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AN OUTLINE OF THE GEOLOGY OF PUERTO RICO

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Friedrich H. Beinroth[1]

INTRODUCTION

Geology has a significant bearing on such related disciplines as geography, mineralogy, soil science, hydrology, and engineering. While some basic knowledge of geology is indispensable for scientists working in these fields, it is also of benefit to foresters, planners, and conservationists. Still others are interested in geology simply because they want to learn more about their natural environment. Thus, many nongeologists are in need of geologic information.

Notwithstanding the extensive literature on the geology of Puerto Rico, the interested layman is hampered in acquiring an overall idea of the Island's geology: First, the two books regarded as standard references, namely those by Meyerhoff (*16*)[2] and Mitchell (*18*), were published several years ago. Consequently, some of the hypotheses and "facts" they present are no longer in accord with the findings of recent research. (These concepts are incorporated in Weyl's work *(27)*, but being published in German, it is linguistically less accessible.) Second, the numerous publications dealing in detail and depth with specific problems and local features of the geology of Puerto Rico are usually not easily available and are, furthermore, written in technical diction.

In view of the many interesting aspects of Puerto Rico's diverse geology the lack of a nontechnical publication on this subject constitutes an impediment. In this Bulletin an attempt is made to diminish this gap in the literature. Its objective is to provide the nongeologist with a concise, general, and up-to-date account of the geology of Puerto Rico. Although basically nontechnical, the geologic vocabulary has not been omitted. However, the terminology used is explained following the standard definitions according to the Glossary of Geology (*1*).

The reader seeking additional information and detailed treatises on special subjects is referred to the bibliographies compiled by Meyerhoff (*16*) and Mitchell (*18*). There, the literature prior to 1953 is covered. The major recent publications are listed at the end of this Bulletin.

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[2]Italic numbers in parentheses refer to Literature Cited, pp. 27-8.

REVIEW OF THE LITERATURE AND GEOLOGIC WORK

Geologic work in Puerto Rico began nearly a hundred years ago when P. T. Cleve (*4*) engaged in some early investigations. At the turn of the century R. T. Hill (*8,9*) published his more detailed studies in several reports. In 1913 the first effort to comprehensively scrutinize the geology of the Island was initiated by the New York Academy of Sciences. The results of these surveys were published from 1919 to 1931 by Semmes (*23*), Hodge (*10*), Mitchell (*17*), Hubbard (*11*), Fettke (*5*), and Meyerhoff (*15*), and are summarized in H. A. Meyerhoff's Geology of Puerto Rico (*16*), issued in 1933. A further comprehensive account is given in R. C. Mitchell's Survey of the Geology of Puerto Rico (*18*). Recently R. Weyl's Geologie der Antillen (*27*) was published, which contains a chapter on Puerto Rico.

Since the early 1950's a team from the U.S. Geologic Survey has been actively engaged in regional and economic studies which resulted in the publication of numerous geologic maps (Geologic Map References, p. 31). Further geologic research in Puerto Rico is carried out by the University of Puerto Rico, College of Agriculture and Mechanic Arts, at Mayagüez, and the Geology Department, Princeton University, in connection with its Caribbean Research Project.

PHYSICAL SETTING

The Island of Puerto Rico, which covers 3,421 square miles (8,858 km.[2]) is the smallest and most easterly of the Greater Antilles, and forms part of the Greater Antilles Geologic Province.

Puerto Rico is surrounded by the Atlantic Ocean to the north, which reaches its maximum depth of 27,922 feet (8,516 m.) in the Puerto Rico Trench some 90 miles northwest and north of the Island; the Caribbean Sea to the South; the 1,200- to 3,800-foot (360 to 1,160 m.) deep Mona Passage to the West; and the shallow Vieques Sound to the East.

Roughly three-quarters of the Island consists of mountain ranges rising to highest altitudes of 4,389 feet (1,338 m.) in the Cerro de Punta, and 3, 493 feet (1,065 m.) in the El Yunque. Further prominent physical features are an area of typically developed karst in the northwest, and coastal plains of varying width along the northern and southern coasts. Approximately one-fourth of the area of Puerto Rico has slopes of 15 percent or less, another fourth ranges in slope from 16 to 45 percent, and the remaining half is even steeper (2).

The Island's main water divide extends E-W and is considerably displaced to the South. Thus, the rivers heading to the Atlantic Ocean are better fed and have greater erosion power than those flowing into the Caribbean Sea. In total, some 50 streams flow into the surrounding seas.

Lying as it does within the Northern Tradewind Belt, Puerto Rico has a tropical, oceanic climate. Temperatures are fairly uniform and average from an annual mean of about 68° F. (20° C.) in the uplands to about 78° F. (25° C.) in the coastal areas. While annual variations are only of the order of magnitude of 10° F. (5.5° C.), diurnal differences are more significant, and may amount to 20° F. (11° C.). The rainfall pattern shows marked seasonal and local differences varying from 230 inches (5,840 mm.) in the Luquillo Tropical Rainforest to 35 inches (890 mm.) annually in the semiarid southwest. However, the almost continuously blowing trade winds in combination with the high temperatures cause evaporation averaging about 80 inches a year (2). The effectiveness of the rainfall is, therefore, reduced significantly which further contributes to the variety of the climate comprising such contrasting subtypes as "wet tropical" (A'Ar) and "arid tropical" (EA'd), according to the Thornthwaite System (*24*).

PHYSIOGRAPHY

In his Survey of the Geology of Puerto Rico Mitchell (*18*) distinguished seven physiographic units which may be used here conveniently. These different regions are delineated on figure 1.

MOUNTAIN UPLANDS OR MONADNOCKS

The monadnocks are the highest summits of the mountain areas of Puerto Rico, namely of the Cordillera Central, the Sierra de Luquillo, and the Sierra de Cayey which range in altitude from 3,000 feet (915 m.) to a maximum of 4,389 feet (1,338 m.). These high peaks rise above the more level upland of the St. John Peneplain and have, therefore, been called monadnocks, the *terminus technicus* for such topographic features. True monadnocks are considered residuals of an old topography standing above a plain of subaerial erosion. Mitchell (*18*) questioned this to be the case for the Puerto Rican monadnocks, on the theory that uparching and faulting provided a sounder explanation than erosion alone.

ST. JOHN PENEPLAIN[3]

The St. John Peneplain[4] is the main skyline feature of the Cordillera Central and lies at an elevation of about 2,400 to 2,600 feet (750 to 800 m.). Although originally it sloped gradually from sea level to the water divides in the interior, the peneplain was subjected to unequal uplift during the Miocene before a mature stage of denudation

[3]The name has been adopted from the Virgin Islands by Meyerhoff (*16*).
[4]"Peneplain" or "Peneplane", as used here, refers to a degradational dissected erosional surface with moderate relief and with a uniform level of summits and ridges rather than to a plain, as the term implies (pene = almost).

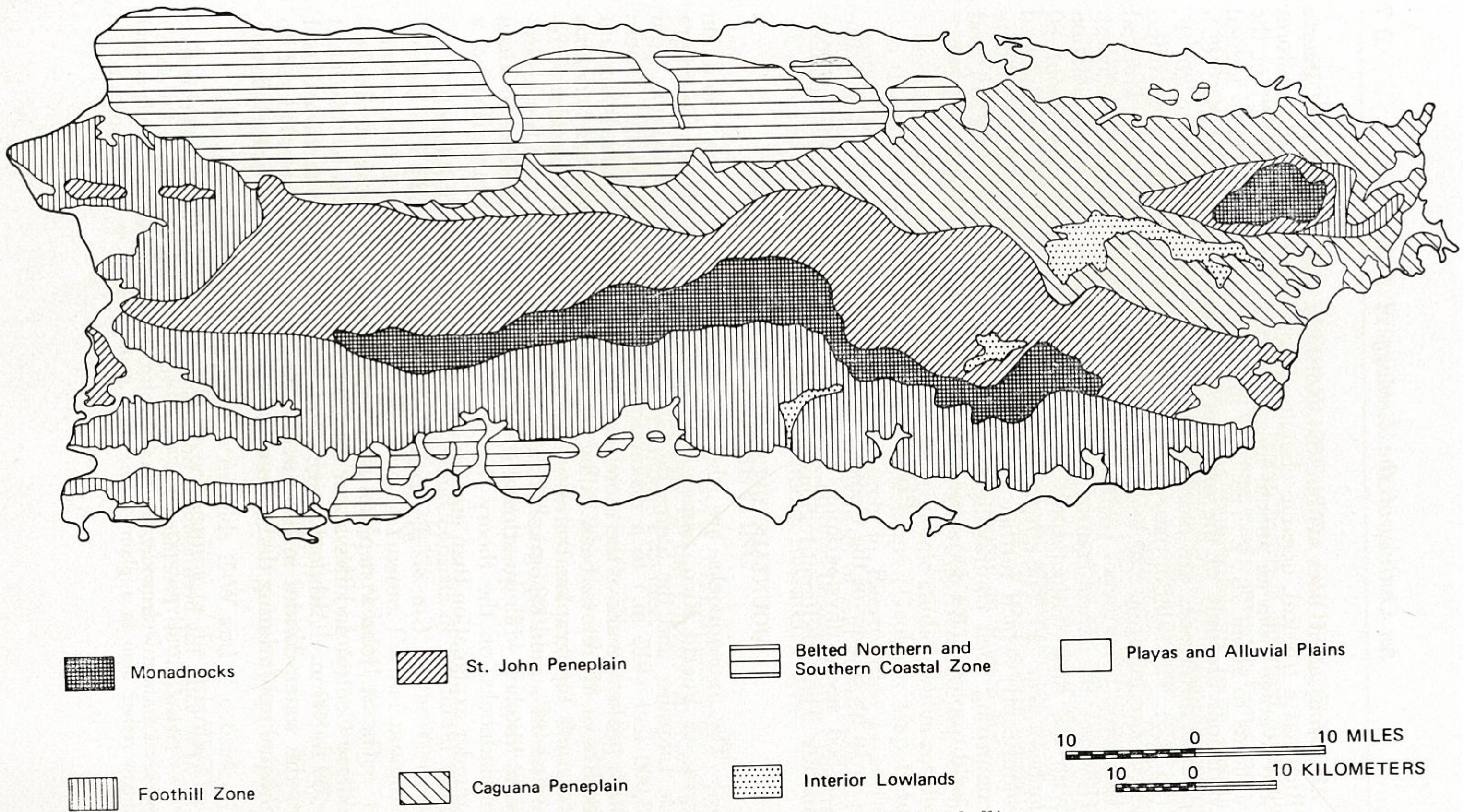


FIG. 1.–Physiographic regions of Puerto Rico (after Mitchell).

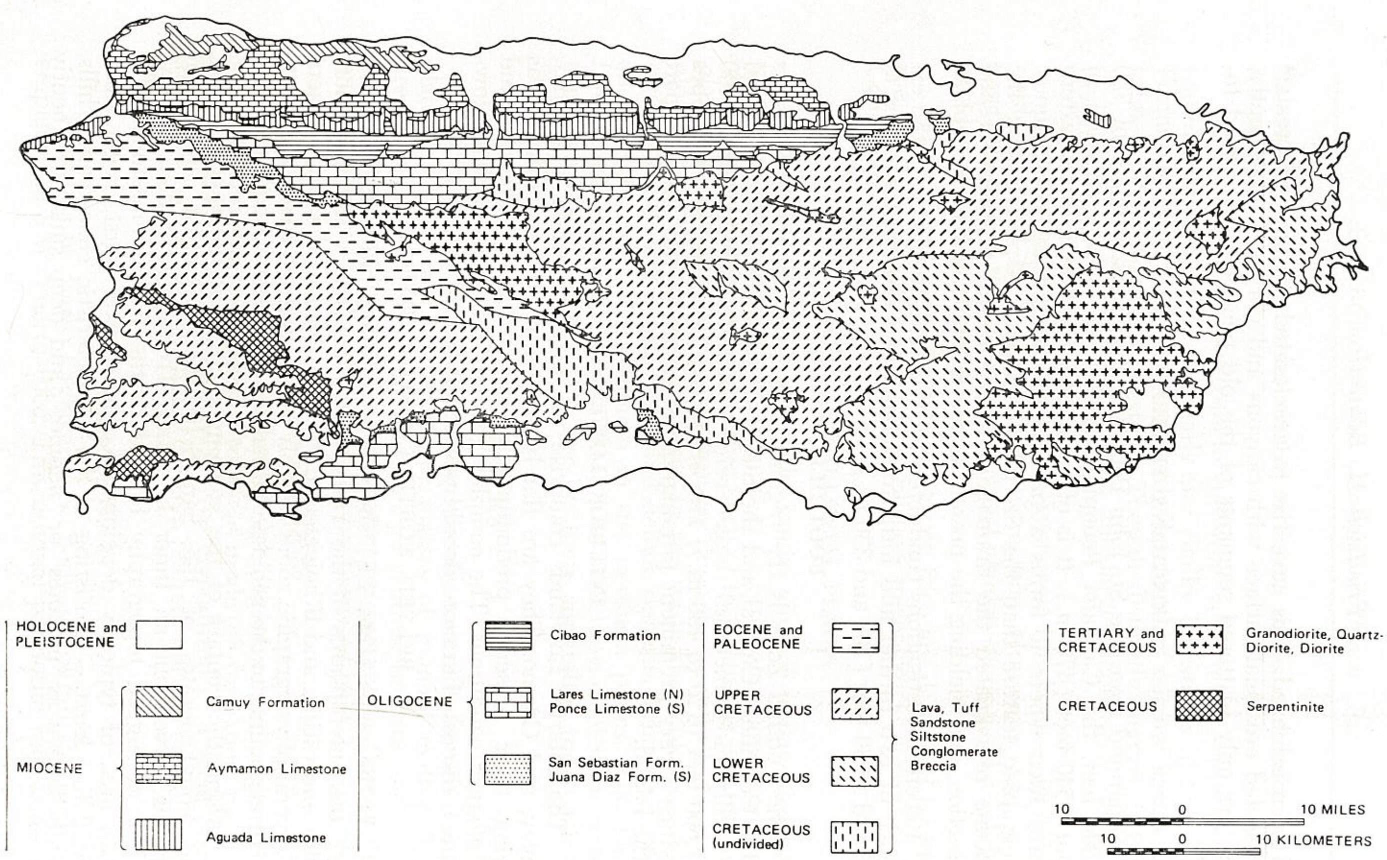


FIG. 2.–Simplified geologic map of Puerto Rico (adapted from "Hydrogeologic Map of Puerto Rico and Adjacent Islands" by Briggs & Akers).

had been achieved. This gave rise to accelerated erosion and created a dissected erosional surface with canyons and gorges. Consequently, there are only scattered remnants of the old peneplain preserved today.

CAGUANA PENEPLAIN

Separated from the St. John Peneplain by an escarpment of 750 to 800 feet, the Caguana Peneplain lies at an average altitude of about 1,540 feet (470 m.). It is of considerable extent in northeastern Puerto Rico where it forms a prominent, though less conspicuous, topographic feature than the St. John Peneplain. Uplift during the Pliocene rejuvenated the drainage system causing degradation and dissection, and yielding the present aspect of the Caguana Peneplain.

Recent investigations conducted by Weaver (*26*) indicate the existence of two further and hitherto undescribed erosional surfaces at 525 and 1,080 feet (160 and 330 m.).

FOOTHILL ZONE

The Foothill Zone is the region adjacent to the southern flanks of the Cordillera Central and the Sierra de Cayey. It is characterized by a hilly and sometimes rugged relief varying in elevation from 400 to 1,600 feet (120 to 490 m.). The often very steep and abrupt slopes produce a very prominent physiographic feature of the southern part of the Island.

INTERIOR LOWLANDS

The Interior Lowlands comprise the three lowlands of Caguas, Cayey, and Coamo. They are flat basins within the mountain areas owing their presence predominantly to particular structural and lithological conditions. The complex geomorphic history of these lowlands is discussed in more detail by Mitchell (*18*).

BELTED NORTH COASTAL ZONE

As the maps (figs. 1,2) show, this physiographic unit coincides with the outcrop area of the Younger Tertiary rocks. In this region, uplift and tilting, and lithological differences lead to the development of several physiographic zones roughly paralleling the coast, and closely corresponding to the geologic formations.

Along the contact of the volcanic rocks, and the sands, shales, and conglomerates of the San Sebastián Formation subsequent streams carved out an Inner Lowland. To the north there follows a belt of rugged topography formed in the Lares Limestone. This is an area of typically developed karst — tower karst, kegel karst, and doline karst — consisting of the characteristic cone-shaped hills, locally known as "mogotes" or "pepinos", and deep sinks. Frequently the surface karst is underlain by extensive caves and underground waterways.

Next follows a contrastingly different zone with a rolling, plateaulike topography on the marls and chalky limestones of the Cibao Formation. Still further to the north lies another narrow karstic belt formed in the Aguada Limestone. Though distinctly rugged, it is not as conspicuous as the Lares Cuesta, and larger depressions occur between the hills.

The northernmost zone — the Aymamón Lowland — includes a well-developed karst area in the Aymamón Mountains and a less rugged region in the east where surficial blanket sands yield a subdued and hummocky topography.

The karst features of northern Puerto Rico are described by Monroe (*19, 20*) and in a recently published speleological survey of the Camuy area (*6*).

PLAYAS AND ALLUVIAL PLAINS

Playas, the flat and generally sandy alluvial plains along the mouths of larger streams, are prominent features along the North and West Coasts, but are found in other parts of the Island as well. Alluvial plains, largely formed by flood-plain deposits, are well developed along the North and South Coasts. In the south these plains are frequently coalescing alluvial fans and deltaic deposits, whereas lagoons and marshes are more common in the northern plains. Though of limited extent in Puerto Rico, these plains are nevertheless of significant agricultural importance due to their suitability for sugarcane production.

ROCKS

Rocks, in a strict geologic sense, are any naturally formed, consolidated or incoherent aggregates or masses of mineral matter. They are customarily classified into three major groups: Igneous, sedimentary, and metamorphic rocks. All of these are present in Puerto Rico, but only the most important types will be discussed here.

IGNEOUS ROCKS

The igneous rocks are formed by solidification from molten rock material (magma). According to their mode of formation they are divided into plutonic rocks, which have crystallized at a great depth, and volcanic rocks, which have been poured out or ejected at or near the earth's surface.

Plutonic Rocks

Probably in Early Cretaceous a body of ultrabasic rock was emplaced in S.W. Puerto Rico. This original peridotite rock consisted largely of olivine, $(Mg, Fe)_2SiO_4$, and minor amounts of other ferromagnesian minerals. Subsequent alteration — mainly hydration — transformed the original peridotite into serpentinite formed essentially by hydrated magnesium silicates. This serpentinite is characterized by its foliated fabric, greenish-white and blue-green colors, and a typical smooth somewhat soapy feel. Weathering produces a deep red clay soil rich in iron (up to 35-percent Fe_2O_3) but excessive leaching makes this soil very low in plant nutrients. These soils — Nipe, Delicias, and Rosario soil series — are characteristically developed in the Las Mesas area and southeast of Mayagüez.

The plutonic igneous activity which accompanied the first orogeny is evidenced by two large intrusive bodies, namely the San Lorenzo and the Utuado batholiths, in addition to numerous minor occurrences. Though emplaced at great depth they are now exposed to the surface as a result of erosion. The plutonics encountered there are largely granodiorite and quartz-diorite, with some diorite, minor quartz porphyry and gabbro.

The granodiorites are rocks intermediate in composition between granite and diorite, and are characterized by a predominance of plagioclase feldspars, $Na(AlSi_3O_8) - Ca(Al_2Si_2O_8)$, over orthoclase feldspars, $K(AlSi_3O_8)$; quartz, SiO_2, amounts to more than 10 percent and further constituents are micas, augite, and hornblende. In the otherwise similar quartzdiorites the plagioclase represents 9/10 or more of the total feldspars. The diorite differs from these two rocks in that the quartz is less than 10 percent by volume, whereas the other components are essentially the same. Quartz porphyry, which approximates granite in composition, contains large well-crystallized minerals of feldspars (usually orthoclase) and quartz embedded in a cryptocrystalline groundmass which further contains mica, augite, and hornblende. The gabbro, finally, is a rather dense rock with less than 10-percent quartz and dominating basic plagioclase. Of these rocks, the gabbro is of least extent in Puerto Rico.

With the exception of the gabbro, these rocks resemble granite in appearance and exhibit a granitoid fabric. When weathered, they disintegrate rather easily into a coarse sandy material yielding sandy, friable and well-drained soils which are readily eroded. The Pandura and Limones soil series are typical examples for these geologic formations.

Locally a dense pattern of diagonally intersecting fractures has been superimposed on these granitic rocks during the orogeny. Along these fractures weathering extends into considerable depth, often only leaving the larger segments at the intersections of the fractures unaffected. When erosion removes the finer material, these blocks are exposed to the surface. Residual boulders of this origin are a typical

landscape feature in the outcrop area of the San Lorenzo batholith, particularly in the vicinity of Yabucoa, Juncos, and Las Piedras.

Volcanic Rocks

The volcanic rocks of Puerto Rico originated mainly during the geosyncline stage of the Island's geologic history from Cretaceous to Eocene times. Their similar chemistry indicates that they are all derived from the same magma reservoir of andesitic composition. Mineralogically, these rocks are characterized by predominating plagioclase (mainly andesine and oligoclase), some dark minerals like augite and hornblende and less than 10-percent quartz. They are intermediate as regards to acidity, but the Lower Cretaceous volcanics are generally somewhat more siliceous than those of the Upper Cretaceous.

When extruding and crystallizing near the surface, andesite was formed with augite- and hornblende-andesite being the commonest variants. These rocks are the extrusive equivalents of diorite. When poured out on the surface, lava flows ensued from the magma. In the Upper Cretaceous they commonly exhibit the characteristics of pillow lava.

More frequently, however, the extrusions have been of the explosive type and the magma was blasted out of the volcano vents. From all that is known, this occurred predominantly in a deep-marine environment and the ejecta settled at the bottom of the sea without ever reaching the air. The pyroclastics formed in this manner thus show the features of both igneous and sedimentary rocks.

The pyroclastics, namely tuffs, are of wide extent in Puerto Rico. They are, in fact, so common that Hill (*9*) described the Island as being "essentially a heap of volcanic debris". The tuffs are normally medium-grained with coarse and fine varieties, and consist of gray-green fragments of volcanic rocks and crystals bound together by a nondescript cement. In consistency they vary from hard-indurated to friable-loose; some are massive and others stratified, and grade into shales and limestones. Unconsolidated tuff is termed volcanic ash. This rock is, however, by far not as widespread in Puerto Rico as the older literature indicates. Moreover, subjected to the conditions of slight metamorphism during the orogeny, the glassy ashes commonly crystallized, thus forming volcanic sandstone or siltstone[5].

Considering their wide extent, andesitic rocks constitute an important parent material for Puerto Rican soils. These volcanic rocks weather deeply, particularly in the high-rainfall section of the St. John and Caguana Peneplains where the weathering zone may acquire a depth of 60 feet, whereas on the steeper slopes, erosion controls the depth of weathering. Owing to the minor quantities of quartz they

[5] "Sand" and "silt" in this context merely connote the grain size.

contain, these rocks produce soils high in clay, medium-low in silt, and low in sand. Formation of iron oxides and hydroxides causes reddish, yellowish or brown soil colors, depending on amount of rainfall, position in the landscape, and duration of soil formation. Typical examples are the Humatas soil series for the more level sites, and the Múcara soil series for the sloping areas.

Table 1 records the chemical analyses of two volcanic and two plutonic rocks. The data show the similar composition of lava and andesite, and quartzdiorite and granodiorite, respectively.

Table 1.—Chemical Analysis (percent) of 4 Igneous Rocks of Puerto Rico

Oxide	Andesitic lava[1]	Pyroxene andesite[2]	Quartz diorite[3]	Grano-diorite[4]
SiO_2	49.96	53.00	62.70	66.70
TiO_2	1.00	.76	.57	.45
Al_2O_3	19.45	17.50	17.67	16.15
Fe_2O_3	4.47	3.21	2.95	2.10
FeO	4.80	3.52	2.82	1.86
MnO	.12	.12	.14	.08
MgO	4.10	2.52	2.11	1.72
CaO	7.88	8.79	5.85	4.23
Na_2O	4.06	3.75	3.26	3.60
K_2O	.60	.65	1.53	2.49
H_2O+	2.03	1.91	.40	.26
H_2O-	1.26	.29	.02	.02
P_2O_5	.53	.38	.02	.02
CO_2	--	3.31	--	--
BaO	.05	--	--	--
Sum	100.31	99.71	100.04	100.70

[1]North Central Puerto Rico; Lidiak (*12*).
[2]SE San Germán; Mattson (*13*).
[3]Utuado pluton, SE San Germán; Weaver (*25*).
[4]Utuado pluton, near Adjuntas; Weaver (*25*).

SEDIMENTARY ROCKS

Sedimentary rocks are formed by the accumulation of sediment in water or from air. The sediment may consist of rock fragments of various sizes, of the remains of animals and plants, of the products of chemical action, or the mixture of these materials. They are, in general, characterized by a layered structure.

The most extensive sedimentary rocks in Puerto Rico are the limestones which consist chiefly of calcium carbonate, $CaCO_3$. All of the three types differentiated by geologists — the autochthonous, allochthonous, and metasomatic limestones — occur in Puerto Rico.

The autochthonous limestones are those which have been formed *in situ* and are, in Puerto Rico, largely of the organic type. They are basically organic precipitates formed predominantly by corals, algae, foraminifera, and mollusks. While fossils are rare in the Cretaceous rocks, foraminifera and corals are very common in the Younger Tertiaries. Massive coralline strata are particularly prominent in the Lares Limestone. In places, chalk, a very soft unindurated limestone, is interbedded with the massive type (as in the Cibao Formation), and some of the limestones intergrade to chalk (*e.g.* in the Lower Ponce Limestone).

The allochthonous limestones are those where the constituents have not been formed *in situ*. They are composed of fragments derived from shells and corals ground by wave action — a process which can be observed along any of the Island's beaches. These detrital limestones, also referred to as calcarenites, are the commonest types in Puerto Rico.

In the metasomatic limestones part of the calcium is replaced by magnesium thus forming the mineral dolomite, $CaMg(CO_3)_2$. The term dolomite is also applied to rocks that approximate the mineral dolomite in composition. This type of limestone is not common in Puerto Rico, but is found in the upper part of the Aymamón Formation in northern Puerto Rico, and also in the southwestern part of the Island.

Most of the limestones of Puerto Rico are thick-bedded and vary in color from darker hues to cream-white and rose-colored. Some are distinctly massive, as is the reef-type Lares Limestone; some are dense and semicrystalline as parts of the Aguada Limestone. They further differ in purity which also seems to reflect the geomorphology of the hinterland.

In times of mature stages of denudation when the gradients of the rivers were low and the streams thus not carrying much suspended matter into the Tertiary basins, the limestones originating there tend to be purer; in times following uparching the rejuvenation of the drainage system enabled the rivers to transport more sediments. In the latter case marls — essentially calcareous clays — are intercalated in the limestones (Cibao Formation, Aguada Limestone), whereas the Lares Limestone and especially the Aymamón Limestone are pure limestones.

Limestones are hard rocks which are resistant to weathering, and hence to mechanical erosion. This is well evidenced in the Upper Cretaceous where limestones now form ridges and summits after the less withstanding pyroclastics have been eroded away. This is such a prominent landscape feature that Hill (9) coined the term "Mountain Limestone" for this pre-Tertiary unit.

Resistant as they are to mechanical erosion, limestones are nevertheless strongly affected by chemical weathering. The mature karst topography along the northern coast is virtually a result of chemical solution. The solution of limestone is a complex process which may be characterized by the equation $CaCO_3 + H_2CO_3 \rightleftharpoons Ca(HCO_3)_2$. This indicates that limestone is dissolved in the form of the much more soluble calcium bicarbonate, and that the reaction is controlled by the presence of CO_2. Carbon dioxide is mainly provided by the respiration of the organic matter in the soil where percolating water takes it up ($H_2O + CO_2 = H_2CO_3$).

The soils derived from the limestones are rather shallow dark-brown or reddish, clayey soils which are not well adapted for agriculture because they are rocky and occupy an unfavorable relief. The Tanamá and Soller soil series are such soils.

Apart from the limestones and the less typically sedimentary pyroclastics the most abundant of the fragmental rocks are shales, according to the older literature. These rocks are defined as laminated sediments of clay grade with a distinct cleavage parallel to the bedding. However, most of the Puerto Rican rocks formerly distinguished as shales do not qualify as such because their texture is coarser than clay. Consisting chiefly of aggregates of volcanic matter – mostly glass – they are, in effect, tuffs. These rocks are very common in the Upper Createaceous and vary in color from red to black. The strongly calcareous types approximate the appearance of thin-bedded limestone. Upon weathering they produce, in general, deep-red soils for which the Río Piedras and Yunes soil series are representative examples. True terrestrial sandstones are scarce in Puerto Rico and most of the rocks thus classified are variants of stratified tuff of sand grade.

Statements pertaining to the paucity of genuine sedimentary rocks in Puerto Rico (*16,18*) tend to neglect the variety of Pleistocene rocks. Even though they are largely unconsolidated, they are nonetheless part of this group as indicated by the definitions given above.

These rocks include alluvial deposits (consisting of sand, silt, and clay), the flood plain and terrace deposits, the swamp and marsh deposits (largely organic muck), blanket deposits, beach rock, and indurated dunes. Quartz, calcite, and debris of volcanic and plutonic rocks constitute the principal components of these sediments. In composition they vary greatly, and the ratios of quartz to other constituents reflect the lithology of the watershed area from which they have been derived.

Both water and wind have been the media of transportation, the latter leading to sediments called eolianites. In places, secondary calcite cemented these airborne and frequently cross-bedded sediments yielding a friable or hard consistency. These conditions are well exhibited at the cliffs on which Old San Juan is built.

The alluvial sediments along the northern and southern coasts provide the parent material for the agriculturally most valuable soils of the Island. These soils range in texture from sands to clays and have favorable fertility status. Owing to their occurrence at low elevations, however, the natural drainage has to be supplemented by artificial drainage systems in many places. These soils – comprising the San Antón, Coloso, Toa, and related soil series – are nevertheless excellent areas for the cultivation of sugarcane.

METAMORPHIC ROCKS

In geology, metamorphism relates to changes in the texture or composition of rocks produced by exterior agencies, mainly heat and pressure. Though such conditions existed in Puerto Rico during the emplacement of the plutonic masses and in association with the overall crustal disturbance during the orogeny, true metamorphic rocks are scarce.

The only high-grade metamorphic rock is found in southwest Puerto Rico. It is an amphibolite-gneiss which originated from andesitic rock and consists mainly of the Si-Mg-Al-silicate hornblende and feldspar. Some hornfels (metamorphosed lava) and some migmatite also occur near the San Lorenzo pluton. When less affected, tuffs and andesitic rocks exhibit an alteration of the origininal feldspars into the clay minerals kaolinite and chlorite.

Furthermore, limestones close to the contact zone are habitually recrystallized and have in a few places even acquired the appearance of marble. Commonly, the metamorphic limestones contain crystals of pyrite or "fool's gold", FeS_2.

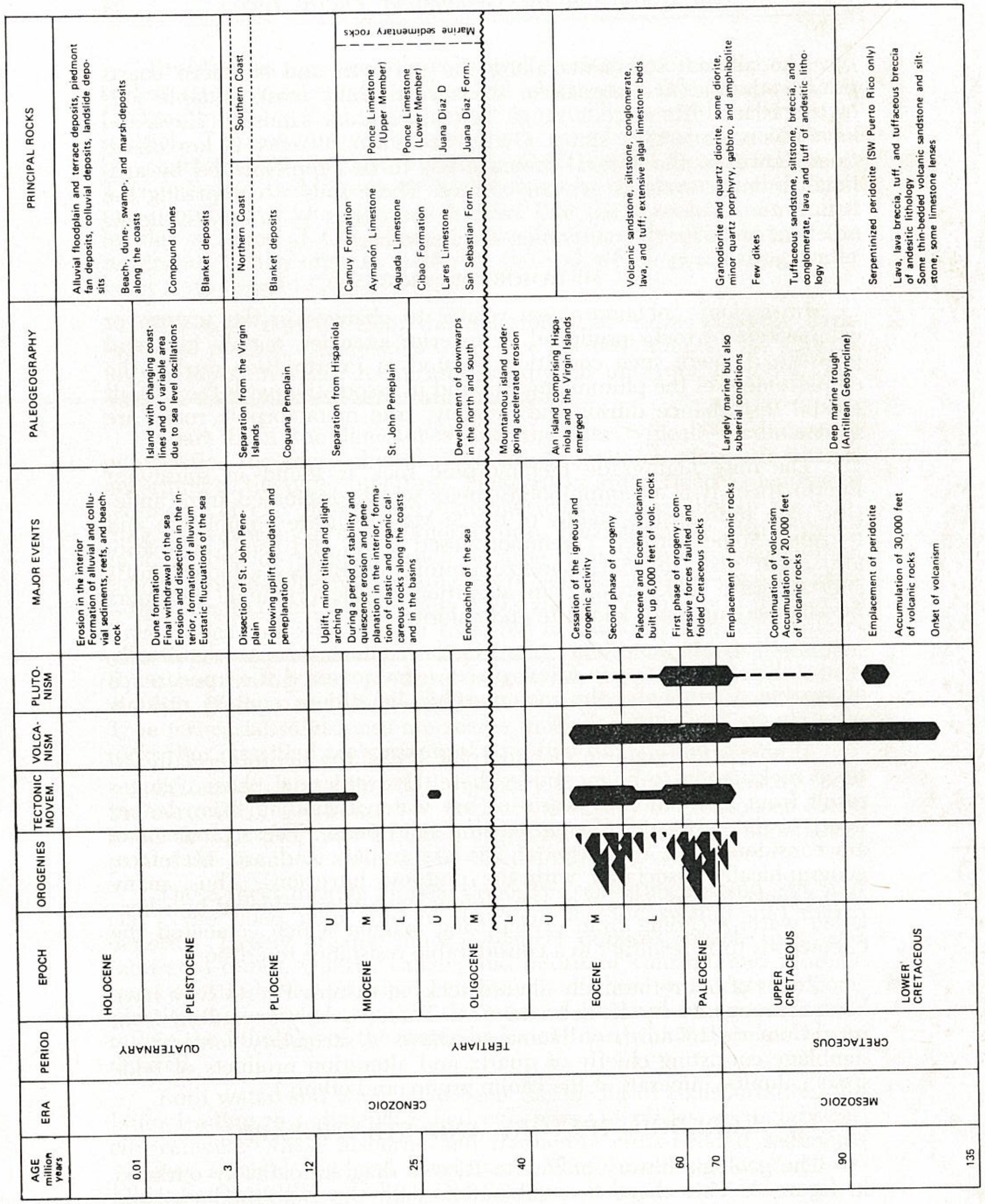
Although not genuine metamorphic rocks, the hydrothermally altered rocks ought to be mentioned here. Hydrothermal phase changes result from interaction of warm or hot water ascending from deeper zones of the earth with the preexisting solid phase. These phenomena are considered the last stage of igneous activity and are, therefore, geographically associated with the plutonic intrusions. Thus, many of the rocks in the vicinity of the plutons have been affected by silica-laden water escaping from crystallizing magma which cemented the Cretaceous tuffs resulting in a considerable resistance to erosion.

Zones of hydrothermally altered rocks in eastern Puerto Rico have been investigated by Hildebrand (7). There, a belt extending from near Comerío to north of Humacao shows a secondary mineral assemblage consisting chiefly of quartz and alteration products of feldspars (alunite, minerals of the kaolin group, and others).

GEOLOGIC HISTORY AND STRATIGRAPHY

The geologic history of Puerto Rico is diagrammatically outlined in figure 3. This chart, in combination with the simplified geologic

Fig. 3.—Diagrammatic outline of the geology of Puerto Rico.



map, provides a general illustration of the Island's geology. But some of the basic facts mentioned there need to be further elucidated.

CRETACEOUS

The datable geologic history of the Caribbean region begins only during Mesozoic time, when roughly nine-tenths of the earth's known history had already elapsed. The Paleozoic and the Precambrian record is virtually blank. Thus, in view of our present state of knowledge, any attempt to trace the history further back – as *e.g.* ventured by Schuchert (22) – constitutes mere speculation.

Although Jurassic rocks have been identified in Cuba, the oldest rocks so far encountered in Puerto Rico are lava and tuff of early Cretaceous age. Formerly an agglomerate found near Cabo Rojo was considered the oldest rock of the Island and was thought to be of probable Upper Jurassic age (*16, 18*). Yet, extensive sampling and detailed studies by Mattson (*13*) do not substantiate the evidence of an earlier land mass.

Lower Cretaceous

During this period the known geologic history of Puerto Rico begins with the onset of a time of active volcanism which initiated the building up of masses of pyroclastics and lavas. Both Meyerhoff (*16*) and Mitchell (*18*) presumed the Island to have been a terrestrial lowland, at times invaded by a shallow sea, with the explosive volcanism occurring predominantly on land. However, recent investigations – particularly the study of the Cretaceous microfauna – indicate that the Lower Cretaceous rocks were formed largely in a deep marine environment. At this time a huge linear trough, the Antillean Geosyncline, extended through our region. It is assumed that its shallowing southern slope was located somewhere near the southern coast of Puerto Rico and that, conceivably, a large land mass, the Caribbean Continent, lay farther to the south (*3*).

Early Upper Cretaceous

The aspect of the Puerto Rican island of Upper Cretaceous times has been compared with that of the Aleutian Peninsula (*16*) and that of the Lesser Antilles (*18*). These concepts need to be modified since, for the Lower Cretaceous, largely marine conditions have to be postulated, whereas Younger Cretaceous rocks show evidence of both marine and subaerial environment. According to Chubb (*3*) it is probable that, during Upper Cretaceous time, geanticlines arose in the trough and the epicontinental areas may have been dry land while the deeper part of the geosyncline definitely never was dry land.

In the lower part of the Upper Cretaceous the volcanism continued much in the same way as during the preceding epoch. Petrographic and structural studies point to several centers of eruption of which the major ones were located southeast of Lares, between Adjuntas and Utuado, northeast of Yauco, north of Juana Díaz, and in the Sierra de Luquillo (*18*).

LATE UPPER CRETACEOUS TO LOWER OLIGOCENE

Following the period of volcanism, the geologic events were dominated by processes of mountain formation which reached climaxes during Paleocene and Middle Eocene times. This orogeny – like the Laramidian Orogeny which formed the Rocky Mountains – is part of a worldwide period of disturbance and diastrophic movements. For the Greater Antilles Province Meyerhoff (*16*) named this diastrophism the Antillean Orogeny, but Mitchell (*18*) considered this an unfortunate choice for several reasons and called it the Caribbean Orogeny.

During this period compressive forces were exerted along a north-south or northeast-southwest direction and the accumulations in the geosyncline were strongly folded and faulted. Both Mitchell (*18*) and Meyerhoff (*16*) expressed the opinion that the then relatively unconsolidated rocks yielded to these distorting forces by folding rather than faulting. Though it is true that asymmetrical and commonly overturned folds are a prominent structural phenomenon, the detailed field investigations carried out by the U.S. Geological Survey established faults to be an equally important feature.

The first orogenic disturbance was accompanied by the emplacement of intermediate plutonic rocks, largely granodiorite, in the central and eastern part of the Island. These intrusions were preceded by the emplacement of the ultrabasic rock peridotite in southwest Puerto Rico, which according to Mattson (*14*) intruded earlier than Upper Cretaceous. The orogenic movements and doming associated with the plutonic intrusions created an island of highly mountainous appearance which subsequently underwent accelerated erosion and denudation, beginning in the late Middle Eocene.

MIDDLE OLIGOCENE TO PLIOCENE

After the final cessation of volcanism during Middle Eocene time there began a period of stability and quiescence in Puerto Rico, possibly the quietest time of the geologic past of the Island. Moreover, in contrast to the igneous geology in Cretaceous and Lower Tertiary times the Younger Tertiaries are predominantly calcareous and argillaceous. Thus, the transition from Eocene to Middle Oligocene marks the most profound structural and lithological break in Puerto Rico.

The encroaching sea scoured off and redeposited the terrestrial weathering products to form a basal conglomerate and clay formation, the San Sebastián Formation. The sedimentation of the Lares Limestone ensued when erosion of the upland became less intense. Subsequent arching, however, caused the sedimentation to change from calcareous to clastic and resulted in the heterogeneous Cibao Formation. The following period of stability is reflected in the Aguada Limestone and the exceptionally pure Aymamón Limestone. Tectonic movements occurred again in Miocene and Pliocene times and raised and slightly tilted the Island. This initiated cycles of erosion which in turn led to the denudation of peneplains.

QUATERNARY

Eustatic fluctuations in the sea level associated with the glacial and interglacial stages of the Pleistocene caused frequent changes of the environment thus giving rise to a complex Quaternary geology. These frequent alterations are reflected in a diversity of sediments of different lithology, as indicated on the diagram (fig. 3).

STRUCTURE

The basic structural framework is clearly seen: A core consisting of faulted and folded lava and pyroclastics, at its northern and southern flanks unconformably overlain by the predominantly calcareous Younger Tertiaries progressively becoming younger towards the coasts. The details, though, are far from being settled completely and subject to further studies.

FAULTS

As indicated above, and contrary to previous concepts, faults are prominent structural features and are nearly ubiquitous throughout the volcanic core of the Island. Though their detailed pattern is intricate, the general trend is dominated by a northwest-southeast or west-northwest – east-southeast strike. Two major fault zones are recognized: One extending from Añasco to Juana Díaz, the other running south of the Luquillo Range from an area east of Dos Bocas Dam to Playa Humacao. Structurally, these are strike-slip-faults or transcurrent faults, *i.e.*, faults the slip and strike of which practically parallel the strike of the strata. The displacement of the rocks along the fractures has been both horizontal and vertical.

FOLDS

Corresponding to the major fault zones the axes of the crests of troughs and the crests of anticlines follow the same general strike. According to Mitchell (*18*) the magnitude of the folds seems to increase from south to north. The same author speculates on the height of the fold-crests, and assumes that they may have risen to 8,000 feet above sea level (*18*), which is exaggerated.

It has been pointed out (*16,18*) that, frequently, the folds are asymmetrical and overturned to the north. Though this is correct for some parts of the Island it does not reflect the overall situation since Mattson (*13*) reported folds overturned to the south for southwest Puerto Rico.

The main structural deformation occurred post-Middle Eocene and pre-Middle Oligocene (*21*) and concluded the geosynclinal phase of mountain formation. In comparison to this diastrophism the post-Miocene movements have been much less vigorous.

UNCOMFORMITIES

The most prominent unconformity is that between Middle Eocene and Middle Oligocene. This feature is morphologically accentuated by the marked lithological differences of the rocks in juxtaposition and marks the transgressive overlap of the sea onto the Eocene land surface. There is a further uncomformable contact between the Pleistocene deposits and the Younger Tertiaries which also constitutes an unconformity, though much less spectacular.

EARTHQUAKES

Geologically, the Greater Antilles Province is a relatively young and tectonically active zone where stability has not been achieved and disturbances are not yet over. This fact is evidenced by some 30 earthquakes of strong to moderate intensity which have been recorded in Puerto Rico since 1858. The most severe shocks occurred on November 18, 1867, and on October 11, 1918. Both were of considerable magnitude — the 1918 earthquake reached IX on the Modified Mercalli Scale — and caused huge seismic waves or tsunami.

Seismologic studies revealed that these and other earthquakes which affected the Island are associated with the fracture lines bordering the Puerto Rico-Virgin Islands Platform. To the west and east these faults coincide with the Mona Passage and the Anegada Trough, respectively; the northern fracture is an eastward extension of the Puerto Rico Trench, and the southern one roughly parallels the coast some 30 miles offshore. The epicenter of the 1918 earthquake was located at the point where the Mona Passage meets the Puerto Rico Trench, and the 1867 earthquake was centered near the southeastern edge of the Puerto Rico-Virgin Islands block. Compared with these two shocks the other earthquakes recorded in Puerto Rico, namely those associated with the east-west faults, have been minor tremors. This indicates that the north-south fractures are more active and hence yield more vigorous shocks.

Along these fracture lines differential movements occur whenever the steadily built-up stresses acquire sufficient strength to overcome the inertia and friction. This usually does not happen in one single shock, and particularly the greater earthquakes are preceded and followed by numerous minor shocks.

It is not improbable that earthquakes will afflict Puerto Rico in the future. Yet statements pertaining to the possible date of such an event would be devoid of any degree of scientific accuracy. However, with no evidence of historic movements along faults within Puerto Rico, it is reasonably safe to assume that a strong earthquake will not be centered in Puerto Rico.

MINERAL RESOURCES

In 1954 the Commonwealth Government passed the Mining Law that created the Mining Commission with the objective of assisting and regulating prospecting and mining in Puerto Rico. Since then considerable amounts of money have been invested in mineral research, mainly by private industry. These expenditures for mineral exploration are substantiated by the fact that the geologic background of Puerto Rico *per se* justifies these investigations. Wherever plutonic activity took place one may expect metalliferous deposits. In Puerto Rico, this promise is enhanced by the widespread occurrence of hydrothermally altered rocks. The magmatic emanations causing these changes are usually enriched with metallic ions and volatiles which, in many other places, created valuable ore deposits. These investigations resulted in a more thorough knowledge of the mineral resources of the Island. They also revealed that — with but a few exceptions — the Puerto Rican ore deposits seem to be of more academic than of commercial interest under the present economic conditions. Therefore, no attempt is made here to elucidate the mineral deposits of Puerto Rico in detail, and only the general aspects are discussed briefly.

METALLICS

Gold occurs in alluvial placers associated with the rivers draining the Sierra de Luquillo and the central part of the Cordillera Central. Approximately 1,250,000 ounces of gold — at present equivalent to roughly 42 million dollars — were obtained by the Spanish, but the considerable part which escaped their antiquated methods could be recovered by modern techniques. However, at the current level of the price of gold this venture would be of doubtful economic utility.

The mining of **copper** is presently under serious consideration, and there can be little doubt that the excavations in the Upper Tanamá region and near Utuado will begin in the near future. The deposits outcropping at these locations contain copper, mainly in the form of chalcopyrite, $CuFeS_2$, of hydrothermal origin and finely disseminated in a porphyric country rock. The copper content of this "ore" amounts only to approximately 0.7 percent. Yet, fairly large orebodies allowing nonselective open-pit mining make the exploitation profitable even at this low level. It may be added parenthetically, that a similar porphyry copper ore with equally low copper content

(0.8 percent) is mined in one of the world's largest copper mines in Bingham near Salt Lake City, Utah.

There are further copper deposits south of Ciales-Morovis, near San Germán, south of Aguada and at other places. But, though the quality of the ore is often quite good, economic importance appears to be doubtful because of limited quantities.

Puerto Rico's best known **iron** deposits occur in the Juncos-Las Piedras district along the northern contact zone of the San Lorenzo pluton in the adjacent Cretaceous rocks. The ore that was mined in the early 1950's consists mainly of magnetite, Fe_3O_4, and is of good quality. Further outcrops of similar iron ores are found in the hills south of Humacao, and north of Arroyo and Ponce. Exploitation of the residual limonite deposits, FeOOH, of Las Mesas east of Mayagüez has also been considered, formerly as a source of iron and now chiefly because of the relatively high **nickel** and **cobalt** contents. Thus this Ni-Co-laterite derived from serpentinite might be developed in the future.

Manganese has been detected in several places in the Island. What seems to be the most important deposit is that of Juana Díaz. Manganese ore — mainly psilomelane, MnO_2 — was mined there from 1915 until 1939, when the mine was closed because of exhaustion of the near-surface supplies.

Lead, zinc, tin, mercury, platinum, and **silver** have also been recorded to occur in Puerto Rico (*18*), but are apparently of little commercial importance.

NONMETALLICS

The general association of mineral resources with ores, and the precious metals in particular, tends to obscure the economic value of the nonmetallics. Yet, they frequently yield considerable and steady monetary returns. This applies especially to Puerto Rico where the value of the nonmetallics produced amounts to approximately $40,000,000 per year.

Limestones provide the basis for a significant cement industry, besides being the source of lime for the sugar, fertilizer, and plaster industries. Furthermore the compact and crystalline variants are widely used as an excellent road construction material. Recently, the use of dolomite is being considered for the production of magnesium and it appears that the dolomites of Mona Island are promising in these respects.

Additional nonmetallic resources of economic interest are deposits of **guano** on Mona Island, several **clay** deposits in the vicinity of San Juan, and **gravel** and **sand**.

FUELS

In the Moca-San Sebastián-Lares district seams of **lignite** are found in the San Sebastián Formation. This is a brownish-black coal in which alteration of organic matter has proceeded further than in peat, but less than in subbituminous coal. The Puerto Rico lignite is so thin, however, that it has little value, and even local use has been abandoned. So far no other grade coal has been encountered in Puerto Rico.

With respect to **oil**, the prerequisites for its formation are present in Puerto Rico: The Cretaceous shales relatively high in organic matter are a possible source rock; many porous pyroclastics could provide suitable reservoir rock; and there are several structures and unconformities which may serve as traps. However, if any oil were present in these pre-Tertiary rocks it has been dissipated by igneous activity, particularly in the central part of the Island.

Conditions for the Lower Tertiary seem to be somewhat more favorable, as indicated by the occurrence of lignite in the San Sebastián Formation. But, since the conditions conducive to the accumulation of organic matter have not been prevailing over long periods, the prospects of finding oil are not very good. Recent prospecting for oil has so far been little encouraging: all of the four oil wells drilled were nonproductive. However, an additional number of wells will be necessary to adequately test the possibilities of the Island. Also the study of the shelf region surrounding Puerto Rico now in progress may reveal some new aspects.

SUMMARY

The geologic history of Puerto Rico — as far as it can be established at our present state of knowledge — begins in the Upper Mesozoic. During Lower and early Upper Cretaceous a geosyncline elongated through the Antillean region. In this trough active volcanism occurred until near the end of Middle Eocene, and gave rise to predominantly submarine accumulation of andesitic tuff, lava, tuffaceous breccias, and other volcanic rocks. Simultaneously limestones and tuffaceous shales originated.

At the very end of the Cretaceous, and extending through Middle Eocene, mountain-forming processes caused by north-south or northeast-southwest compressive forces resulted in extensive faulting and folding. This orogeny was accompanied by the emplacement of plutonic rocks, largely granodiorite, quartzdiorite, and some diorite, which are now exposed in the San Lorenzo and Utuado plutons. The serpentinized peridotite of S.W. Puerto Rico intruded earlier, probably in Lower Cretaceous.

The diastrophism entailed the appearance of an Island which, during mid-Tertiary, was bordered by marine basins to the north and to the south. There the Younger Tertiary limestones were formed from Middle Oligocene to Middle Miocene. This interim of quiescence was succeeded by reviving movements causing further uplift and slight tilting, thus shaping the Island's present form. These periodic movements also controlled cycles of erosion in the interior: At least two peneplains were denuded and, as a result of subsequent uplift, dissected by rejuvenated rivers. In the Quaternary a variety of sedimentary rocks accumulated, ranging from indurated dunes to unconsolidated alluvials and organic deposits.

Structurally, Puerto Rico consists of a central core of strongly faulted and folded Cretaceous and Lower Tertiary rocks unconformably overlain by the Younger Tertiaries on its northern and southern flanks. The general strike is NW-SE or WNW-ESE. Besides folds, transcurrent faults are the dominating structural features, the two major ones extending from Añasco to Juana Díaz and south of the Sierra de Luquillo, respectively. The hiatus between Eocene and Middle Oligocene marks the most profound lithological and structural break in Puerto Rico.

Seven physiographic units are recognized: the Mountain Uplands or Monadnocks, the St. John Peneplain, the Caguana Peneplain, the Foothill Zone, the Interior Lowlands, the Belted North Coastal Zone, and Playas and Alluvials.

Mineral resources are limited. Of the various metallic ore deposits occurring in Puerto Rico, only copper warrants commercial exploitation under the present economic conditions. With the exception of a low-grade lignite, no fuels have been found yet. The nonmetallics, however, constitute resources of considerable economic importance.

RESUMEN

La historia geológica de Puerto Rico, hasta donde los actuales conocimientos permiten conocerla, comienza en el Mesozoico Superior. Durante el Cretáceo Inferior y la primera parte del Cretáceo Superior, se desarrolló un geosinclinal a través de la Región Antillana. En este geosinclinal, ocurrió un volcanismo activo que, extendiéndose hasta el Eoceno Superior, causó la acumulación de tobas andesíticas, lavas, brechas tobásicas, y otras rocas volcánicas. Simultáneamente, se originaron calizas y arcillas pizarrosas de naturaleza tobásica.

Desde las postrimerías del Cretáceo hasta el Eoceno Medio, procesos orogénicos engendrados por fuerzas tectónicas compresivas del norte al sur y del noreste al suroeste, causaron plegamientos y fallas extensivas. Simultáneos a esta orogenia fueron los emplazamientos de rocas plutónicas, mayormente granodioritas, cuarzodioritas y algunas dioritas, que hoy día afloran en los cuerpos plutónicos de Utuado y San Lorenzo. Probablemente, la intrusión de los peridotos

serpentinados del suroeste isleño ocurrió durante el Cretáceo Inferior.

Este diastrofismo ubica la génesis de una isla que, durante el Terciario Medio, estuvo rodeada por cuencas oceánicas al norte y al sur. Fue en éstas en donde se formaron las calizas Terciarias, desde el Oligoceno Medio hasta el Mioceno Medio. A la quietud tectónica que comprendió ese intervalo, siguieron movimientos recurrentes los cuales comenzaron a determinar la morfología presente de la Isla y regularon luego los ciclos de erosión en el interior, dando origen, por lo menos a dos penillanuras que, como resultado de los levantamientos tectónicos subsiguientes, fueron indentadas por ríos rejuvenecidos. Durante el Cuaternario, se formó una gran variedad de rocas sedimentarias, incluyendo areniscas dúnicas, aluviones y depósitos orgánicos.

El eje estructural de Puerto Rico ha quedado constituido por un núcleo central de rocas de las edades Cretácea a Terciaria Temprana, altamente plegadas y cortadas por fallas. En sus flancos norte y sur, se encuentran las calizas Terciarias. El rumbo regional de ese eje estructural es, aproximadamente, noroeste-sureste u oeste-noroeste a este-sureste. Las fallas de corrimiento constituyen, conjuntamente con los pliegues, los elementos estructurales predominantes de la Isla. Las dos fallas más grandes son las que se extienden desde Añasco hasta Juana Díaz y al sur de la Sierra de Luquillo. La ausencia de un registro geológico entre el Eoceno y el Oligoceno Medio, señala la mayor y más profunda ruptura litológica y estructural en Puerto Rico.

Siete unidades fisiográficas han sido reconocidas: la región de los "monadnocks", la Penillanura St. John, la Penillanura Caguana, la región sur de los cerros frontales a la Cordillera, los valles interiores, las franjas calizas Terciarias de la costa norte y las Playas, Llanos y Aluviones Costaneros.

Los recursos minerales de la Isla son limitados. Unicamente el cobre, entre los distintos yacimientos de menas metálicas en Puerto Rico, es explotable bajo las presentes condiciones económicas. Con la excepción de un lignito, no se han encontrado, hasta la fecha, fuentes de combustible. Sin embargo, los no metálicos constituyen recursos de considerable importancia económica.

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