, which will move in the direction of least resistance. The effect will be like that of the emanations from the magma, for the steam will drive any water contained in the rock outward and away from the magma. This steam will not be able to move toward the magma, because of cubical expansion close to it, because of the outward traveling injected bodies, and because of the emanations. Before, therefore, a block could be assimilated, all the water contained would probably be driven out of it. As the intrusive works its way into the fracture zone, the indigenous gases will escape outward. They will drive all other gases before them. Their outward velocity is great and penetration power most complete, which is illustrated by the way in which these gases follow out and open up the cleavage planes of calcite grains of a limestone in the phenomena of contact metamorphism. The waters which the outward moving gases meet with are dissolved, but the speed of diffusion in the gaseous solution is undoubtedly slower than the speed of the outward moving gases, and all waters in the invaded rocks would be carried along the crest of the first wave of emanations. The upward movement of the magma is slow and this process will act continuously until all the gases are spent. Apparently, then, only an unimportant fraction of water contained in the invaded rocks could diffuse into a magma and we must conclude that the probabilities are highly in favor of the theory that the waters of the Coamo Springs are appearing at the surface for the first time in their history.

MINERAL RESOURCES

General Considerations

The possibilities of metal mining in Porto Rico are discouraging for several reasons: One is the absence of cheap power. Coal and oil must be imported and water-power sites are limited. Another is due to the fact that the ore could not be smelted locally; hence only high-grade ore could be shipped. This would mean the building of railroads on the island and long ocean transportation. The few railroads built on the flat coastal plains have cost between $5,000 and $10,000 per mile. As the mountainous interior is extremely rugged and broken, railroads, where they could be built, would have to rise on steep grades and make very sharp turns. In many places railways are practically impossible and long, expensive aërial tramways would be the only means of transportation. An ore deposit would need to be very rich and large to warrant exploitation under the above-mentioned difficulties.

The island of Porto Rico has been explored for centuries, but up to date not a single paying mine has been developed. No large area contains a more dense population. Nearly every nook and corner has been observed, yet no ore deposit of importance has been discovered. Despite popular legend, there is no evidence that the early Spaniards, though they sought long and zealously, ever found a deposit which could be worked even with slave labor. For centuries the Spaniards and later the ever enthusiastic Yankee prospector searched for ores. Nevertheless, the few prospects opened have never developed into mines.

Metallic Minerals

In the Coamo-Guayama district near Barrio del Carmen several prospects have been opened, which I have had opportunity to examine. The character of the larger one, situated just south of Carmen, will be described (Fig. 50).

Several openings have been made in a hill composed almost entirely of a conglomerate with a tuffaceous matrix. The workings follow mineralized crush zones and true veins, and are extensive enough to show the general geological relations. Conglomerate is cut by an intrusion which varies in composition from an augite to a feldspathic andesite. The conglomerate is found in the main drift and the first lateral; it is also found in the various prospect pits on this hill and in the pits north and west of Carmen. The intrusive rock appears in the major part of the workings and a dike cuts the first 20 feet of the first lateral. Mineralized faults of small displacement are common in the andesite and are accompanied by a green andesite gouge, which may be a few inches to two feet thick. The andesite is highly fractured, which may have been due to cooling or to resurgent movements of the subjacent liquid portions after the peripheral portions have solidified, or to tectonic movements. Whatever the cause, the fracturing took place while the magma was still giving off emanations, for the numerous small fractures have a calcite filling and into some of the larger veins pyrite came and filled the central portions. The andesite is incrusted by calcite at its contact with the country rock, and apparently at the time of the intrusion of the andesite $CaCO_3$ bearing waters were given off in great quantity, some of which followed the outer wall of the andesite and precipitated calcite, while others worked up through the fractures and faults and formed calcite veins.

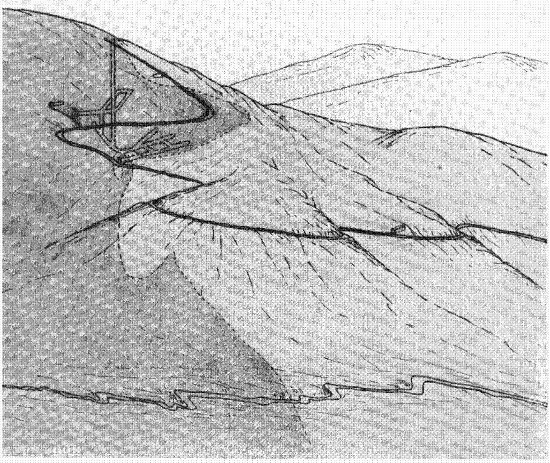


FIG. 50.—*Barrio del Carmen Prospect*

Darker shade indicates an andesite intrusion. Medium shade indicates the tuffaceous conglomerate country rock.

True veins occur, which are crustified and show several generations of quartz deposition. The prospect pits north and west of Carmen open up quartz veins of identical character. Near each, andesitic rock occurs, to which the veins are undoubtedly related. The quartz veins contain pyrite and galena; the succession, which can be plainly made out, is quartz or galena, pyrite and calcite. Not all of the quartz veins are mineralized, for in some veins pyrite was developed first and in others galena. Where galena was formed first, pyrite always followed. Those veins which leave the andesite and penetrate the country rock always show a preponderance of pyrite over galena. Apparently, then, pyrite was the more mobile of the minerals and traveled farthest.

Since the galena is genetically related to the andesite and is the least mobile mineral, it should increase with depth. Considering the difficult transportation problems, the veins of galena exposed in the present prospect make it unworkable unless the galena is rich in silver, which as far as I know is not the case. Much of the present workings have followed slips and gouges and not the true veins. If, in all the exploratory work, the galena-bearing veins had been followed in depth and the slips and seams neglected, the presence or absence of galena in paying quantities would have been completely demonstrated.

Coal

A few coal beds have been reported. One near San Sebastian and another near Juana Dias were examined and in each case the "bed" proved to be merely a thin seam of highly marcasitic low-grade bituminous or lignitic coal. In the Coamo-Guayama district one small seam was observed south of Cayey near the crest of the Sierra de Cayey Mountains.

Oil Shales and Petroleum

An investigation was made of the oil shale and petroleum possibilities of Porto Rico. Shales were gathered from many localities in Porto Rico which were reported to carry oil or were considered by the writer to have oil possibilities. The results of many analyses of the shales collected were all negative. Detailed study of the structure of the older series was impossible in the limited time devoted to study. In most places, however, it is apparent that the strata have been folded to too high angles and eroded too deeply to preserve intact an oil reservoir which may have existed. There are a few localities, however, where the beds show the gentle folds suitable for oil storage, as, for instance, between Cidra and Cayey. Perhaps a more careful study would reveal structures worth testing for oil.

Road-metal

Limestone outcrops are numerous, most of which are suitable for road-metal. Along the San Juan to Ponce Road outcrops were noted at the following places:

Kilometer	.9
Kilometer	55.8
Kilometer	61.1
Kilometer	61.4
Kilometer	67.0
Kilometer	73.2
Kilometer	78.2
Kilometer	84.0
Kilometer	85.1
Kilometer	87.7
Kilometer	90.9
Kilometer	94.2
Kilometer	99.5
Kilometer	100.3
Kilometer	104.1
Kilometer	105.3
Kilometer	106.6
Kilometer	107.5
Kilometer	108.2
Kilometer	111.9

West of Cidra two good limestone outcrops exist. Limestone is almost absent from the Cayey to Guayama Road, but andesite intrusives occur almost continuously. The Aibonito to Barranquitas Road shows many outcrops of silicified shales suitable for road-metal. The limestone of the Coamo Springs Range serves as a convenient source of suitable rock for the Coast Road.

Salt

Two salt pans exist just southeast of Salinas. About 30,000 pounds of salt have been obtained from these pans by evaporation of sea water.

Clays

The surface of the mountainous interior of Porto Rico is universally covered by a heavy, sticky, ferruginous clay akin to the gumbo found in the United States. This clay is too plastic and too ferruginous to be used for structural brick, paving brick or sewer pipe unless properly mixed with shales and carefully burnt, and fuel is too expensive to make elaborate burning feasible. Such clays, however, are suitable for low-grade tile and pottery. Some building bricks have been made in Porto Rico. In the Coamo-Guayama district low-grade red bricks were made near the following places:

Coamo	20,700 brick, valued at $140
Guayama	250,000 brick, valued at $2,000
Santa Isabel	50,000 brick, valued at $300

The bricks manufactured are extremely friable, as would be expected, considering the primitive methods of manufacture employed. The clay is mixed and ground in a circular pit around which a wagon wheel is pulled by a horse. The wheel is attached to a long beam which is fixed to a pole in the center of the pit. The prepared clay is hand-molded and dried in the sun, after which the green brick are built into a rectangular kiln. Charcoal is used to burn the brick.

Lime

Stone suitable for lime burning is probably not present in this district. As shown in the earlier part of this report, all the limestones are high in tuffaceous materials, which makes them unsuitable for a lime as pure as required by the sugar industry.

Natural Cement

The presence of the tuff, however, makes the limestones of a composition required for natural cements. This fact was demonstrated by the Central Aguirre. This Sugar Company burnt some of the limestones in the Aguirre Hills hoping to prepare a pure lime, but the product they obtained was a cement.

Structural Limestone

Limestone is the best tropical building stone. The heavy vegetation keeps the carbon dioxide content of the rain and ground water so low that solution has but little influence. This is shown by the San Juan fortress and castle, which, after standing for centuries, are as good and solid as the day they were built. The best limestone in the Coamo-Guayama district is that of the Coamo Springs Range, which offers an inexhaustible supply. This limestone in most places is heavy bedded, solid and uniform. West of kilometer 108, on the Military Road, a quarry is being worked in a desultory fashion. The limestone is not only easily quarried, but is accessible from the Coast Road along nearly the whole of the district.

Thermal Springs

Three thermal springs exist in Porto Rico. The Quintana Spring is located in a subsequent valley, lying north of Ponce, just at the foot of the mountainous interior, where the rocks in the immediate vicinity indicate the former loci of volcanoes. The Coamo Spring has been described. North of Arroyo and situated far out in the coastal plain is the Virella

Spring. The following analyses of the waters of the above springs were made for this report by Mr. Louis Hernandez, of the Porto Rican Service of Sanitation:

Quantitative Analysis

	COAMO. Parts per million.	VIRELLA. Parts per million.	QUINTANA. Parts per million.	Amount of water used. (c. c.)
Nitrites	.002	.00	.004	100
Nitrates	.03	.02	.02	100
Free ammonia	.048	.0432	.012	.....
Albuminoid ammonia	.072	.048	.012	.....
Total ammonia	.12	.0912	.024	1000
Potassium	.0184	.0697	.012	500
Sodium	.14908	.819	.26517	500
Lithium	.003861	.00287	.00389	10000
Sulphates	.60892	.4598	.125	1000
Magnesium	.00409	.0012	.0437	1000
Calcium	.41976	1.6877	.0846	1000
Chlorine	.13184	1.35796	.16269	100
Iron	......	....	.002	1000
Iron and aluminum	.0233	....	......	1000
Silicon dioxide	.0596	.3678	.037	1000
Carbonates as CO_3	.01787	1.06577	.00178	100
Bicarbonates as HCO_3	.00302	....	......	100
Ferric oxide	......	.00402	......	.....
	1.60374	5.84702	.78583	

	COAMO.	VIRELLA.	QUINTANA.
Sodium nitrite	.006	....	.00643
Sodium nitrate	.1108	.0739	.0729
Ammonium chloride	.1809	.1374	.03615
Lithium chloride	.00542	.00343	.00467
Potassium chloride	.0389	.1469	.025
Sodium chloride	.12346	2.1991	.3476
Magnesium sulphate	.01023	.004	.1094
Calcium sulphate	1.02254	1.1088	.1439
Ferric carbonate	..03797	.00759	.00378
Ferric bicarbonate	.00418	....	......
Silicon dioxide	.0593	.3678	.037
Calcium carbonate	......	1.7721	......
	1.59970	5.82102	.78683
Total solids	1.6048	5.8242	.7914

Qualitative Analysis

	Coamo.	Virella.	Quintana.
Bromine	Negative.	Negative.	Negative.
Iodine	Negative.	Negative.	Negative.
Hydrogen sulphide	Negative.	Negative.	Negative.
Carbonic anhydride (Free)	Negative.	Negative.	Negative.
Free sulphurous anhydride	Negative.	Negative.	Negative.
Phosphoric anhydride	Negative.	Negative.	Negative.
Boric acid	Negative.	Negative.	Negative.
Lithium (spectroscopically)	Positive.	Positive.	Positive.
Specific gravity	1.003	1.006	1.004
Temperature	44° C.	30° C.	34° C.

Coamo Water: No reaction on litmus; alkaline to phenolphthalein, but on boiling the color disappeared.
Virella Water: Alkaline to litmus and phenolphthalein.
Quintana Water: Neutral to litmus, but alkaline to phenolphthalein.

The high sodium chloride content of the Virella waters is probably due to wind-carried salt spray of the near-by coast and to the fact that the waters issue through the recent coastal plain deposits, which have not as yet been completely freed of their connate sodium chloride. The high magnesium chloride content of the Quintama Springs makes their waters unsuited for drinking purposes. The waters of the Coamo Springs are good to drink and a trade in bottled waters should be developed. The temperature of the Quintama and Coamo Springs has encouraged their owners to build comfortable bathing pavilions, which will attract more and more tourists as their fame spreads abroad.

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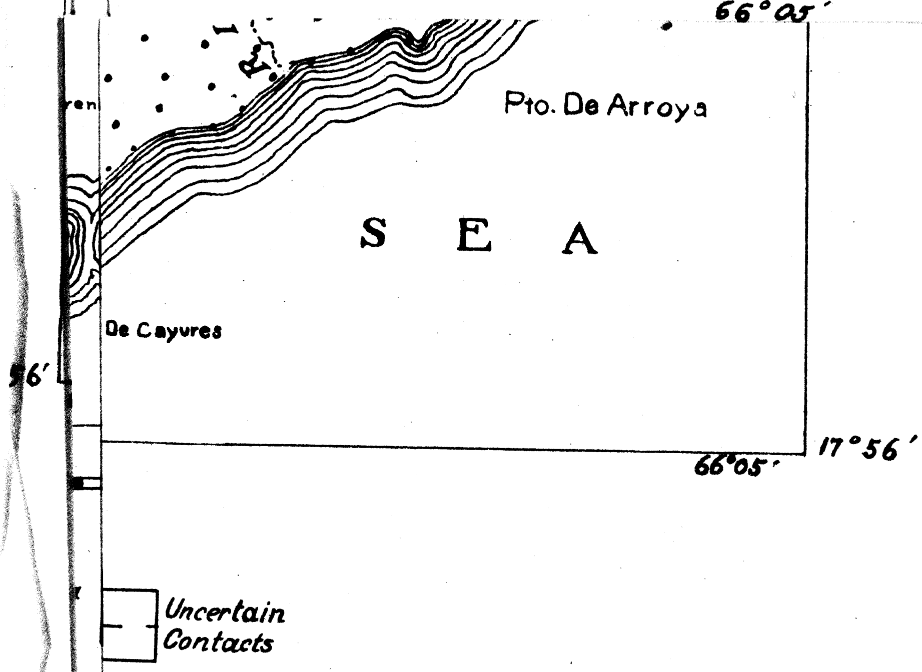
GEOLOGIC MAP

Explanation

Recent–Santa Isabel formation; mostly alluvia.

Oligocene–Arecibo formation; mostly limestone.

Eocene......	Rio Descalabrado series; a thick series of shales with a little limestone and chert. Coamo Springs series; a heavy bedded limestone. Rio Jueyes formation; a complex series, mostly limestone, but with much shale, some tuffs and conglomerates.
Comanche to Cretacic.....	Guayma series; a complex series, mostly of shale, but with much chert, some tuff, limestone and conglomerate. Sierra de Cayey series; mostly conglomerate, with a little tuff and some shale.
Comanche...	Barranquitas–Cayey series; mostly shales, with much limestone and a little tuff. Rio de la Plata series; mostly tuff, with a few agglomerates, shales and limestones.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