Geology of the Coamo Area, Puerto Rico, and Its Relation To the Volcanic Arc-Trench Association

GEOLOGICAL SURVEY PROFESSIONAL PAPER 636

Prepared in cooperation with the Commonwealth of Puerto Rico Economic Development Administration, Industrial Research Department

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By LYNN GLOVER III

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Stratigraphy, petrography, and structural development of Lower Cretaceous (Albian) to Holocene rocks and sediments with comments on Greater Antillean volcanic island arc-trench phenomena

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By Lynn Glover III

ABSTRACT

The Coamo area, centering on the town of Coamo, encompasses about 200 square miles in south-central Puerto Rico. It is approximately bounded on the north by the east-trending crest of the Cordillera Central and on the south by the shore of the Caribbean Sea. The area lies on the flank of a much-faulted geanticlinal volcanic core that is partly overlapped by a sequence of post-Eocene epiclastic and carbonate rocks and sediments.

The oldest rocks in the area consist of an unnamed sequence of pre-Robles massive and thick-bedded andesite and dacite submarine pyroclastic breccias with intercalated lavas, tuff, and rare limestone. The rocks are Albian or older and were deposited mostly in deep water. The pre-Robles rocks were not studied in detail for this report.

The Robles Formation comprises 500 to 1,500 meters of thin- to medium-bedded pyroxene andesite tuffs and tuffaceous plankton-bearing mudstones that are generally of deep-water marine origin. It contains intercalations of trachyandesite and potassic pyroxene andesite pillow lavas, minor thick-bedded volcanic breccia, and a basal transgressive limestone. The Robles ranges in age from Albian to Santonian. Although most of the Puerto Rican volcanic rocks seem to be calc-alkalic, the lavas of the Robles show subalkalic affinities. The principal sources of Robles volcaniclastic rocks were submarine vents north of the Coamo area.

The Cariblanco Formation of Santonian age rests disconformably upon the Robles Formation and is a coarsely conglomeratic sequence of about 1,000 meters of reworked and primary tuff and lapilli tuff. The Cariblanco includes minor members of basalt lava, limestone, and a distinctive well-sorted sanidine-bearing, plagioclase-rich crystal tuff. The drab marine Cariblanco of the Coamo area interfingers to the north with the bright grayish-red nonmarine Achiote Conglomerate. The sources of Cariblanco sediment probably were subaerial andesitic to dacitic volcanoes 15 to 20 km north of the Coamo area on a high area formed by volcanic upbuilding and tectonic arching. In central Puerto Rico, weathering and erosion at the source produced the ill-sorted nonmarine Achiote fanglomerate which interfingers with the marine Cariblanco to the south. Contemporaneous eruptions added primary pyroclastic debris to the weathered and reworked pyroclastic debris of both the Achiote and Cariblanco Formations. Submarine sliding is suggested as the mode of transport of the Cariblanco coarse boulder conglomerate where it is interleaved with fine-grained plankton-rich turbidites. Submarine slides transported boulders as much as 3.3 meters in diameter as far as 12 km south of the strand. Dark organic-rich beds in the southern Cariblanco suggest euxinic conditions, possibly created by a stagnant submarine fault trough.

The Maravillas Formation, which conformably overlies the Cariblanco, is a heterogeneous sequence 500 to 1,400 meters thick, containing subequal amounts of hornblende-augite andesite pyroclastic rocks and tuffaceous mudstone. Less common are limestone and wacke conglomerate. Most of the Maravillas apparently is Campanian. It may contain rocks as old as the Santonian and as young as the Maestrichtian. At the beginning of Maravillas deposition, two events occurred to change the sedimentary regime in the Coamo area. The first event was subsidence, which allowed the sea to transgress northward across the Achiote Conglomerate. The second event was the eruption of large quantities of pyroclastic rocks from newly established centers in south-central Puerto Rico. One large and several small bodies of porphyritic diorite were emplaced in the Coamo area at this time, and some of these mark eruptive centers.

The Coamo Formation conformably overlies the Maravillas and comprises about 1,500 meters of coarse massive pyroxene andesite tuff breccia and lapilli tuff. Tuff and lava are minor constituents. The formation is principally a marine deposit which accumulated near a vent site probably situated within the Coamo area. The Coamo may be Campanian and (or) Maestrichtian in age.

The Cuyón Formation is a heterogeneous sequence about 75 meters thick, comprising (from oldest to youngest) reddish-gray volcaniclastic rocks, drab reworked tuff and conglomerate, and limestone. These nonmarine to shallow-water marine deposits rest unconformably upon the Robles Formation. The Cuyón appears to be Maestrichtian in age.

The Jacaguas Group of Maestrichtian to middle Eocene age unconformably overlies the Coamo and comprises the dacitic Miramar, Raspaldo, and Río Descalabrado Formations, the andesitic Los Puertos Formation, the Guayo Formation, and the Cuevas Limestone.

The oldest unit of the group is the Miramar Formation, which probably ranges from Maestrichtian to Paleocene in age. It probably rests with angular unconformity on the oldest Cretaceous rocks. The Miramar is mostly red thick-bedded to massive tuffaceous conglomerate. It may be more than 700 meters thick. Oysters and rudistids are locally abundant. The Miramar is a shallow-water marine deposit that may be in part subaerially deposited. The Paleocene Los Puertos Formation is about 350 meters of massive to thick-bedded andesitic tuff breccia and conglomeratic breccia with rare tuffaceous mudstone interbeds. It apparently is a somewhat reworked marine near-vent deposit. The base of the formation is concealed by faulting.

The Paleocene to lower Eocene Raspaldo Formation is a sequence of marine thin- to medium-bedded vitric-rich dacite tuff and tuffaceous mudstone that interfingers with the Los Puertos Formation. There are minor conglomerate and limestone units. The formation probably is more than 600 meters thick; its base is concealed by faulting. The Raspaldo probably was deposited by ash-fall, turbidity-current, mudslide, and pelagic sedimentation below wave base in the open sea.

The middle(?) Eocene Cuevas Limestone consists of about 35 meters of algal limestone resting uncomformably upon Cretaceous to lower Eocene rocks. It is principally composed of fragments, oncolites, and coralline heads of calcareous red algae. It seems to have been deposited in very shallow water.

The middle Eocene Río Descalabrado Formation is a deep-water dacitic tuff and mudstone deposit at least 500 meters thick that conformably overlies the Cuevas Limestone. It is similar in lithology to the Raspaldo Formation.

The Guayo Formation comprises thick-bedded and massive conglomeratic tuff that seems to interfinger with the Río Descalabrado Formation. The Raspaldo, Río Descalabrado, and Guayo dacite-tuff-bearing formations probably originated largely from source vents in the vicinity of the Utuado batholith.

A megabreccia forms a tectonic unit of Cretaceous(?) to early Oligocene age. It is widely distributed in the western Coamo area where it formed during gravity gliding of the Jacaguas Group. The megabreccia contains individual blocks more than a kilometer in greatest dimension. Many of the blocks are of greenschist grade; they must therefore have originated from sources of this metamorphic grade south of their present location.

The middle Tertiary sequence rests with conspicuous unconformity upon the older volcanic sequence. It is only moderately folded and faulted.

The Juana Díaz Formation forms the basal conglomeratic part of the nonvolcanic middle Tertiary sequence. The formation contains a maximum of 655 meters of coarse bouldery gravel made up of rocks from the older sequence; it grades upward into sandy limestone. The Juana Díaz is probably of Oligocene age.

The Oligocene and Miocene Ponce Limestone conformably overlies the Juana Díaz. This formation is composed of more than 380 meters of soft to well-indurated limestone of shallow-water origin.

Oil test wells along the south coast have revealed the presence of as much as 1,000 meters of unconsolidated and semiconsolidated gravel, sandy, silty clay, and limestone of middle(?) Tertiary to Holocene age. This sequence probably overlies the indurated middle Tertiary sequence with angular unconformity.

Surficial deposits of Quaternary age include coral reefs, beach, and mangrove-swamp deposits along the Caribbean coast. Alluvial fans coalesce to form a broad alluvial plain along the south coast. Terraced alluvium occurs along some streams, and colluvium blankets the lower slopes of many large stream valleys.

Intrusive igneous rocks crop out over about 5 percent of the Coamo area. Most of these rocks occur as dikes, but small stocks are common; sills seem to be rare. The igneous rocks include the following:

1. Pyroxene andesite and microdiorite dikes probably equivalent in age to rocks of the upper Robles Formation.
2. Hornblende microdiorite as dikes and small stocks. Here is included the Los Panes chonolith (or disruptive laccolith) near the center of the area. (At least one of these intrusive centers contains explosion breccia and appears to have been an eruptive site during the Campanian. The pyroclastic fragments of the Maravillas Formation and the Los Panes chonolith are petrographically identical.)
3. Pyroxene andesite dikes and the diorite Zanja Blanca stock of probable Coamo age.
4. Hornblende quartz diorite and basic granodiorite in the Cuyón stock of latest Cretaceous or early Tertiary age.
5. Dacite and quartz microdiorite dikes of latest Cretaceous or early Tertiary age.

Most of the volcaniclastic rocks in the Coamo area have been altered in part to mineral assemblages characteristic of diagenetic or low-grade metamorphic facies. In general, the younger rocks are less altered, but locally the metamorphic facies abruptly transgress stratigraphic boundaries. The facies represented include the low heulandite and high laumontite zones of the zeolite facies, the prehnite-pumpellyite metagraywacke facies, and locally the quartz-albite-epidote-chlorite greenschist assemblage. The metamorphic history apparently is complex, but there may have been a thermal maximum during the Maestrichtian-Paleocene interval corresponding to emplacement of the batholiths.

The largest folded structure of the region is the east-trending Puerto Rico geanticline of middle Tertiary to Holocene age. The Coamo area makes up a small part of the southern flank of this element. Smaller and earlier but more intensely deformed structural elements at least partially encompassed by the Coamo area include: (1) the southern flank of the west-northwest-trending Late Cretaceous Barranquitas anticlinorium comprising the Coamo syncline and the Lapa anticline, (2) dome and thrust-fault structures associated with the Campanian Los Panes intrusive, (3) the Asomante volcanic pipe, and (4) dikes of Santonian Achiote Conglomerate that intrude the overlying Campanian Maravillas Formation.

Major fault structures include the great southern Puerto Pico fault zone, a complex of high-angle west-northwest-trending sinistral wrench faults that also have experienced intermittent upthrust and normal movement since Early Cretaceous. This is one of two major fault zones that divide Puerto Rico into three principal structural blocks of generally dissimilar stratigraphy and structure.

The Jacaguas Group was strongly folded and faulted by gravity sliding during the middle to late Eocene. Tilting of the major blocks that make up the great southern Puerto Rico fault zone dumped the shallower and somewhat less indurated parts of the sequence toward the north-northeast.

Post-Ponce Limestone (middle Miocene) normal faulting appears to have created the north-northeast-trending Caja de Muertos fault. This fault, indicated principally by seismic and bathymetric data, is on the southeast side of the Ponce basin, which seems to have been filled with a semiconsolidated gravelly sequence of Miocene(?) to Holocene age.

The Isla Caja de Muertos shelf is a feature 50 by 10 km in overall dimensions. It is submerged to a depth of about 15 fathoms and lies offshore south of the Coamo area. It seems to be principally a wave-planed tectonic feature bounded on the north by the great southern Puerto Rico fault zone and probably by faults on the other sides as well.

To judge from the Coamo district, embryonic Puerto Rico was a topographically positive area of intermittently shoaling primary and reworked pyroclastic rocks and minor lava and limestone. The sedimentary prism was generated locally, principally from submarine eruptions along fissures and centers related to the Greater Antillean fracture system, an easterly zone of sinistral wrenching and high-angle dip-slip movement. Orogeny was continuous from the time of earliest deposition (Early Cretaceous) in the Coamo area, but a broad orogenic climax was reached during the Maestrichtian to middle Eocene interval. Some of the geophysical and other geological data can be interpreted to indicate either that the present Puerto Rico Trench did not exist during the pre-Oligocene or that, if it did exist, subsequent great left-lateral displacement along the southern trench boundary fault has juxtaposed a thinner and more nearly oceanic crust against the thick andesitic pyroclastic sequence of Puerto Rico.

INTRODUCTION

The geology of the Coamo area provides a detailed picture of the succession of geologic events in south-central Puerto Rico. Emphasis is herein placed upon the petrography of the rocks, conditions of deposition, and the structural development of the area. The report is intended as a contribution to the literature of island arcs, a literature replete with reports of geophysical investigations, reconnaissance geological investigations, and physiographic interpretations. In spite of the attention that island-arc geology has received, a structural-geology textbook (de Sitter, 1964, p. 367), as recently as 1964, stated that:

> The discussion of island arcs starts from a number of general data which are rarely realized in any other typical feature of crustal disturbance. Nowhere do we know so much of the general character, and, I am tempted to say, so litt'e of the geological detail.

Nonetheless, based largely upon this body of data, which is so lacking in geological detail, a number of far-reaching theoretical constructions have come to compose an important part of our literature on orogenic processes.

The detailed field investigator, having arrived rather late in the island-arc setting, is thus offered a sophisticated collection of orogenic models to choose among. In a sense the choice has passed from the computer to the pick, for any orogenic model that survives must predict the sequence of geological events discovered by the geologist on the ground.

Puerto Rico is unique among the lands of similar geologic setting in being the first to present the necessary combination of conditions making detailed geologic field investigations possible; that is, it has a combination of good access, sufficient outcrops, excellent large-scale topographic maps and air photographs, and an enlightened view that orderly economic development requires large-scale general-purpose geologic maps.

The Coamo area is in southern Puerto Rico, easternmost of the Greater Antilles (fig. 1). The area encompasses parts of about half of a block of six 7½-minute topographic quadrangles as shown in figure 2, or approximately 200 square miles of the 384 square miles encompassed by all six quadrangles. Most of the area is on the dry southern slope of the Cordillera Central, which forms an east-trending drainage divide separating a steep southern from a relatively gentle northern slope. Deep lateritic soils commonly mantle bedrock north of this divide, but such soils are mostly absent in the Coamo area, where outcrops are generally less weathered and more abundant. Much of the bedrock area is devoted to pasture land, and access by road and trail is excellent.

Fieldwork was begun in the area in late 1955 and was virtually completed by June 1960. Geologic maps and preliminary results have been published principally in a series of U.S. Geological Survey Miscellaneous Geologic Investigations Maps by Berryhill (1960), Berryhill and Glover (1960), Glover (1961a, b), and Glover and Mattson (unpub. data). Additional topical reports by members of the Geological Survey include data from parts of the Coamo area (Berryhill, Briggs, and Glover, 1960; Glover and Mattson, 1960; Mattson and Glover, 1960).

Petrographic and X-ray examination of the rocks was performed by Glover during 1960–1964 at Princeton University, and most of the text was written there.

Little geological work in the Coamo area had been done before 1955. The area was included in a report on the geology of the Coamo-Guayama District by Hodge (1920), done under the auspices of the New York Academy of Science. Zapp, Bergquist, and Thomas (1948) reported on the middle Tertiary rocks of Puerto Rico. Their map includes rocks of this age in the southwestern Coamo area. More recently Pessagno (1960a, 1961, 1962, 1963a, b) has published reports on the biostratigraphy and paleontology of the Ponce-Coamo area, which includes most of the Coamo area of this report.

PETROGRAPHIC METHODS

Descriptions of the Coamo area rocks are based upon field observations and laboratory study of a collection of about 1,000 rock samples. Several hundred polished and lacquered rock slabs were prepared for binocular microscope examination of textures and fossil and mineral content. These slabs proved to be a valuable source of data and allowed excellent resolution of detail at a scale of magnification intermediate between the scales of the hand lens and the petrographic microscope. Potassium feldspar was detected by sodium cobaltinitrite staining on the unlacquered side of a rock slab which was first etched in hydrofluoric acid vapor. Limestone slabs were ground and lightly etched in dilute hydrochloric acid solution before spraying with clear lacquer.

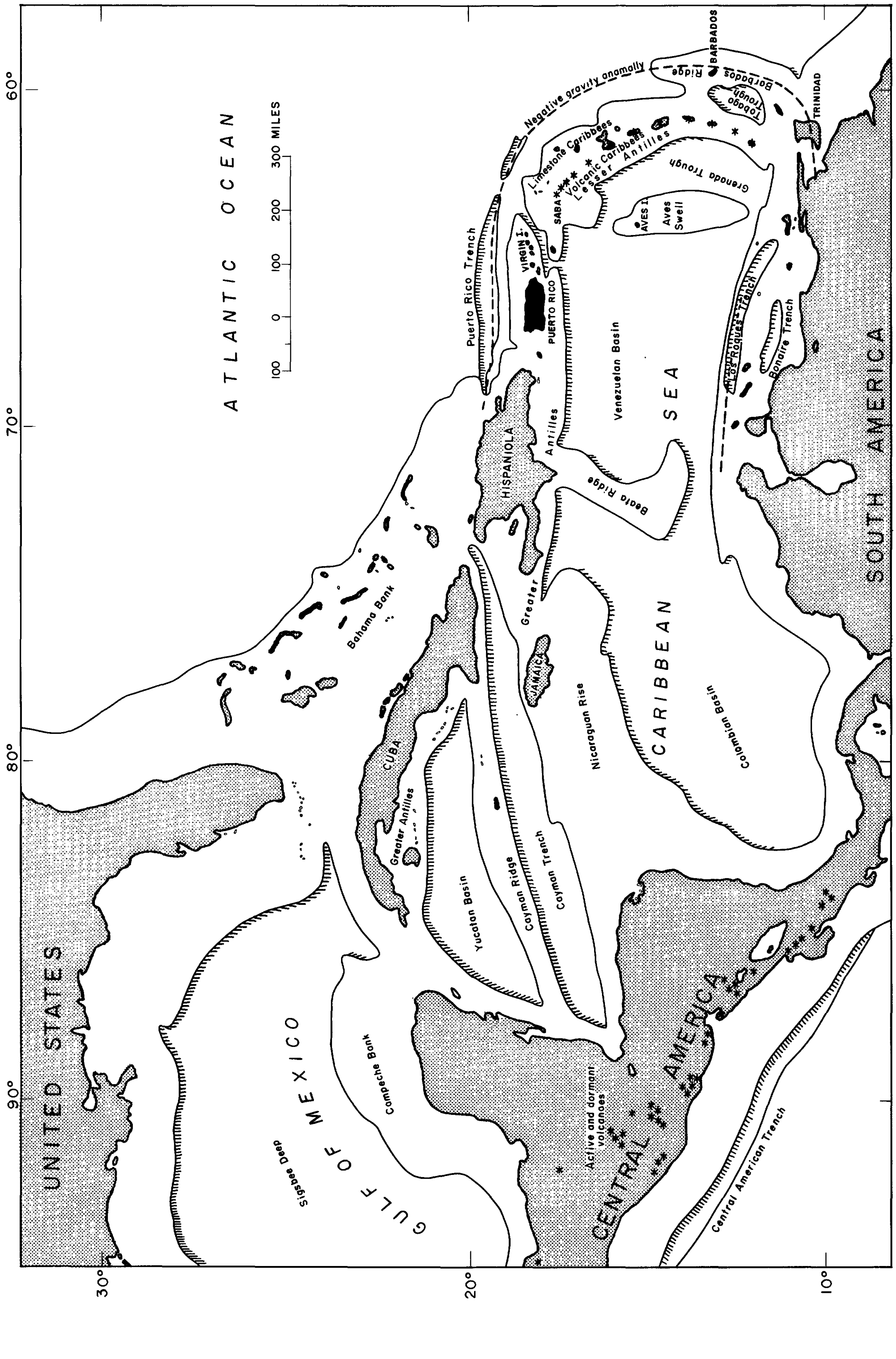


FIGURE 1.—Index map showing location of Puerto Rico and the major physiographic elements of the Caribbean region.

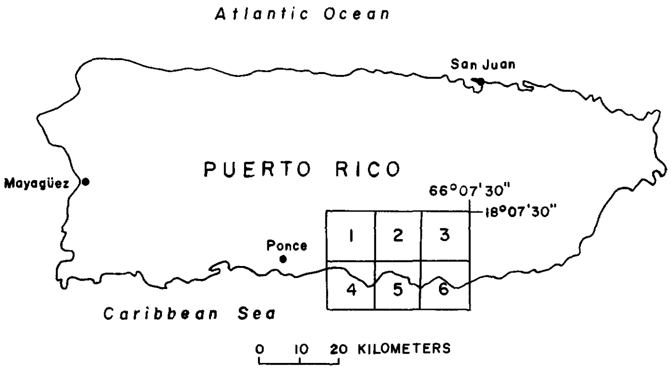


Figure 2.—Location of the Coamo area in Puerto Rico. The following 7½-minute topographic quadrangles are included in the Coamo area: (1) Río Descalabrado, (2) Coamo, (3) Cayey, (4) Santa Isabel, (5) Salinas, and (6) Central Aguirre.

Approximately 450 thin sections were examined with a petrographic microscope. Optic axial angles were measured on a Universal stage. Indices of refraction were measured using a sodium-vapor light source and the values were then corrected for temperature. Compositions of clinopyroxenes were determined by measuring nY and $2V_z$ according to the method of Hess (1949). This procedure yields partial compositions expressed as atomic percentages of the major cations Ca, Mg, and Fe^{+2}. According to Deer, Howie, and Zussman (1963), these values probably do not differ by more than 5 percent from their actual compositions. Plagioclase was determined by extinction-angle measurements, and the figures given are probably accurate to within about 8 percent. Identifications of zeolites and most other secondary minerals were confirmed by X-ray diffraction analysis. Mineral-concentration procedures were aided by use of the Franz magnetic separator. Chemical analyses of five lava samples and one limestone were made by rapid rock-analysis methods in the laboratories of the U.S. Geological Survey.

DEFINITIONS OF SOME TERMS

The classification of volcaniclastic rocks used in this report is modified principally from that of Fisher (1961). Some changes and additions to Fisher's classification are employed herein for clarity to emphasize genetic differences among somewhat similar rock types. In the writer's opinion communication is improved by employing the familiar, if not altogether well-chosen, terminology for pyroclastic rocks. Hence, the familiar term "lapilli tuff" replaces "lapillistone" in Fisher's classification. "Pyroclastic breccia" seems a good general term for "tuff breccia" or "lapilli tuff."

One of the principal contributions of Fisher's classification is the distinguishing of reworked tuff from rocks formed by epiclastic processes.

The writer has found it desirable to discriminate between (1) reworked pyroclastic rocks, which were redeposited from *coeval* sources that were largely but not entirely unconsolidated, and (2) epiclastic volcaniclastic rocks that were eroded from the *older* and generally more indurated formations. This classification attaches greater importance to the relationship between tectonic or eustatic changes in sea level and the erosion of older rocks than it does to the rounding, sorting, and weathering of essentially loose pyroclastic debris prior to final deposition and consolidation.

Neoclastic rocks are herein introduced as a fourth class of volcaniclastic rocks. Neoclasts are eroded from the *consolidated* parts of volcanic cones that are *coeval* with the incorporating volcaniclastic unit. Source rocks would most commonly be lava, shallow dikes and sills, and welded tuffs and agglutinates. Neoclasts may commonly form the blocks and gravel of conglomeratic reworked pyroclastic deposits. They may be recognized by their petrographic similarity to contemporaneous pyroclastic debris. In this report the gravel of the Cariblanco Formation serves as a type example. The classification of volcaniclastic rocks used herein is shown in figure 3.

Volcanic glass is used a few times in this report even though none of the original glass in the Coamo area seems to have survived the attacks of devitrification, diagenesis, and low grade metamorphism. The former existence of volcanic glass is generally recognized by relic perlitic cracks, welding, and shard structures.

Wacke conglomerate is used to indicate a poorly sorted conglomerate generally having more than 10 percent clay and silt in the matrix.

Limestone technology is generally that of Folk (1962). The bases of this classification are the proportions of fine carbonate mud matrix (micrite) and the sorting and rounding of allochems (intraclasts, oölites, fossils, and pellets). The classification aids in estimating the energy and environment of origin and the energy and environment of deposition.

Most other terminology generally follows that of Williams, Turner, and Gilbert (1954).

Rock-color designations are commonly based on the "Rock-color chart" of the National Research Council (Goddard and others, 1948).

Bedding character is described as (1) massive when there is a general absence of planar structure through about 4 meters of stratigraphic section, and (2) thin, medium, and thick bedded when strata are less than about 10 cm (centimeters), 60 cm, and 3.6 meters respectively.

PREDOMINANT GRAIN SIZE (mm.)	AUTOCLASTIC[1]	PYROCLASTIC[1]			NEOCLASTIC[1]	EPICLASTIC[1,2]	EQUIVALENT NONGENETIC TERMS[1,2]
		Primary or reworked					
256	Lava breccia	Tuff breccia	Pyroclastic breccia	Agglutinate (welded)	Breccia or conglomerate	Breccia or conglomerate	Volcanic breccia or volcanic conglomerate
64	Autobreccia						
32	Intrusion breccia	Lapilli tuff					
2	Tuffisite	Coarse tuff	Tuff		Sandstone	Sandstone	Volcanic sandstone
1/16		Fine tuff			Siltstone	Siltstone	Volcanic siltstone
1/256						Claystone	

[1] May be mixed with nonvolcanic clastic material. [2] Add "tuffaceous" to rocks containing pyroclastic material <2 mm in size.

FIGURE 3.—Classification of volcaniclastic rocks that is used in this report.

Locations are commonly given by reference to the Puerto Rico meter grid system. Ticks referring to this grid appear on the margins of the maps.

"Shallow water" as used in this report refers to rocks whose sedimentary structures, sedimentary textures, or faunal contents indicate that they were deposited in the zone of surf action or in the upper zone of wave action (shallower than 60 or 70 meters) in an open-sea environment. Surf base (Dietz, 1963) probably is near 10 meters. Wave base, under open-sea conditions, may extend to depths as great as 200 meters or more at the edge of the continental shelf (Dietz, 1964), but the slight and infrequent agitation of sediment at this depth is probably not easily read from the textures and structures of the subsequently indurated sediments. From the stratigrapher's point of view it is important to note (1) that wave energy falls off exponentially with depth, and (2) that, as measured by the ability of waves to move sediment, there is an effective wave base for each size of particle (Moore and Curray, 1964, p. 1268). Reliable figures do not seem to be available, but muddy sands might not be much cleaned by winnowing below depths of about 60–70 meters.

ACKNOWLEDGMENTS

Support and encouragement from the cooperating agency, the Industrial Research Department, Puerto Rico Economic Development Administration, was essential to the successful completion of this investigation. The Department was headed during the early stages of this project by Mr. Rafael Fernández García, who, upon his retirement in 1956, was succeeded by Mr. Carlos Vincenty.

It is a particular pleasure to acknowledge the encouragement of members of the faculty at Princeton University, where this report was largely prepared and presented as a thesis in candidacy for the Ph. D. degree in geology. Professors H. H. Hess, F. B. Van Houten, and A. G. Fischer provided many stimulating discussions and a fund of helpful suggestions during the course of the work. Conversations with Richard S. Fiske over a period of several years, culminating in a field conference in the spring of 1965, were exceptionally helpful in understanding many aspects of the deposition of marine volcaniclastic deposits.

The writer has benefited from discussions of regional stratigraphic and structural relations with R. P. Briggs, P. H. Mattson, H. L. Berryhill, W. Bergey, M. H. Pease, and T. W. Donnelly. Donnelly, Guillermo Otálora, Victor Seiders, and James P. Owens contributed valuable discussions on various aspects of petrology of the rocks. N. F. Sohl, E. A. Pessagno, Earle Kauffmann, and Jeremy Reiskind provided most of the paleontological data. Lastly, grateful acknowledgement is herein made for able assistance in the field by Allen Perry, J. H. Glover, Pedro Gelabert, and David Phail.

GENERAL GEOLOGIC SETTING

The Coamo area lies on the southern flank of a much-faulted geanticlinal volcanic core that forms the easterly-trending Cordillera Central of Puerto Rico. The outcropping volcanic rocks are principally andesitic and range in age from Early Cretaceous to middle Eocene. In the southwestern part of the island the volcanic rocks rest unconformably upon an older complex of sheared serpentinite, foliated amphibolite, and thin-bedded black chert. Small batholiths of intermediate composition were intruded near the central and southeastern parts of the island during the Late Cretaceous and early Tertiary.

A sequence of moderately soft mid-Tertiary limestone, commonly with a basal epiclastic formation, transgressively overlaps the deformed volcanic core. In general the mid-Tertiary rocks dip gently to the north and south away from the core, but locally on the south coast they are tilted to angles as high as 30° and are moderately deformed by faulting and folding.

Unconsolidated and semiconsolidated terrigenous material with minor amounts of intercalated limestone of mid-Tertiary to Holocene age onlaps the mid-Tertiary limestone sequence. These general relations are best shown on the provisional geologic map of Puerto Rico (Briggs, 1964).

The principal geologic elements of Puerto Rico are shown in figure 4. The island is divided by two major fault zones into three structural blocks. Late Cretaceous to early Tertiary folds and faults generally trend northwest at an angle to the east-trending middle Tertiary to Holocene Puerto Rico geanticline.

The geologic map of southeastern Puerto Rico (pl. 1) shows the general geologic setting of the Coamo area in greater detail. On this map a multitude of formation- and member-rank units have been grouped into 10 major stratigraphic sequences. Intrusive igneous rocks of many ages and compositions are grouped together on the map, and some contact metamorphism and most large zones of hydrothermally altered rocks are shown. The reader is referred to the explanation of the geologic map for brief descriptions of the rock units.

The two major fault zones divide the island into three structural units of dissimilar stratigraphy. The great northern Puerto Rico fault zone (R. P. Briggs, unpub. data, 1967) trends from west to northwest across the northern margin of the region shown in figure 3, and the great southern Puerto Rico fault zone trends northwest through the southern third of the region. Hence the geologic map of southeastern Puerto Rico (pl. 1) covers principally the central of the three main structural blocks that compose the island.

Characteristic features of the central block include the structural crest of the Barranquitas anticlinorium, which is shown in cross section on plate 1. Noteworthy is the rather gentle folding that most of the rocks have undergone. The central part of the block has been shattered by closely spaced faults, but no really large-scale lateral displacements have been detected. Both batholiths lie in the central block, and they are clearly discordant to the regional structural grain; the west end of the Coamo syncline is truncated by doming attending emplacement of the Utuado batholith.

A submerged shelf named for Isla Caja de Muertos (Coffin Island) lies offshore at an average depth of less than 33 meters. The rather precipitous slopes at the southern edge of the shelf suggest a structural origin, and projections of the faults of the great southern Puerto Rico fault zone would bracket the shelf on the north and west.

The geologic map of the Coamo area (pl. 2) includes a large part of the central structural block of Puerto Rico and part of the great southern Puerto Rico fault zone. In the following sections descriptive material is drawn from studies in the Coamo area, and occasional references are made to the geologic map of southeastern Puerto Rico (pl. 1) principally for purposes of correlation and to point out the regional significance of some geologic features in the Coamo area.

The succession of stratigraphic units in the Coamo area is summarized in figure 5.

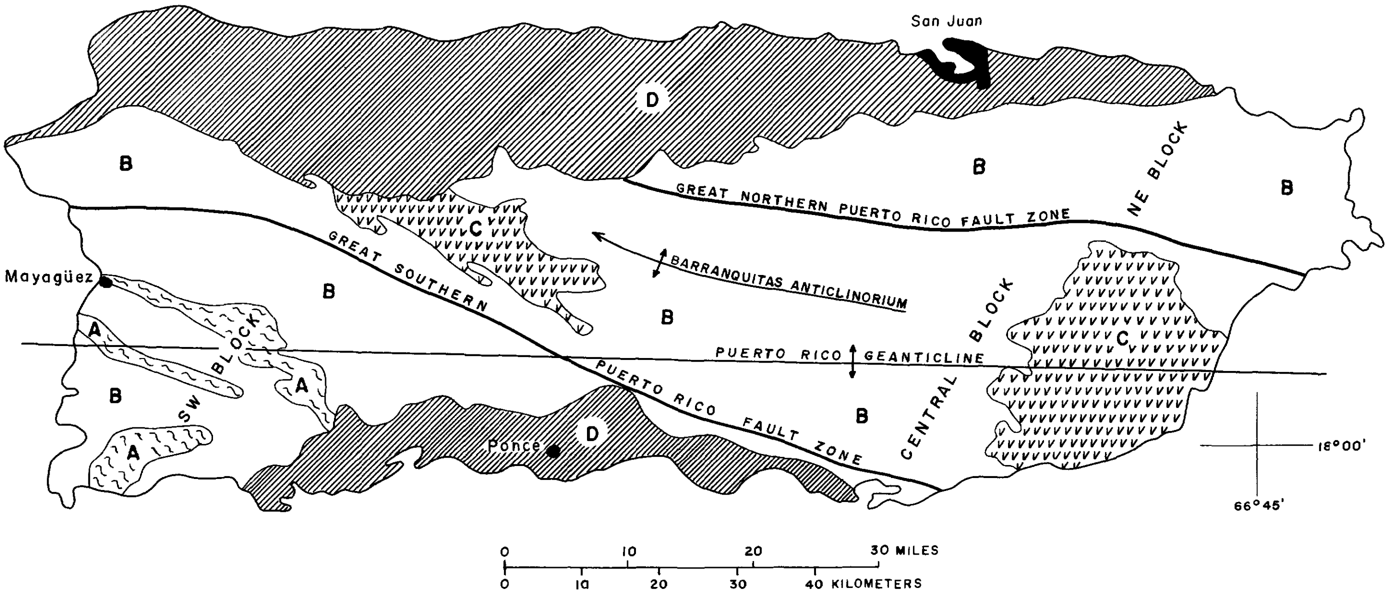


FIGURE 4.—The principal geologic elements of Puerto Rico. *A*, Serpentine-amphibolite-chert Bermeja complex. *B*, Cretaceous and lower Tertiary volcanic complex. *C*, Batholiths. *D*, Middle Tertiary to Holocene carbonate and epiclastic rocks and sedimerts.

CRETACEOUS ROCKS

PRE-ROBLES ROCKS

Massive and thick-bedded pyroclastic breccias with intercalated lavas, tuff, and rare limestone underlie the sequence of Robles and younger rocks that are the principal subject of this report. In the upper part of the pre-Robles sequence pyroxene andesite appears to be abundant, in the middle part feldspathic andesite and pyroxene andesite are common, and in the lower part dacite, feldspathic andesite, and pyroxene andesite are common.

The oldest rocks exposed in eastern Puerto Rico are parts of the pre-Robles that crop out along the margin of the San Lorenzo batholith in the southeastern part of the island (pl. 1).

Studies of the pre-Robles rocks are still in progress, and they have not been given formal stratigraphic names in the region east of the Coamo area. Total outcropping thickness probably exceeds 3,000 meters.

The upper and middle parts of the pre-Robles seem to be principally coarse near-vent pyroclastic breccias deposited in a marine environment. They contain rare lentils of limestone rubble derived from reefs. The lower part of the sequence comprises near- and distant-vent submarine ash-fall and pyroclastic flow deposits. The more dacitic composition of this part of the pre-Robles seems to correlate with more pumice-rich debris.

Fossils of Albian age have been collected from the Aguas Buenas Limestone Member of the Fajardo Formation near the middle of the pre-Robles in the Comerío quadrangle (Pease and Briggs, 1960) and at the top of the lower dacite-bearing pre-Robles in the Cayey quadrangle (O. Renz, Paleontological Laboratory, Bataafse Internationale Petroleum Mij. N.V., The Hague, written commun., 1961).

ROBLES FORMATION

The Robles Formation comprises 500 to 1,500 meters of marine andesite tuffs, tuffaceous mudstone, radiolarian mudstone, and basic pillow lavas and minor amounts of limestone, volcanic breccia, and conglomerate (fig. 6). A characteristic feature of the formation is the conspicuous and persistent thin to medium bedding of its volcaniclastic component (fig. 7*A*).

The Robles Formation was named by Pease and Briggs (1960) for outcrops in Barrio (Ward) Robles of the Municipio (Municipality) de Aibonito in southwestern Comerío quadrangle. The formation has been discussed by Briggs and Gelabert (1962), Glover (1961a), Pessagno (1960a), Berryhill and Glover (1960), and Berryhill, Briggs, and Glover (1960). Berryhill and Glover (1960), gave member names to parts of the volcaniclastic sequence that are separated by lavas, but these names are not used herein. Member names are retained for the distinctive lavas and a limestone within the relatively homogeneous volcaniclastic rock. In ascending order they are: the Río Matón Limestone, the Lapa Lava, and the Las Tetas Lava Members.

BEDDED VOLCANICLASTIC ROCKS

Thin- to medium-bedded volcaniclastic rocks make up more than 60 percent of the Robles Formation in its type area, and in contrast to massive and thick-bedded formations above and below, they are one of its most characteristic features. Tuffaceous mudstone, andesite tuff, and radiolarian mudstone are, in order of decreasing abundance, the major rock types. Andesitic lapilli tuff and fine tuff breccia locally constitute about 8 percent and congolmerate less than 2 percent of the bedded volcaniclastic rocks.

Stratification, superficially expressed in color banding, is due to variation in grain size and composition. The thickness of bedding is about 3 to 10 cm; it is generally thinner in the finer and thicker in the coarser grained material. Graded beds of lapilli tuff, 3 to 5 meters thick, occur locally.

Volcaniclastic rocks are commonly graded, and small-scale primary sediment deformation structures are common. These structures include load casts and flame structures, slump folds, small slides, and wisplike structures resulting from thixotropic(?) breakup of thin-bedded sediments. Small-scale crossbedding or current bedding probably related to turbidity-current deposition is common.

Grayish-green colors predominate in the tuffaceous rocks and olive-gray to dark-gray colors in the mudstones. All the bedded rocks are very well indurated.

TUFFACEOUS MUDSTONES

Tuffaceous mudstones constitute about 40 percent of the volcaniclastic sequence and are somewhat more common in the north than in the south. Typically, beds several centimeters thick contain 1- to 10-mm (millimeter) laminae and lenses of coarser tuff (fig. 7*B*, *C*). Soft-sediment disruption was common but was generally not so intense that the distinct bedding was much affected. An optically indeterminate turbid groundmass makes up as much as 80 percent of these rocks. Angular crystal fragments in the coarser layers are about ⅛ to $\frac{1}{16}$ mm in diameter and $\frac{1}{16}$ to $\frac{1}{32}$ mm or less in the finer layers. The mudstones are 15 to 50 percent tuff, which is composed largely of crystal fragments of plagioclase and clinopyroxene.

Plagioclase is about twice as abundant as clinopyroxene and occurs as unzoned fragments of oligoclase-andesine (An_{27-34}). Albite twins are very abundant, carlsbad-albite twins are less so, and pericline twins are common. Much of the plagioclase is very fresh, especially in the fine-grained layers. Clinopyroxene appears to be augite and is always very fresh. Hornblende fragments are rare in the Robles. Fragments of chloritized glass make up a small fraction of the larger clasts and probably also a large amount of the fine clay-size fraction. Opaque minerals, mostly magnetite(?), amount to several percent. Radiolaria are common and may make up 15 percent of a lamina; Foraminifera are more rarely seen. About 1 percent organic matter occurs as thin lenses and disseminations associated with the less tuffaceous mudstone.

TUFFS

Greenish-gray pyroxene andesite tuff composes about 30 to 40 percent of the volcaniclastic sequence. These rocks commonly occur in graded beds 2 to 10 cm thick, and they are more common in the northern part of the area.

Crystal-vitric and vitric-crystal tuffs are common. Both vitric and crystal fragments are generally angular, and evidence of rounding or weathering in transport is lacking. Some beds are rich in pumice fragments which show no evidence of abrasion or weathering. Accidental fragments and epiclastic fragments are rare.

Rare unaltered albite-twinned plagioclase was found to be about An_{30} in composition. Many grains are spongy with chlorite-filled cavities; the chlorite may be a replacement of glass. Zoning in the altered plagioclase is not evident. The clinopyroxene seems to be augite, and it, unlike the feldspar, is clear and unaltered. Some of the vitric clasts are vesicular, and they are rarely oxidized, to judge by their green color. Opaque minerals may amount to as much as 5 percent in a few layers. Organic material is virtually absent.

The graded beds of fine tuff may be capped by tuffaceous mudstone abruptly or transitionally. The mudstone in turn may be overlain abruptly by a graded tuff unit, or it may exhibit a transitional mixed zone of tuff and mudstone at the base of the graded tuff unit. Such a transitional zone is expressed by medium to thick bedding at the outcrop, the beds consisting of a number of transitionally graded units. Both well-sorted and poorly sorted graded tuffs seem to be common.

RADIOLARIAN MUDSTONES

About 10 to 20 percent of the bedded rocks are radiolarian mudstones, but in the southern areas of outcrop the percentage increases to about 40 percent. The mudstones are very hard and, when they are fresh, break with a blocky to conchoidal fracture. Bedding on a scale of 2 to 10 cm is sharp and gently undulatory. Within such beds, pockets of fine tuff and blebs and lenses of dark-gray organic-rich mudstone in lighter greenish-gray mudstone are generally alined with the bedding, though some convolutions were found.

System	Series	Sequence or group	Formation	Lithology and geologic map symbols	Thickness (meters)	Environment of deposition
QUATERNARY TO TERTIARY(?)	Holocene to Miocene(?)	Surficial deposits		Living and recently dead coral reefs (Qco), beach deposits (Qb), and swamp deposits (Qs) along the Caribbean coast; rare landslides (Ql), streambed alluvium (Qa), alluvial terraces (Qat), alluvial fans (Qf), and colluvial deposits (Qc) occur on the southern flank of the Cordillera Central; and the coastal alluvial plain deposits (Qap and Qaps [saline]) comprise coalescing alluvial fan deposits. Data from oil test wells CPR-1, -2, -3 along the south coast suggest that the alluvial-plain deposits may be as old as Miocene in the subsurface.	0–1000	Terrestrial and shallow marine.
TERTIARY				ANGULAR UNCONFORMITY		
	Lower Miocene to upper Oligocene	Middle Tertiary sequence	Ponce Limestone	Soft limestone (Tp), thin- to thick-bedded, light gray to buff. Only the lower part crops out in the Coamo area.	>380	Shallow(?) marine.
	Upper to lower Oligocene		Juana Díaz Formation	Conglomeratic sandstone and conglomerate, calcareous lithic arenite, and minor limestone (Tjd); medium bedded to massive.	300	Shallow marine.
				ANGULAR UNCONFORMITY		
	Eocene to lower Oligocene		Megabreccia	Tectonic megabreccia, in part probably extrusive; includes fragments of Upper Cretaceous and lower Tertiary rocks as much as 1 kilometer in greatest dimension (B, mB_1, mB_2).	0–130?	Tectonic extrusion(?) and gravity sliding.
				TECTONIC CONTACT		
	Middle Eocene	Jacaguas Group	Río Descalabrado Formation	Dacitic tuff and mudstone (Tds), minor thin limestone lenses (Tdl), and rare pebble to cobble conglomerate (Tdc). Mostly thin- to medium-bedded, common graded bedding and small-scale crossbedding; tuffaceous strata are commonly greenish gray to light olive gray. Plankton-rich microfauna.	>500	Deposited below wave base under transgressive, open-sea conditions.
			Guayo Formation	Conglomeratic lapilli tuff, tuff, and minor mudstone (Tgb); thick bedded and massive. Interfingers(?) with Río Descalabrado Formation.	>200	Same as Río Descalabrado Formation.
	Middle Eocene to lower(?) Eocene		Cuevas Limestone	Algal limestone (biomicrite with an intact framework of coarse to fine fragments of calcareous red algae); thick bedded or massive, less commonly thin bedded; nearly white, but the basal impure facies may be grayish red. (Tc)	35	Shallow water just below wave base in a transgressing sea.
				DISCONFORMITY		
	Lower Eocene to lower Paleocene		Raspaldo Formation	Dacitic tuff and mudstone (Trs), minor limestone (Trl), and minor conglomerate (not mapped). Tuff and mudstone are light olive gray, to yellowish gray; thin to medium bedded, with common graded bedding and small-scale crossbedding. The fauna is plankton rich. Rudistids reworked from older formations are common in the Raspaldo Formation.	>600	Deposited below wave base under open-sea conditions.
			Los Puertos Formation	Tuff breccia and conglomeratic tuff breccia (Tlpt), and tuff (Tlps), minor limestone (Tlpl); mostly pyroxene- and feldspathic-andesite in massive to thick-bedded units; grayish red purple to pale brown. Interbeds of plankton-bearing tuffaceous mudstone, some reworked rudistids. Grades laterally into the Raspaldo Formation. Base concealed by faulting.	>350	Deposited below wave base.

CRETACEOUS	Maestrichtian		Miramar Formation	Coarse, red volcanic-wacke conglomerate with abundant reworked dacite tuff (Kmi); medium bedded to thick bedded; contains an oyster-rich limestone at and near the top (Kmil).	700(?)	Shallow marine and nonmarine.
			Cuyón Formation	Red volcanic breccia (Kcu) overlain by drab reworked conglomeratic tuff and limestone (Kcul).	>75	Shallow marine and nonmarine.
				ANGULAR UNCONFORMITY		
	Maestrichtian and (or) Campanian	Coamo and Maravillas sequence	Coamo Formation	Massive to thick-bedded coarse pyroxene-andesite tuff breccia and tuff (Kcot); dark-gray to reddish- and greenish-black colors predominate.	>1500	Shallow marine to marine below wave base.
			Maravillas Formation	Hornblende-rich, andesitic, marine lapilli tuff (Kmab, Kmad); tuff and tuffaceous mudstone (Kmas); limestone (Kmah, Kmaa); very calcareous tuff, tuffaceous mudstone and limestone (Kmal); minor conglomerate (Kmac). Coarse pyroclastic units tend to be massive to thick bedded. Abundant macrofossils, planktonic and benthonic microfossils.	400–1400	Shallow marine, at and below wave base.
	Santonian	Caribanco Achiote sequence	Achiote Conglomerate	Red tuffaceous-wacke conglomerate and tuffaceous wacke (Ka); very well rounded cobbles and boulders of pyroxene-andesite lava and dacite welded tuff; reworked tuff of similar composition occurs in the formation; medium to thick bedded. Interfingers with the Cariblanco Formation.	800?	Shallow marine and nonmarine. Mud flow and alluvial fan deposits.
			Cariblanco Formation	Coarse, bimodal conglomerate, comprising well rounded pebbles, cobbles, and boulders of pyroxene-andesite lava and dacite welded tuff (Kcc); coarsely conglomeratic rocks grade into fine conglomerate and reworked tuff and tuffaceous mudstone (Kcs) toward the south; minor constituents of the formation are limestone (Kcj, Kcp), and basaltic-andesite lava (Kcg). Drab shades of green and gray. Grades laterally into the Achiote Conglomerate.	800–1000	Shallow marine to deep marine.
				DISCONFORMITY OR PARACONFORMITY		
	Santonian to Albian	Robles-Río Orocovis sequence	Robles Formation	Pyroxene-andesite tuff and tuffaceous mudstone are dominant (Krs); potassic pyroxene-andesite lava is common (Krl, Krt); lapilli tuff (Krb), conglomerate (Krc), and limestone (Krr,) are rare to common. Greenish-gray color is common. Abundant macrofossils in the basal limestone; plankton-rich microfossil assemblages dominate most of the formation. Dominantly thin- to medium-bedded.	700–1500	Mostly deep marine (below wave base), transgressing sea.
				DISCONFORMITY		
	Albian to pre-Albian(?)	pre-Robles sequence		Generally massive rock including pyroxene andesite pyroclastic rock and lava in the upper part, and dacite to acid andesite pyroclastic rock in the lower part. Sparsely fossiliferous.	>?	Mostly deep marine.

FIGURE 5.—Stratigraphic summary of the Coamo area, Puerto Rico.

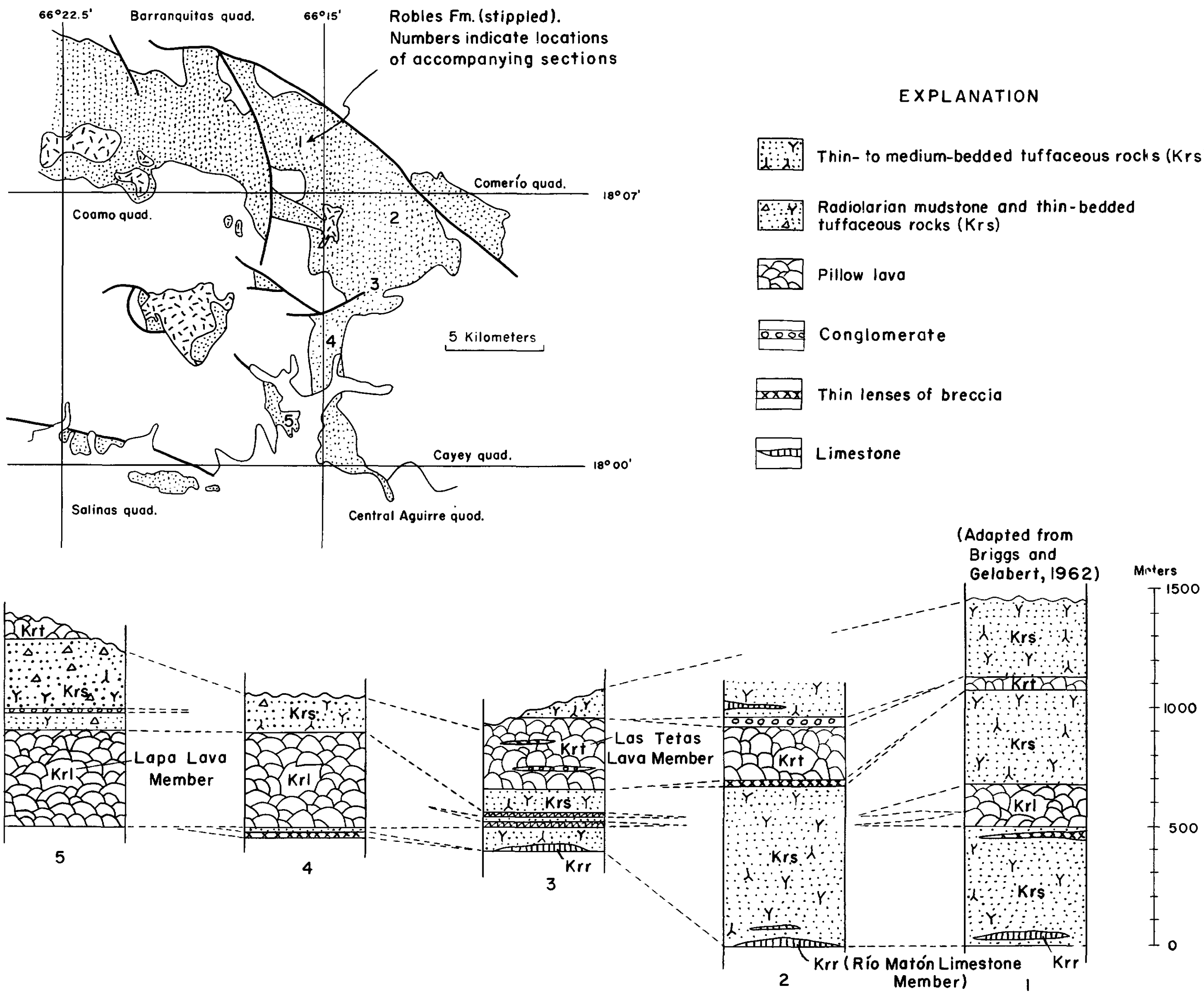


FIGURE 6.—Distribution of the Robles Formation and stratigraphic diagram of relations of homotaxial units.

The radiolarian mudstones contain less than 10 percent fine crystal tuff like that in the tuffaceous mudstones. Plagioclase is generally very fresh, and albite-twinned fragments have compositions near An_{30-32}. Radiolaria amount to about 20 percent. The matrix is a siliceous or calcareous argillite.

LAPILLI TUFF AND FINE TUFF BRECCIA

Less than 10 precent of the bedded Robles is composed of coarse grayish-green pyroclastic breccia. Typically these lapilli tuffs and fine tuff breccias occur as massive crudely graded lenses 3 to 15 meters thick and a kilometer or two in outcrop length. They are distributed rather randomly through the sequence but are more commonly found in the northern part of the area.

One such lapilli tuff (Krb) occurs at the base of the Las Tetas Lava Member and is shown on the geologic map of the Cayey quadrangle (Berryhill and Glover, 1960). Subangular clasts of microlitic devitrified glass with plagioclase and clinopyroxene phenocrysts compose more than 75 percent of the large fragments and another 20 percent of the fragments are plastically deformed tuff. The lapilli framework is generally intact, and tuff of the lapilli composition fills the voids.

Plagioclase crystals from the lapilli and matrix suggest groupings of composition near An_{70} and An_{35}, but relatively few compositions could be determined because of pervasive alteration. The clinopyroxenes are probably augite and are characteristically very fresh. Scattered red pumiceous fragments and a single calcite shell fragment were seen in the lapilli tuff.

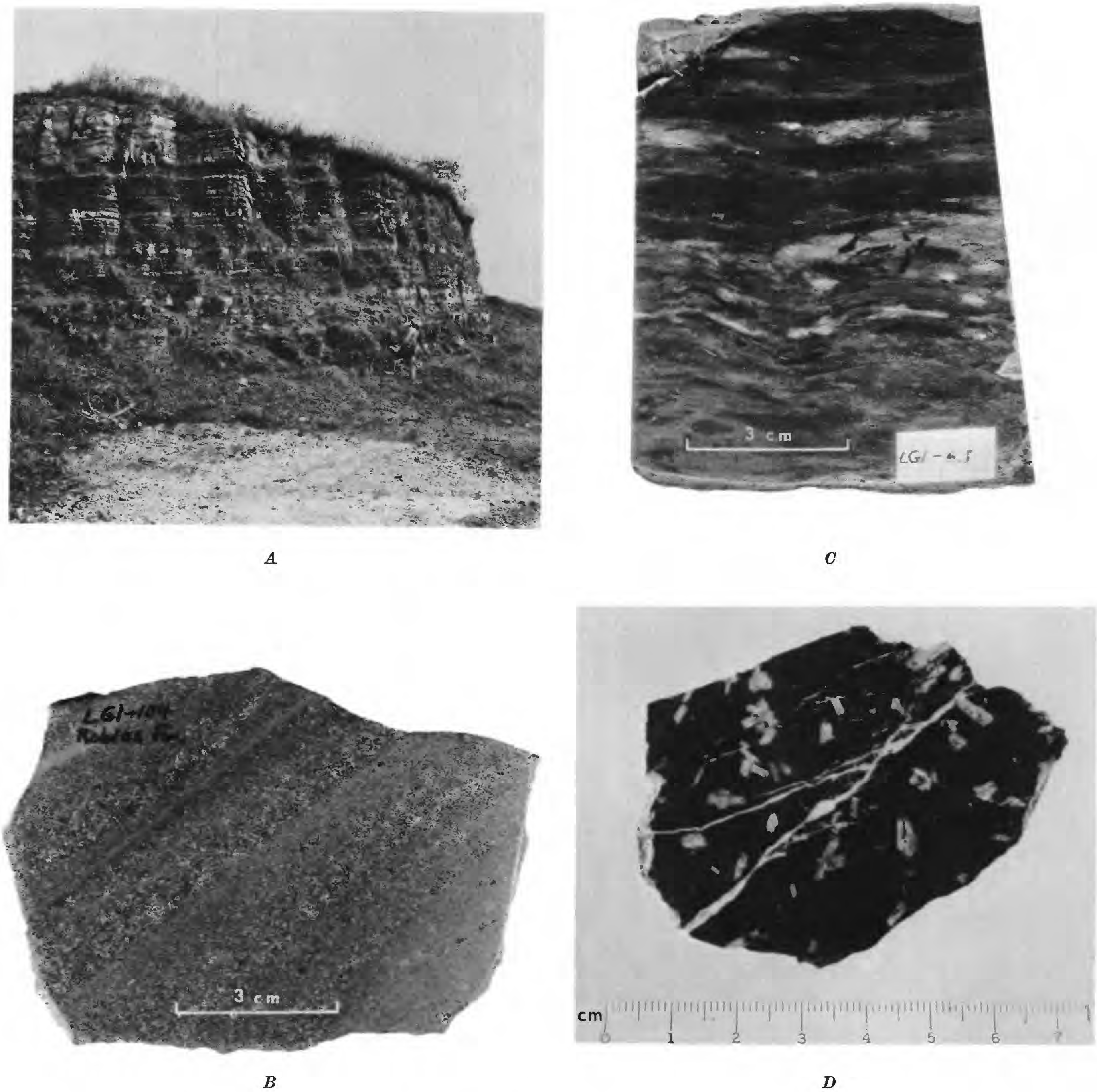


FIGURE 7.—Rocks of the Robles Formation: *A*, Typical thin- to medium-bedded tuff and tuffaceous mudstone of the Robles Formation. Quarry along Highway 1, just west of Cayey. *B*, Hand sample of typical Robles tuff and tuffaceous mudstone showing graded bedding. Tops of beds are to the upper left. *C*, Hand sample of typical Robles tuffaceous mudstone and radiolarian mudstone. Dark areas are relatively rich in finely divided organic material. Disrupted fabric probably produced by thixotropic deformation of interleaved viscous silty plastic clayey material. *D*, Lapa Lava Member, typical texture in hand sample. Glomerophenocrysts of plagioclase and augite. Veinlets are quartz-prehnite.

CONGLOMERATE

About 2 percent of the stratified Robles is thick-bedded to massive generally polymictic conglomerate. Both intact and disrupted frameworks are formed of subrounded to well-rounded commonly porphyritic pebbles and cobbles.

A conglomerate (Krc) in southeastern Coamo quadrangle contains a wide variety of well-rounded pebble-size clasts of andesite and dacite(?) porphyry, radiolarian mudstone, andesitic, tuff, limestone, felsic pumiceous tuff, pyritized and silicified porphyry with red oxidized margins, and hornblende andesite porphyry. The conglomerate is poorly sorted and is interbedded with radiolarian mudstones and graded tuffs.

Most of the Robles conglomerate occurs in the upper part of the formation, overlying the Las Tetas Lava Member. The conglomerate is poorly stratified and consists of subrounded to well-rounded pebble- to small boulder-size gravel of porphyritic andesite with an intact framework. The matrix consists of varying proportions of volcanic sandstone and pyroxene-rich crystal tuff. Epiclastic fragments are petrographically similar to Robles and pre-Robles rocks.

Thin unmapped lenses of conglomerate occur between Cuyón and Highway 14 to the west. These conglomerates are graded and intercalated in the radiolarian-mudstone-bearing sequence.

Conglomerate near Proyecto Vázquez was mapped as part of the Robles Formation by Berryhill and Glover (1960). This conglomerate is herein considered part of the overlying Cariblanco Formation because of a distinctive hornblende-bearing feldspathic tuff component common to both. The conglomerate is unconformable upon the Las Tetas Lava Member northwest of Proyecto Vázquez.

RÍO MATÓN LIMESTONE MEMBER

The Río Matón Limestone Member was named by Berryhill and Glover (1960) for outcrops along Highway 1 just west of the Río Matón, in the northern part of the Cayey quadrangle. The limestone occurs at the base of the Robles in lenticular bodies as much as 50 meters thick. Briggs and Gelabert (1962) and Pease and Briggs (1960) have also mapped this limestone in the quadrangles to the north. The distribution of outcrops suggests a northerly elongated area of lenses of limestone, the individual lenses having similar northerly alinements. The original easterly extent of the lenses is indeterminate because of erosion of the formation.

The Río Matón most commonly consists of medium- to thick-bedded hard medium- to dark-gray biomicrite. Less commonly, the amount of included volcanic debris dominates, so that the rock may be called a calcareous volcanic sandstone or breccia. In the type area a thin lens of limestone occurs locally about 20 meters above the lower main body.

A thin section of the limestone from a quarry along Highway 1 about 3 km (kilometers) west of Cayey is herein described as a representative of the finer facies of the member. It is a biomicrite composed almost entirely of very well rounded 10- to 0.5-mm calcite shell fragments. The shell cavities are now filled with recrystallized calcite showing rare relict stratification of fine lime mud in the larger fillings. The ground mass of medium-grained calcite is about 10 to 15 percent of the total, and about 2 percent is pyrite, organic matter, and volcanic sand. The coarse grain size of the matrix and fillings is probably due to diagenetic or low-grade metamorphic recrystallization of a fine lime mud.

A rapid rock analysis of the above described sample, BC–220, by P. L. D. Elmore and S. D. Botts of the U.S. Geological Survey, is as follows:

	Percent
SiO_2	3.1
Al_2O_3	1.2
Fe_2O_3	.36
FeO	.12
MgO	.66
Cao	53.2
Na_2O	.09
K_2O	.28
TiO_2	.06
P_2O_5	0
MnO	.03
H_2O	.24
CO_2	40.4

Assuming no solid solution of the small amount of MgO in $CaCO_3$, the analysis is equivalent to 92 percent of $CaCO_3$ and 8 percent of impurities high in calcium, aluminum, and silicon.

The stratigraphic diagram in figure 6 shows overlap of the basal Robles toward the south, so that in detail the Río Matón is a homotaxial unit which is somewhat younger in the southern areas.

LAPA LAVA MEMBER

The Lapa Lava Member was named by Berryhill and Glover (1960) for outcrops in the hills north of Sabana Llana and Rabo del Buey along the border between the Coamo and Cayey quadrangles. The member is a composite lava unit about 370 meters thick at the type locality. A similar thickness persists to the south in the Cayey quadrangle, probably in the western Central Aguirre quadrangle, and also in the faulted outcrops in Salinas quadrangle and southwestern Coamo quadrangle (fig. 6). The maximum thickness recorded is 650 meters in the southwestern part of the Barranquitas quadrangle (Briggs and Gelabert, 1962). The Lapa Lava wedges out in north-central Barranquitas, southwestern Comerío (Pease and Briggs, 1960), and northwestern Cayey quadrangles.

Characteristic of the Lapa Lava are large glomerophenocrysts of plagioclase and pyroxene (fig. 7*D*) set in a dark bluish- to brownish-gray matrix of pillowed lava. In the lava there is also a pyroxene-rich facies, which generally overlies the plagioclase-rich facies. Similar relations are described by Briggs and Gelabert (1962) and Pease and Briggs (1960) from localities in the Barranquitas and Comerío quadrangles.

Pillows in the lava are about 1 to 3 meters in greatest dimension (fig. 8*A*). Locally, especially at the top of the type section and in northwestern Central Aguirre quadrangle, the lavas are massive and show flow layering. Red and gray siliceous interpillow mudstone and chert are common.

Interbeds of typical Robles volcaniclastic rocks generally occur near the middle of the Lapa Lava Member. In northwest-central Cayey quadrangle one such parting of tuff separates the lower feldspar-rich from the upper pyroxene-rich facies of the Lapa.

The Lapa overlaps the lower part of the Robles in the area southwest of Cayey. In southwestern Barranquitas quadrangle (Briggs and Gelabert, 1962) the Lapa is 1,200 meters above the base of the formation, whereas it is in contact with the pre-Robles in southeastern Cayey quadrangle.

The Lapa is typically a porphyritic trachyandesite containing 15 to 20 percent of large phenocrysts and cumulophyric aggregates of plagioclase and clinopyroxene. Euhedral to subhedral augite crystals about 2 to 3 mm long constitute 30 percent or less of the phenocrysts, but near the top of the member they may account for more than 70 percent. The 2- to 7-mm long plagioclase phenocrysts are dominantly turbid sodic andesine after clear labradorite. Zoning is largely obliterated, though relic zoning remains. Many of the plagioclase crystals are conspicuously spongy (fig. 8*B*), having holes filled with chlorite or microlitic chlorite probably after glass. Rare olivine phenocrysts can be recognized by the shapes of their chlorite pseudomorphs.

The groundmass consists of sodic(?) oligoclase and sanidine(?) microlites and rare to common acicular clinopyroxene. About 3 percent of the rock consists of opaque minerals, largely titaniferous magnetite(?), which occurs as small equant or elongate skeletal crystals in a microcrystalline chloritic and felsitic intersertal base. The textures are dominantly pilotaxitic to intersertal, less commonly hyalopilitic or subvariolitic. The Lapa Lava is not commonly amygdular.

Rarely relic calcic cores (An_{45-64}) of plagioclase phenocrysts are found. These cores are clear, weakly zoned, and always twinned; they are surrounded by turbid commonly twinned plagioclase of about An_{30-34} composition. In most of the slides examined, only turbid plagioclase of the An_{30-34} composition remained. The calcic cores are twinned according to carlsbad-albite, albite, and pericline laws. During the alteration to sodic andesine, much of the twinning was destroyed, leaving simple carlsbad twins which resemble sanidine in sections nearly parallel to [001]. Late skeletal growth is common at the margins of these phenocrysts and may be slightly more sodic than the An_{30-34} average.

Compositions of some of the larger albite-twinned groundmass plagioclase crystals were estimated to range from nearly pure albite to about An_{30}. However, some of the albite may be secondary.

Presumably the turbid condition of the sodic andesine resulted from separation of a calcium-bearing mineral during alteration from labradorite. The mineral is possibly clinozoisite and is slightly bluish green, pleochroic, and clear of inclusions; its refractive index is greater than that of the host plagioclase. Calcite is also a common finely disseminated replacement mineral. Clear albite(?) forms veinlets in primary andesine and labradorite. Sericite is a rare to common alteration product of plagioclase.

Clinopyroxene phenocrysts from the Lapa Lava Member

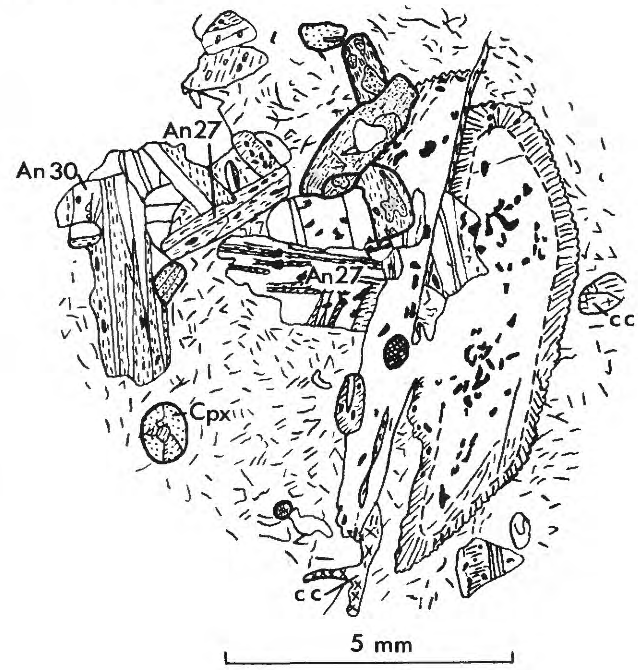
Sample	$2V_z$
LG57–165	57°
LG57–165	55°
LG57–167	56°
LG57–170	56°
LG57–209	56°
BC–227	56°

The value of nY for LG57–209 is 1.6926±0.005(?); from this value and the $2V_z$ of 56°, the partial composition of the clinopyroxene is calculated to be $Ca_{46.3}Mg_{37.7}Fe_{16}$.

The $2V_z$ measurements suggest a remarkably constant Ca content for these calcic augites. The phenocrysts are euhedral to subhedral, commonly are twinned, and rarely seem to be zoned. Groundmass pyroxene seems to be clinopyroxene with a large $2V_z$. Pyroxene is generally fresh but is altered to chlorite and calcite in contact aureoles.

The three chemical analyses given in table 1 indicate that the Lapa is rather low in SiO_2, high in Al_2O_3, high in total alkalies, and very high in K_2O. In the norm this is expressed as very high orthoclase content, general lack of quartz, and presence of corundum and olivine. Normative plagioclase in the two feldspar-rich specimens, BC–225 and BC–239, is about An_{20}; it is about An_{50} in the augite-rich specimen, BC–237.

A



B

FIGURE 8.—Rocks of the Robles Formation: *A*, Pillow structure in Lapa Lava Member at Proyecto Vázquez, Highway 1. *B*, Lapa Lava glomerophenocryst of partially resorbed and marginally albitized plagioclase with augite in a pilotaxitic groundmass. Cpx, augite; cc, calcite; An_{30} plagioclase composition.

Potassium feldspar was identified by staining with sodium cobaltinitrite solution. A potassium reaction was obtained only for the small microlites in the groundmass.

A plot of $FeO+Fe_2O_3$ and $FeO+Fe_2O_3+MgO$ from the Lapa and the overlying Las Tetas Lava Members against weight percent SiO_2 in figure 9 shows a trend similar to that for tholeiitic series, which in turn is similar to that for fractional crystallization in the system $MgO–FeO–Fe_2O_3–SiO_2$ for constant total composition (Osborn, 1959). The suggested iron enrichment is characteristic of melts undergoing fractional crystallization in systems having a low or decreasing partial pressure of oxygen. According to Osborn, this is generally equivalent to low water pressure, but theoretically a similar result might occur from hydrogen loss by diffusion. In the case of the Lapa and Las Tetas Lavas, the lack of abundant vesiculation upon extrusion suggests that the lavas were relatively dry and that the composition was, therefore, influenced by the low concentration of oxygen in the magma chamber.

The chemical and mineralogical compositions of the Lapa indicate that it is a trachyandesite in the nomenclature of Williams, Turner, and Gilbert (1954).

LAS TETAS LAVA MEMBER

The composite trachyandesite Las Tetas Lava Member was named by Berryhill and Glover (1960) for the prominent topographic features at Las Tetas in northwestern Cayey quadrangle. The Las Tetas attains a maximum thickness of about 400 meters in the type area and is thin or absent in areas of Robles outcrop to the west and south. Toward the north and east the record is lost by erosion. The Las Tetas is generally 100 to 400 meters above the Lapa Lava, and tuffs and radiolarian mudstones occur between the two members.

Abundant phenocrysts and an intersertal texture with amygdule-like bodies of chlorite distinguished the Las Tetas Lava Member. In a typical hand specimen one sees about 50 percent phenocrysts, a third of which are pyroxene and the rest, plagioclase. Intersertal bodies of dark-green chlorite make up another 15 percent of the rock, and the remainder is a fine-grained dark groundmass. The chlorite bodies are believed to be of magmatic origin. True amygdules are rare in the member. The texture of the dark-grayish-green Las Tetas lavas is unique in the Coamo area.

Pillow lava is very common in most areas of outcrop, but in the vicinity of Las Tetas much of the lava is massive or comprises a number of thin locally amygdaloidal lava flows.

TABLE 1.—*Chemical analyses, CIPW norms, and modes of the Lapa Lava Member*

[Rapid rock analysis by P. L. D. Elmore and S. D. Botts. U.S. Geological Survey, Mar. 22, 1957. CIPW norms recalculated to 100 percent minus calcite and water]

Field No.	BC-225	BC-239	BC-237
Chemical analysis			
SiO_2	52.8	48.4	48.7
Al_2O_3	16.2	16.0	13.9
Fe_2O_3	2.6	3.2	4.4
FeO	4.6	5.7	5.4
MgO	4.3	5.6	7.6
CaO	5.1	5.4	9.8
Na_2O	4.5	2.6	2.0
K_2O	3.6	5.6	3.7
TiO_2	.88	.88	.74
P_2O_5	.49	.44	.51
MnO	.10	.15	.18
H_2O	2.70	3.60	2.6
CO_2	2.20	2.80	.93
Total	100.1	100.4	100.5
CIPW norms			
Quartz	.58	------	------
Orthoclase	22.80	36.59	22.85
Albite	41.40	24.30	18.09
Anorthite	9.05	6.94	18.50
Corundum	1.95	3.71	------
Diopside	------	------	18.09
Hypersthene	17.2	13.92	3.92
Olivine	------	6.40	9.25
Apatite	1.08	1.12	1.23
Magnetite	4.02	5.12	6.65
Ilmentie	1.81	1.84	1.46
Total	99	99	100
Approximate modes			
Phenocrysts	22	5	25
Plagioclase	15(An_{30})	3	2
Augite	5	2	20
Orthopyroxene(?)	2(Chlorite pseudomorphs)		3(Chlorite, garnet pseduomorphs)
Groundmass	78	95	75
Plagioclase	40	60	30
Clinopyroxene	5	------	20
Opaques	3	5	5
Intersertal chlorite, white minerals.	25	20+Quartz, epidote.	15
Calcite	5	10	5

BC-225. Cayey P.R. quadrangle: along Highway 1 west of Proyecto Vázquez; in south bank of roadcut about 0.1 km southeast of school.
BC-239. Cayey P.R. quadrangle: about 2.4 km airline south of intersection of Highways 1 and 162, on hill northeast of Proyecto Vázquez and north of Río Lapa; lower of two thin lavas.
BC-237. Cayey P.R. quadrangle: same as BC-239 above upper of two thin lavas.

In part of northwestern Cayey quadrangle the member lies on a thin lapilli tuff. Elsewhere the underlying rocks are thin-bedded Robles tuffs and radiolarian mudstones. Several lenticular intercalations of bedded tuff and conglomerate occur in the lava sequence north of Proyecto Vázquez.

The upper contact relations are complex. Near the northern margin of the quadrangle, lenticular bodies of conglomerate are in contact with, as well as stratigraphically above, the Las Tetas. Southward, near the Collao fault, the amount of conglomerate increases. South of the Collao fault, the Las Tetas is overlain by typical Robles tuffs and mudstones.

Plagioclase constitutes 25 to 50 percent of the lava as spongy euhedral crystals ranging from 6 to 0.1 mm in maximum dimension. Phenocrysts can be distinguished from microlites only on the basis of shape, phenocrysts being nearly equant whereas microlites are prismatic and often skeletal or swallowtail. Some of the larger crystals are spongy, unzoned, and turbid from replacement by clinozoisite(?). The smaller phenocrysts are fresher, commonly albite twinned, and strongly zoned. The most frequent range of composition found in the zoned phenocrysts is An_{26} to An_{37}, and the extreme range of composition for all crystals is An_0 to An_{57}. Reverse zoning is common.

Subophitic clinopyroxene phenocrysts (5 to 0.5 mm) constitute 15 to 17 percent of the rock. They are very fresh and contain magnetite and glass inclusions. The glass inclusions show incipient devitrification at the crystal contact. Many of the inclusions contain an equant opaque crystal, probably magnetite; others contain an undetermined prismatic mineral.

Clinopyroxenes from the Las Tetas Lava Member

Sample	$2V_z$	nY	*Partial composition*
LG57-201	52°	1.6945+0.0005(?)	$Ca_{43.3}$ Mg_{38} $Fe_{18.7}$.
BC-212	53°	------	------
BC-212	52°	------	------
BC-214	53°	------	------
BC-214	53°	------	------
BC-223	53°	1.6963±0.0005(?) ($2V_z$, 54°).	Ca_{44} Mg_{36} Fe_{20}.
BC-223	54°	------	------
BC-240	52°	------	------
BC-240	52°	------	------

By comparison with the Lapa Lava Member, the Las Tetas augites are consistently lower in calcium. Iron enrichment by comparison with the Lapa is suggested by the βnY values of Las Tetas augites. This supports the trend toward iron enrichment shown by the chemical data in figure 9.

Groundmass microlites are mainly prismatic plagioclase, but acicular clinopyroxene (augite?) is common. The microlites range in length from 0.3 to 0.1 mm, and many are skeletal. Opaque minerals, mostly magnetite, constitute 2 to 5 percent of the rock.

About 10 to 15 percent of the rock is chlorite having anomalous blue interference colors. Most of the chlorite occurs as amygdulelike bodies that may not be a gas-vesicle filling. In some samples, euhedral quartz crystals with zones of impurities occur in the bodies of chlorite; the amount of quartz seems to be proportional to the amout of chlorite. Phenocryst and microlite plagioclase crystals commonly extend into the chlorite bodies, and disseminated epidote(?) is concentrated near the margins of the chlorite bodies. Some clear albite occurs as small crystals or overgrowths on more calcic plagioclase around the margin of the chlorite. The shapes of the chlorite bodies suggest droplets of liquid magma con-

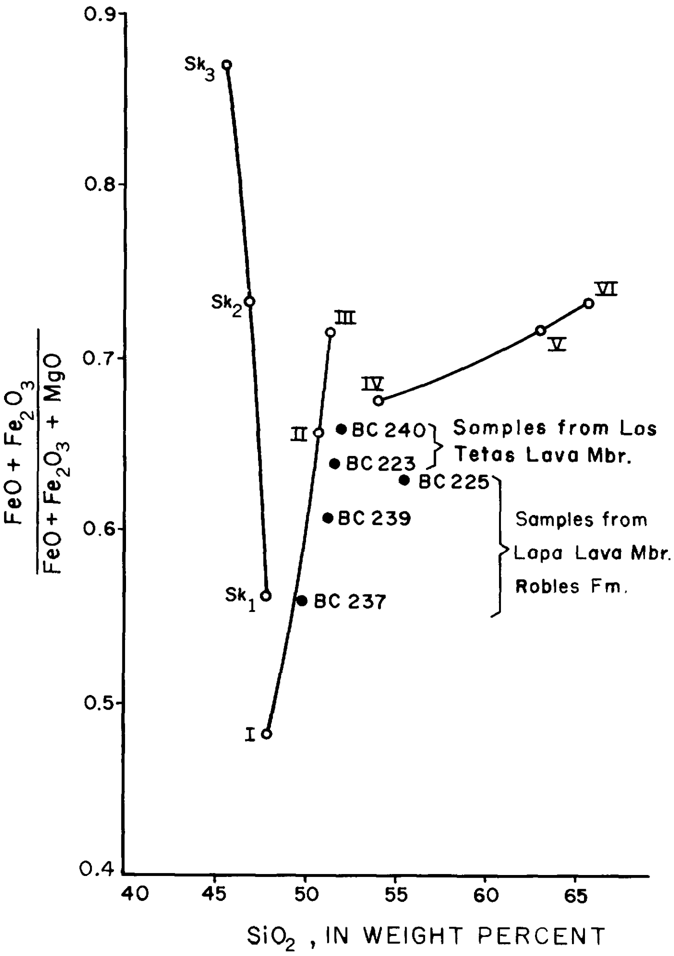


FIGURE 9.—Curves for magma series, from Osborn (1959, fig. 11). Sk_{1-3}, Skaergaard intrusion (Wager and Deer, 1939); I, II, III, tholeiitic olivine basalt, normal tholeiitic basalt, and tholeiitic andesite, respectively (from Nockolds, 1954); IV, V, VI, average andesite, dacite plus dacite obsidian, and rhyodacite plus rhyodacite obsidian, respectively (from Nockolds, 1954).

centrates in a nearly solidified crystal mush. The mineralogy and texture of the quartz-albite-epidote-chlorite assemblage suggests crystallization at temperatures characteristic of the greenschist grade.

The texture of the Las Tetas is probably best described as subophitic-intersertal, and as previously pointed out, it is unique in the Coamo area.

The chemical analyses in table 2 indicate a moderately low SiO_2 content, although quartz appears in the norm and mode of BC-223. Alumina is high with respect to SiO_2 in common with Lapa analyses. There is an increase in total iron over the Lapa as is also shown by figure 9 and as is indicated by the optical data on augites. Potassium content is high but is less than the values in Lapa analyses. Potassium feldspar was not identified.

The normative plagioclase is about An_{57}, which is the most calcic plagioclase identified optically. Most of the unaltered modal plagioclase is sodic andesine or oligoclase. The discrepancy between the values for normative and modal plagioclase may be accounted for by assuming deuteric alteration of calcic plagioclase to more sodic plagioclase and epidote(?).

The Las Tetas may be considered a potassic pyroxene andesite or trachyandesite, according to the nomenclature of Williams, Turner and Gilbert (1954).

TABLE 2.—*Chemical analysis, CIPW norms, and approximate modes of the Las Tetas Lava Member*

[Rapid rock analysis by P. L. D. Elmore and S. D. Botts, U.S. Geological Survey, Mar. 22, 1957. CIPW norms recalculated to 100 percent minus calcite and water]

Field No.	BC-223	BC-240
Chemical analyses		
SiO_2	49. 4	50. 3
Al_2O_3	16. 1	16. 8
Fe_2O_3	3. 7	3. 5
FeO	7. 6	6. 6
MgO	6. 0	5. 0
CaO	8. 5	7. 7
Na_2O	2. 6	3. 6
K_2O	1. 0	2. 1
TiO_2	. 82	. 8
P_2O_5	. 22	. 22
MnO	. 16	. 20
H_2O	3. 0	2. 6
CO_2	. 20	. 92
Total	99. 30	100. 34
CIPW norms		
Quartz	2. 0	------
Orthoclase	6. 26	13. 37
Albite	22. 95	31. 78
Anorthite	30. 24	24. 15
Diopside	9. 23	7. 10
Hypersthene	21. 40	11. 10
Olivine	------	5. 23
Apatite	. 32	. 32
Magnetite	5. 56	5. 33
Ilmenite	1. 58	1. 59
Total	99	100
Approximate modes		
Phenocrysts	65	55
Plagioclase	50	40
Augite	15	15
Groundmass	35	45
Plagioclase	12	15
Clinopyroxene	5	10
Opaques	3	5
Intersertal chlorite, quartz, epidote, albite (?)	15	15

BC-223. Cayey quadrangle: 0.7 km by road south of intersection of Highways 1 and 162; sample from rock face on east side of road.
BC-240. Cayey quadrangle: near crest of hill just below conglomerate, about 2.4 km airline south of intersection of Highways 1 and 162, on hill northeast of Proyecto Vázquez and north of Río Lapa.

SOME CHEMICAL PECULIARITIES OF THE LAVAS

Lavas of the Robles-Río Orocovis sequence are unique in some ways among the Puerto Rican volcanic rocks. They are potassium rich and are intermediate between calc-alkalic and alkalic suites (Mattson, 1968). Inasmuch as most other Puerto Rican rocks belong to the calc-alkalic (Mattson, 1968) "orogenic" suite, the Robles-Río Orocovis sequence is unusual in its setting. Discovery of the potassic nature of these lavas suggests the possibility that the small syenite intrusive bodies of the Ciales (Berryhill, 1965) and Barranquitas (Otálora, 1961) quadrangles are of Robles age also. Lidiak (1965) noticed the high potassium content of Río Orocovis lavas in north-central Puerto Rico. He was uncertain of its origin, but suggested potassium contamination (1) by alkalic rocks or sediments, or (2) by incorporating the low-melting fraction of unspecified material during magma generation or during ascent of magma.

The primary copper content of rocks of the Robles-Río Orocovis sequence is also unusually high, being commonly greater than 200 ppm (R. P. Briggs, P. H. Mattson, and Lynn Glover III, unpub. data).

AGE

In the Coamo area the Robles Formation probably ranges in age from Albian to Santonian (pl. 3). Fossils identified from the Río Matón Limestone Member along Highway 1 and 1.7 miles southwest of Cayey include *Archaeolithothamnium* sp., *Orbitolina oculata*, and *Nerinea* sp. According to Richard Rezak (written commun., 1955) the calcareous red alga *Archaeolithothamnium* sp. resembles Aptian-Albian species from southern France. Douglas (1961) considers the *Orbitolina* to be of Albian age, but stresses the possibility of reworking because the Foraminifera are covered with algae. Reworking can be discounted for lack of sufficient source material in the pre-Robles sequence to furnish the large quantity of *Orbitolina* collected. The *Nerinea* was identified by N. F. Sohl. The basal Río Matón Limestone Member of the Robles Formation is considered Albian in the vicinity of Cayey, but it may be as young as Cenomanian where it is overlapped by the Lapa Lava Member in the southeastern part of the Coamo area.

A Cenomanian age for the Robles tuff just above the Lapa Lava Member north of Barranquitas is indicated by the following fossil identifications by P. Bronnimann (Otálora, 1961, p. 63).

Locality: OP–147

Fossils: "*Globigerina*" *cretacea* group
"*Globigerinella*" sp., *Globigerina* cf. *washitensis*, *Glotruncana appenninica* group.
"Stratigraphic determination: Cenomanian"

Two inoceramids collected from near the top of the Robles (locality LG–1–105) south of Aibonito suggest a Santonian age for this part of the formation. E. G. Kauffman reports (written commun, 1965), "*Inoceramus* (*Platyceramus*) sp. aff. *I.* (*P.*) *cycloides cycloides* Wegner are generally characteristic of Santonian rocks in Europe."

SOURCE AND CONDITIONS OF DEPOSITION

The principal sources of pyroclastic material in the Robles Formation were submarine volcanoes that probably formed an east-trending belt about 8 miles north of the Coamo area (fig. 10). Coarse near-vent pyroclastics and thick lava sequences of that belt are called the Río Orocovis Formation (Berryhill, 1965). Volcanic activity is believed to have been chiefly submarine because (1) the lavas are pillowed, (2) strongly oxidized volcanic material is not abundant, suggesting limited access of hot magma to air, (3) shallow-water fossils are rare, though planktonic microfossils implying deep water are common above the base of the Río Orocovis (and Robles), (4) there is little evidence of strongly reworked volcanic material, and (5) shallow-water sedimentary structures are rare. During later Robles time, another volcanic source developed in south-central Orocovis quadrangle (R. P. Briggs, oral commun., 1964). Toward these source areas the Robles Formation of the Coamo area becomes coarser and lava generally increases in abundance.

Eruptive activity in the Coamo area was restricted principally to the effusion of the Lapa and Las Tetas Lava Members. The Lapa pinches out in the east and basinward northeast of the Coamo area, whereas it seems to be thickest along a northwesterly trend through the center of the Coamo area. This trend of maximum thickness probably marks a fissure or fissures through which the Lapa was erupted.

The abrupt buildup of the Las Tetas Lava also suggests proximity to a vent in the area just east of the type locality. The coarse lapilli tuff at the base of the Las Tetas may have resulted from the initial breakthrough of the lava.

A shoal area or landmass of pre-Robles rocks existed just east of the Coamo area during deposition of the Robles Formation. The high area is indicated by overlap of the basal Robles units toward the southeast, by the northerly elongate lenses of reef-derived Río Matón Limestone, and by the local conglomerate lenses in the Robles that wedge out toward the west. The pre-Robles shoal was a volcanic island that built up from the deep ocean floor. Volcanic activity may have ceased before a very large pre-Robles island was formed, because there is little epiclastic debris in the overlapping Robles Formation.

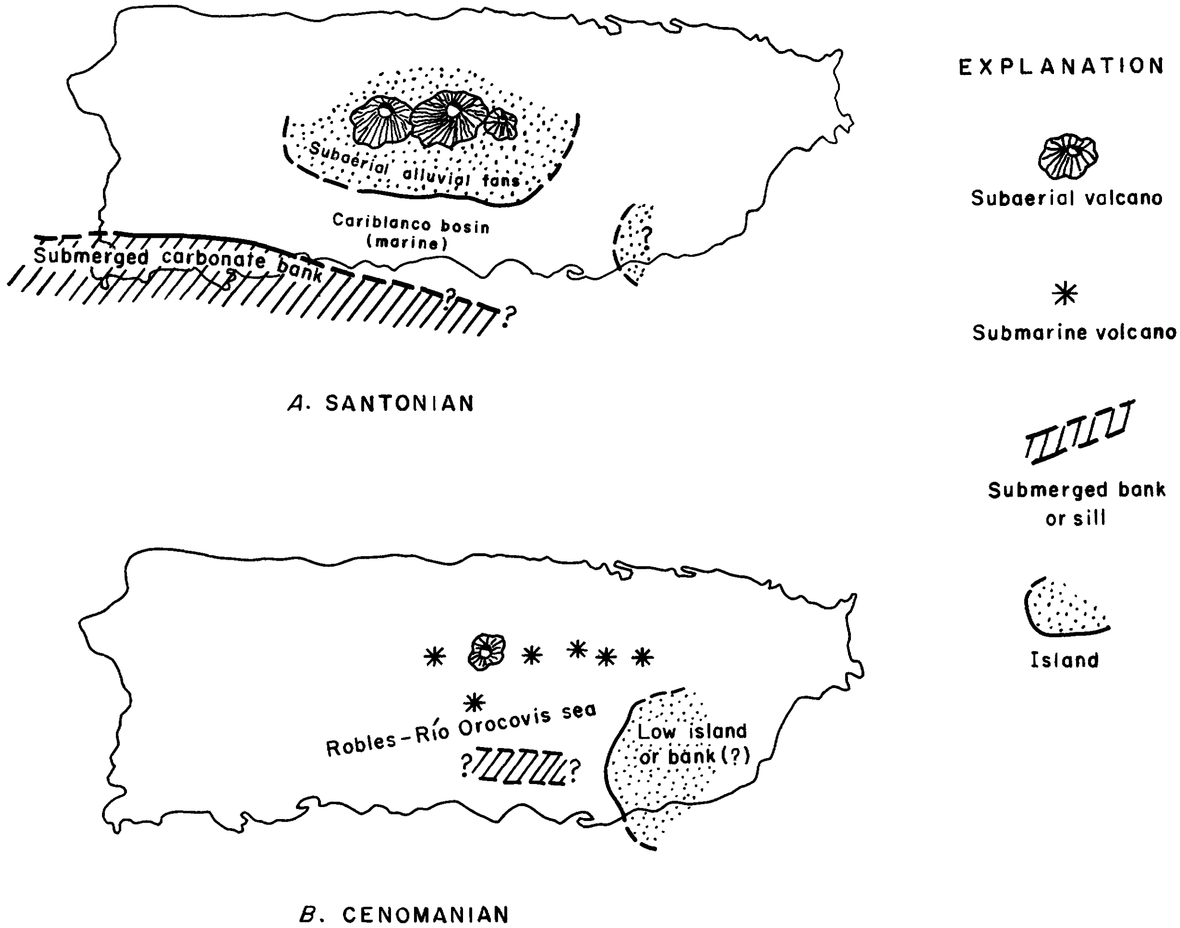


FIGURE 10.—Paleogeographic reconstructions of Puerto Rico during Cretaceous time.

The general paucity of shallow-water benthonic fossils, the abundance of Radiolaria and planktonic Foraminifera, and the persistent thin beds of graded tuff and tuffaceous mudstone indicate that most of the Robles was deposited in fairly deep water, below effective wave base, and relatively far from volcanically active islands. Probably most of the fine-grained volcaniclastic debris in the Robles Formation of the Coamo area was deposited by turbidity currents and by fallout from the remnants of submarine eruption columns that drifted laterally into the area. Much of the coarser material was deposited by flows of pyroclastic debris that traveled downslope from the Robles volcanoes. Fiske (1963) has used the name "subaqueous pyroclastic flow" for flows of this type. The dearth of strongly oxidized pumice and glass fragments suggests that airborne ash was not common.

There is a rather abrupt change in thickness of the Robles north of the fault through Proyecto Vázquez, and the Las Tetas Lava is localized north of the fault as well as north of an easterly faultline(?) through the Los Panes intrusive. These relations, coupled with the lack of field evidence for an unconformity at the base of the overlying Cariblanco Formation in this area, suggest graben control of deposition during late Robles (Cenomanian to Santonian) time. The Las Tetas Lavas of the Robles Formation apparently accumulated in the area north of the fault through Proyecto Vázquez, because that area was structurally downdropped with respect to the block to the south. The sea bottom seems to have been graded by latest Robles time, because there is no indication that the thickness of the Cariblanco changes across the fault.

CARIBLANCO FORMATION

The Cariblanco Formation is a coarse conglomeratic sequence that was named by Glover (1961a) for outcrops in the general vicinity of Cerro Cariblanco. The type area includes much of the southeastern third of the Coamo quadrangle. Particularly good exposures of the base of the formation occur on the hill north of the community of Sabana Llana, and good exposures of its upper contact occur along the trail road south of Sabana Hoyos.

The bulk of the formation is volcaniclastic and was subdivided into informal map units based on the abundance of gravel. Lava and limestone are much less abundant and occur as lenticular units that have been given member names. In general order of decreasing age they are the La Guaba Lava Member, the Jobo Dulce Limestone Member, and the Pío Juan Limestone Member. In addition, the Hacienda Larga Tuff Member was originally named in the belief that it was a unique isochronous rock unit. Subsequent laboratory studies have shown that the Hacienda Larga is merely a rather pure accumulation of a crystal tuff component of the matrix that is common throughout the formation.

The Cariblanco has been discussed by Briggs and Gelabert (1962), Glover (1961a), Pessagno (1960a), Berryhill and Glover (1960), and Otálora (1961). Rocks that include the Cariblanco Formation, as well as the overlying Maravillas Formation, were encompassed in the Ildefonso Formation of Pessagno (1960b), and this usage was continued by Otálora (1961). More recently Pessagno (1962) has dropped the name Ildefonso in favor of Cariblanco but has redefined Cariblanco to include all the strata previously assigned to Ildefonso. The Cariblanco Formation as used in this report conforms essentially to the original definition of the Cariblanco (Glover, 1961a), but excludes the Sabana Hoyos Limestone herein included as a member of the overlying Maravillas Formation. The evolution of nomenclature is outlined in plate 3.

The distribution of the Cariblanco Formation and correlative Achiote Conglomerate in the Cayey, Coamo, Barranquitas, Orocovis, Jayuya, and Adjuntas quadrangles is shown on the geologic map of southeastern Puerto Rico (pl. 1).

In southern Barranquitas and northern Coamo quadrangles the coarsely conglomeratic facies of the Cariblanco underlies much of the drainage divide along the Cordillera Central as well as the rugged southern slope of the Cordillera. Some of the more southerly salients of the Cordillera such as Cerro Jobo Dulce and Cerro de la Mesa are capped by limestone members of the formation. In the southern half of the Coamo quadrangle the Cariblanco contains less conglomerate and more volcanic sandstone and mudstone.

The most prominent gross characteristic of the Cariblanco Formation is the abundant well-rounded coarse gravel (fig. 11*A*) that marks its outcrop for more than 20 miles through south-central Puerto Rico. Such very well rounded detritus contrasts sharply with the more angular pyroclastic debris that makes up most of the volcaniclastic formations of the island. During the early stages of fieldwork it was thought, because of the moderate degree of rounding and sorting, that this great volume of conglomerate was truly epiclastic in origin, that is, that it had resulted from the erosion of older rocks tectonically uplifted to form a rugged land area. It is now clear, however, that the bulk of the gravel was derived, not from erosion of older formations, but from the erosion of active volcanic cones north of the Coamo area that formed coevally with the Cariblanco Formation itself. Thus the Cariblanco comprises principally a mixture of primary and reworked pyroclastic debris with abundant well-rounded neoclasts (p. 5) of lavas, dikes, and welded tuff from the cone. True epiclastic material is present but probably makes up less than 10 percent of the volume of the Cariblanco.

The Cariblanco Formation in the Coamo quadrangle may be described in general nongenetic terms (Fisher, 1961) as predominately a coarse bimodal conglomerate with a volcaniclastic matrix. The matrix material also constitutes most of the nonconglomeratic strata in the formation. The conglomeratic strata are coarser and more abundant in the northern part of the quadrangle and interfinger with finer volcaniclastic rocks toward the south. The geologic map of the Coamo area (pl. 2) shows most of the details of this change of facies as tongues of conglomeratic (Kcc) and nonconglomeratic (Kcs) volcaniclastic rock. Some of these, such as Kcs_4, have been given informal designations according to stratigraphic position.

In addition to the great bulk of volcaniclastic material, about 5 percent of the Cariblanco Formation in the Coamo quadrangle consists of (1) the La Guaba Lava Member near the base of the formation, and (2) the Jobo Dulce and Pío Juan Limestone Members in the upper part of the formation.

The Cariblanco is about 1,000 meters thick in the type area, and it thins northward to about 800 meters near the limit of outcrop along the border between the Barranquitas and Coamo quadrangles. Westward, in the southern part of the Orocovis quadrangle (Briggs, oral commun., 1964), the correlative Achiote Conglomerate pinches gradually toward the west and markedly toward the north.

VOLCANICLASTIC ROCKS

Conglomerate, which is the conspicuous and characteristic lithology of the Cariblanco Formation, is shown by the map unit Kcc to be abundant in the northern part of the Coamo area and less common in the southern part. At a more detailed level of observation, however, the volcaniclastic body of the formation, encompassed by map units Kcc and Kcs, is a complex mixture of lithic components perhaps best described by use of the end-member concept. In addition to the conspicuous gravel, other components of the rocks found in the volcaniclastic sequence are (1) a plagioclase-hornblende-biotite-sanidine-quartz crystal ash. (2) vitric-crystal tuff and reworked lapilli tuff of lithic and vitric fragments, (3) grayish-red volcanic wacke, (4) drab plankton-bearing mudstone, (5) chert, and (6) limestone.

The informal volcaniclastic map units (Kcc, Kcs, Kcsy) delimit the characteristic gravel component, but they tend to obscure the abundance and distribution of some of the other components. Radiolarian mudstone, for example, is nearly as common in the conglomeratic as in the nonconglomeratic units. In a general way, however, the formation does comprise coarser and more thick-bedded material in the north than it does to the south, and to this extent the subdivision into a conglomeratic and a nonconglomeratic facies is both valid and useful.

In the following discussion of the volcaniclastic part of the Cariblanco Formation, which is divided principally into informal stratigraphic units, the end-member components and the more frequent combinations of components are described. The degree of mixing, common associations, antipathetic relations, and trends in distribution of the lithic components are discussed where appropriate. Sections dealing with the Hacienda Larga Tuff Member and the Achiote Conglomerate, the only named volcaniclastic units, are also included.

CONGLOMERATE: MIXTURES OF GRAVEL, ASH, AND REWORKED PYROCLASTICS

The most abundant rock in the Cariblanco Formation is a bimodal conglomerate (fig. 11*A*). Where the coarse gravel mode is very abundant and the conglomerate makes up more than about 80 percent of the volcaniclastic sequence, it has been mapped (Glover 1961a) as volanic conglomerate (Kcc, Kcc_2, Kcc_x). Where the gravel is sparse or occurs in only a few beds in the sequence, it has been mapped as volcanic siltstone and sandstone (Kcs, Kcs_2, Kcs_y). Massive beds 3 to 4 meters thick are common in the conglomeratic rocks, whereas beds thicker than about 1 meter are rare in the nonconglomeratic rocks. Many of the conglomerate beds are imperfectly graded.

GRAVEL

The gravel in the Cariblanco Formation ranges in size from small pebbles to boulders more than 3 meters in greatest diameter. The most frequent size is probably in the coarse pebble range (32–64 mm) according to the Wentworth scale (Pettijohn, 1957, p. 18), and boulders are rare to common. The coarsest gravel tends to be concentrated in the lower half of the formation in the northern part of the Coamo quadrangle; however, boulders as large as 3.3 meters in greatest diameter occur in the lower part of the formation as far south as the head of an unnamed valley just southeast of Cerro Cariblanco. Nearly all the gravel is very well rounded, generally ellipsoidal, and not much flattened. Gravel generally makes up less than 50 percent of the conglomeratic strata, and disrupted frameworks are common. Hornblende dacite welded(?) tuff forms the most abundant and coarsest gravel in the Coamo area (pl. 2). Next in abundance is pyroxene andesite gravel. These two rock types and minor variants constitute an estimated 80 percent of all gravel in the formation. Minor lithic constituents of the gravel are feldspathic porphyry, basalt(?) rich in pyroxene phenocrysts, andesitic tuff, limestone and rudistid shells, microlitic felsite with perlitic cracks, scoria, and rare ampibolite.

DACITIC(?) CRYSTAL-RICH WELDED TUFF GRAVEL

Welded tuff forms the largest and most abundant gravel in the Cariblanco Formation. This type of gravel also occurs in the red-matrix Achiote Conglomerate. In hand specimen the gravel is seen to comprise as much as 60 percent white and dark-colored crystal debris (fig. 11*B*) and about 15 percent lithic fragments in a grayish-red-purple (5*RP* 4/2) matrix. The mineral fragments in decreasing order of abundance are 30 to 40 percent plagioclase, 15 to 20 percent biotite, 0 to 10 percent sanidine, and 0 to 1 percent quartz. In addition, 5 to 15 percent lithic fragments are commonly present. The texture is best revealed on polished and lacquered surfaces, where one sees a crude alinement of crystals and crystal fragments into a very poorly defined planar fabric. The whole and fragmental crystals are angular and euhedral to rounded, though most plainly show some effects of abrasion. The rock is very poorly sorted. An originally welded(?) glassy matrix is revealed by the local preservation of compressed pumice structures (fig. 11*C*) that probably have flowed in a plastic state while still hot. However, most of these compressed pumice structures have been obliterated by growth of secondary minerals in the glass.

The plagioclase has oscillatory zoning, and marginally it is completely altered to albite(?). Albite, carlsbad-albite, and pericline twins are common. Plagioclase constitutes 30 to 40 percent of most slides and seems to average about An_{30} in composition. Hornblende is green, pleochroic in green and yellow-green, and commonly rimmed by hematite. Some hornblende is replaced by a microgranular dull-gold chlorite(?). Biotite occurs in amounts less than 1 percent. Clinopyroxene is rare. As much as 1 percent quartz occurs as partially resorbed crystals and bipyramids. Sanidine is common and generally very fresh. A few sanidine crystals poikilitically include twinned plagioclase crystals. Fragments of andesite and fine-grained tuff are common. The matrix is now mostly altered to a fine-grained mosaic containing varying amounts of quartz, albite, and potassium feldspar and minor dark-colored silicate minerals and opaque oxides, probably hematite. Under very dim light with the upper nicol out, relict structures of welded(?) glass, shards, and pumice can be seen in some specimens.

According to Ross and Smith (1961), welded tuff containing as much as 60 percent phenocrysts is very rare and originates most frequently from dacitic magmas. These authors cite an occurrence of such a tuff in southern Nevada which superficially resembled a granitic rock even to weathering by exfoliation into rounded knobs. Similar weathering may explain the origin of the large well-rounded boulders of the welded tuff in the Cariblanco Formation.

Pyroxene Andesite Gravel

Porphyritic andesite(?) containing phenocrysts of plagioclase, clinopyroxene, and, in half the specimens examined, biotite is the second most abundant component of gravel in the Cariblanco Formation. Phenocrysts 1 to 3 mm in length vary in abundance from about 30 percent to nearly 50 percent of the rock. Plagioclase (15 percent) occurs as euhedral laths and interpenetrating cruciform crystal aggregates and is generally turbid with alteration products. Clinopyroxene, probably augite, occurs as single crystals and granular aggregates and makes up about 10 percent of the rock. Biotite crystals range in abundance from a trace to about 5 percent in half the specimens examined. All the biotite is altered in part or completely to granular aggregates of opaque oxides and calcite. Chlorite patches occur in the matrix of some specimens, and the groundmass is a fine-grained aggregate of feldspar, clinozoisite(?), sphene(?), and possibly zeolites and chalcedony. Green copper carbonates have replaced clinopyroxene as well as groundmass in some of the red-matrix conglomerate cobbles from the Achiote Conglomerate. This type of gravel is widely distributed through the formation from southeastern Coamo quadrangle at least to southeastern Orocovis quadrangle. It commonly occurs associated with tuffs of a similar composition.

Minor Lithic Components of the Gravel

The following rock types make up about 20 percent of the gravel in the Cariblanco Formation:

1. Feldspathic porphyry containing less than 20 percent phenocrysts in a subvariolitic(?) to pilotaxitic matrix; mafic phenocrysts rare and replaced by chlorite; rare to common amygdaloidal bodies of chlorite in the matrix; resembles lavas of the Avispa Formation (Berryhill, 1965) of the Ciales quadrangle more closely than lavas of the Lapa Lava Member of the Robles Formation with which they have been compared (Pessagno, 1960b).
2. Pyroxene-phenocryst-rich basalt(?) as amygdaloidal lava and breccia cobbles derived from the underlying Cotorra Tuff (R. P. Briggs, unpub. data); occurs in the Cariblanco where it overlies the Cotorra lavas and hyaloclastite lava breccias in the Orocovis and southwesternmost Barranquitas quadrangles; more rarely it occurs in the conglomerate in the northern half of the Coamo quadrangle.
3. Pebbles and rare cobbles of perlite-cracked felsite with fluidally alined microlites; X-ray diffraction analysis indicates a high percentage of albite and quartz; the felsite is light gray to nearly white and contains rare feldspar phenocrysts; possibly keratophyre or altered rhyodacite(?).

4. Pebbles of fine- to medium-grained feldspathic vitric-crystal tuff; tuff in some pebbles shows graded bedding, in others the tuff is very poorly sorted and was probably deposited subaerially; some pebbles of tuff resemble tuff from the underlying Robles Formation, but others are similar to tuffs from the Cariblanco.
5. Rare to common pebbles of scoria and pumice.
6. Rare cobbles of amphibolite similar to amphibolite in the Bermeja complex of southwestern Puerto Rico.
7. Rare pebbles of vein quartz.
8. Rare to common pebbles and cobbles of bioclastic limestone and rudistid shell.

CONGLOMERATE MATRIX AND COARSE VOLCANICLASTIC STRATA

The matrix of the conglomerate (Kcc) and most of the nonconglomeratic strata (Kcs) is generally composed of mixtures of crystal tuff and reworked tuff and lapilli tuff. The crystal tuff fraction is made up of plagioclase (dominant), hornblende, pyroxene, biotite, sanidine, and rare quartz. The reworked tuff and lapilli tuff comprise principally subequal amounts of andesitic lithic fragments and andesitic(?) to dacitic devitrified porphyritic glass fragments. In general the reworked pyroclastic components increase in abundance toward the top of the formation. This increase is also accompanied by a general decrease in abundance and coarseness of the gravel component. Locally, virtually pure end-member components occur. The crystal tuff Hacienda Larga Tuff Member is an example discussed below. The conglomerate matrix, as well as the nonconglomeratic rocks of the same composition, is composed of moderately well sorted grains. Only the red Achiote Conglomerate commonly has a poorly sorted wacke matrix. Coalified woody plant fragments are common in the tuffaceous rocks. Calcareous macrofossil debris is rare to common as rounded clasts ranging in size from sand to cobbles.

CRYSTAL TUFF AND THE HACIENDA LARGA TUFF MEMBER

The Hacienda Larga Tuff Member was named by Glover (1961a) for outcrops at Hacienda Larga on the U.S. Military Reservation in southeastern Coamo quadrangle. The Hacienda Larga is composed of the nearly pure crystal tuff end member described below. At the time the member was named, it was believed to be a unique ash fall constituting an isochronous stratigraphic unit within the Cariblanco. Subsequent petrographic work has shown that coarse crystal tuff of similar composition occurs in varying quantities as a component of the volcaniclastic rocks throughout the vertical and lateral extent of the formation. Hence, although the concentrations of nearly pure crystal tuff mapped at Hacienda Larga south of the Río Cuyón probably represent a nearly isochronous unit, specific correlation with the Hacienda Larga Member as mapped north of the Río Cuyón is not implied.

Locally, in the northern Coamo quadrangle, as at some localities along Highway 14 and on Cerro Jobo Dulce, the upper parts of the member include beds of graded conglomerate with disrupted frameworks (figs. 11*D*, 12*A*). Hence, the member includes some redistributed tuff and gravel.

Crystal tuffs make up about 35 percent of the volcaniclastic fraction of the Cariblanco Formation. These are light-colored rocks commonly containing as much as 70 percent plagioclase, the remainder of the rocks being mostly hornblende, pyroxene, biotite, and minor sanidine and quartz. The crystals and crystal fragments are subangular to angular, moderately well sorted, and at different localities range in size from less than a millimeter to about 5 millimeters. There are variations in grain size, mineral abundances, and degree of mixing with gravel and reworked pyroclastics so that the overall color of the rock varies accordingly. The most frequent color of nearly pure crystal tuff is pale orange mottled by about 30 percent olive-gray specks. The feldspathic tuffs are among the lightest colored volcaniclastic rocks in Puerto Rico.

About one-third of the tuffs contain rare to common pumice and devitrified glass fragments, and two-thirds of the samples examined contain common lithic fragments. Many lithic fragments are porphyritic and cognate with the enclosing tuff; others are fragments of unidentified greenish tuff. By addition of gravel and reworked pyroclastics the crystal tuffs grade into the conglomerates described above.

The primary mineralogy of the tuffs examined, in order of decreasing abundance, is: plagioclase, clinopyroxene, hornblende, magnetite, biotite, sanidine, and quartz. In general, only plagioclase, clinopyroxene, and hornblende individually constitute more than 10 percent of the primary crystal fraction. Hornblende-rich crystal tuff apparently is slightly more abundant then clinopyroxene-rich crystal tuff, but they are not mutually exclusive, and both minerals commonly occur together. Biotite, quartz, and sanidine are more commonly associated with the hornblende-rich tuff, but there are no antipathetic relations, and in one sample all these minerals occurred together.

Plagioclase varies in abundance from approximately 40 percent to 70 percent of the tuff and is the only mineral that occurred in all the samples examined. Unaltered crystals are rare, and in the 25 thin sections examined, only 13 estimates of composition by extinction-angle measurements were possible. These estimates ranged from An_{17} to An_{58}, the most frequent value being near An_{30}. Fresh plagioclase is more common in the rare beds that are cemented by calcite. Moderately strong oscillatory zoning occurs in a few fresh crystals, and albite, carlsbad-albite, and pericline twins are common. Plagioclase was replaced by albite-sodic oligoclase and laumontite.

Clinopyroxene, present in about 75 percent of the slides examined, varies in abundance from a trace to as much as 15 percent. It is characteristically very fresh. Optic axial angles measured in thin section ranged from 55° to 59°, the entire range occurring in one thin section. A faint greenish pleochroism is characteristic. The variation in $2V_z$ within a single slide suggests mixing of clinopyroxenes from different sources. Because of this, nY could not be matched with $2V_z$ on a routine basis, and determinations of composition were not attempted. The pleochroism and high $2V_z$, however, leave little doubt that these clinopyroxenes are high-calcium augites.

Hornblende occurs in about 75 percent of the slides examined and varies in abundance from a trace to about 10 percent. In hand specimens it appears much darker and more prismatic than the pyroxene. In thin section the hornblende has a moderately strong pleochroism in shades of green. A single $2V_z$ was measured to be 67°. Hornblende is generally quite fresh. Magnetite occurs in all samples in varying amounts and reaches a maximum of about 10 percent. Much of it was concentrated into thin magnetite-rich layers by sedimentary processes. Locally the concentration is sufficient to deflect the needle of a compass.

Biotite occurs in two-thirds of the samples and varies in abundance from a trace to about 10 percent. Concentrations greater than 5 percent are rare. Crystals and crystal fragments ("books") are a common form of the mineral, but thin cleavage fragments are the abundant form of biotite in the tuffs.

Sanidine makes up a trace to 10 percent of one-half of the tuffs examined. Concentrations greater than 3 percent are rare. Percentages of this mineral were estimated by examination of 25 thin sections and 17 slabs of rock stained with sodium cobaltinitrite solution. The sanidine is fresh and clear, somewhat resembling quartz in the hand specimen. In thin section it has rare carlsbad twinning. The sanidine apparently is a low-temperature form. Staining revealed a cryptic layering of sanidine-rich beds in the tuff. In one case, tuff with no sanidine is sharply separated from otherwise similar tuff containing 10 percent sanidine.

Quartz was found as crystal fragments in one-third of the tuffs examined. It occurs in trace amounts never exceeding 1 percent of the tuff. It is clear, and in one slide it showed resorption features.

The following secondary minerals occur in the tuffs: Laumontite is very abundant and occurs as void fillings and replacements of intermediate and calcic plagioclase. It is clear and limpid in thin section, has a low birefringence, and commonly has two prominent cleavages nearly at right angles. The optic axial angle is about 40° but is difficult to measure because of the low birefringence and small size of the crystals. Laumontite most commonly occurs as an interfering mosaic of crystals showing undulatory extinction. Secondary albite is abundant. It is untwinned and has a higher birefringence than either the laumontite or the intermediate primary plagioclase. It generally occurs with laumontite, both minerals replacing the primary plagioclase of the tuffs. Secondary quartz occurs rarely as interstitial anhedral patches and veinlets. Chlorite commonly occurs as replacement masses in the groundmass and vitric fragments. Analcime is rare and was found in only one thin section.

Reworked tuff and lapilli tuff

Reworked tuff and lapilli tuff constitute about 15 percent of the volcaniclastic part of the Cariblanco Formation (fig. 12*B*). They are commonly mottled in shades of medium green, gray, and brown. Locally as much as 10 percent of the rock is composed of light-gray and bright-red fragments. At a distance the mass color effect is near olive gray to dark greenish gray. Grain size varies from 1 mm to about 7 mm at different localities. These reworked coarse tuffs and lapilli tuffs are moderately well rounded and well sorted.

The clasts that compose these rocks include approximately equal amounts of devitrified glass fragments (recognized by such textures as pumice and perlitic cracks) and lithic fragments and generally are less than 10 percent crystal fragments and shell debris. The following vitric and lithic fragments are described in decreasing order of abundance: (1) Microlitic to trachytic felsite having rare to common plagioclase phenocrysts and abundant perlitic cracks; these are similar

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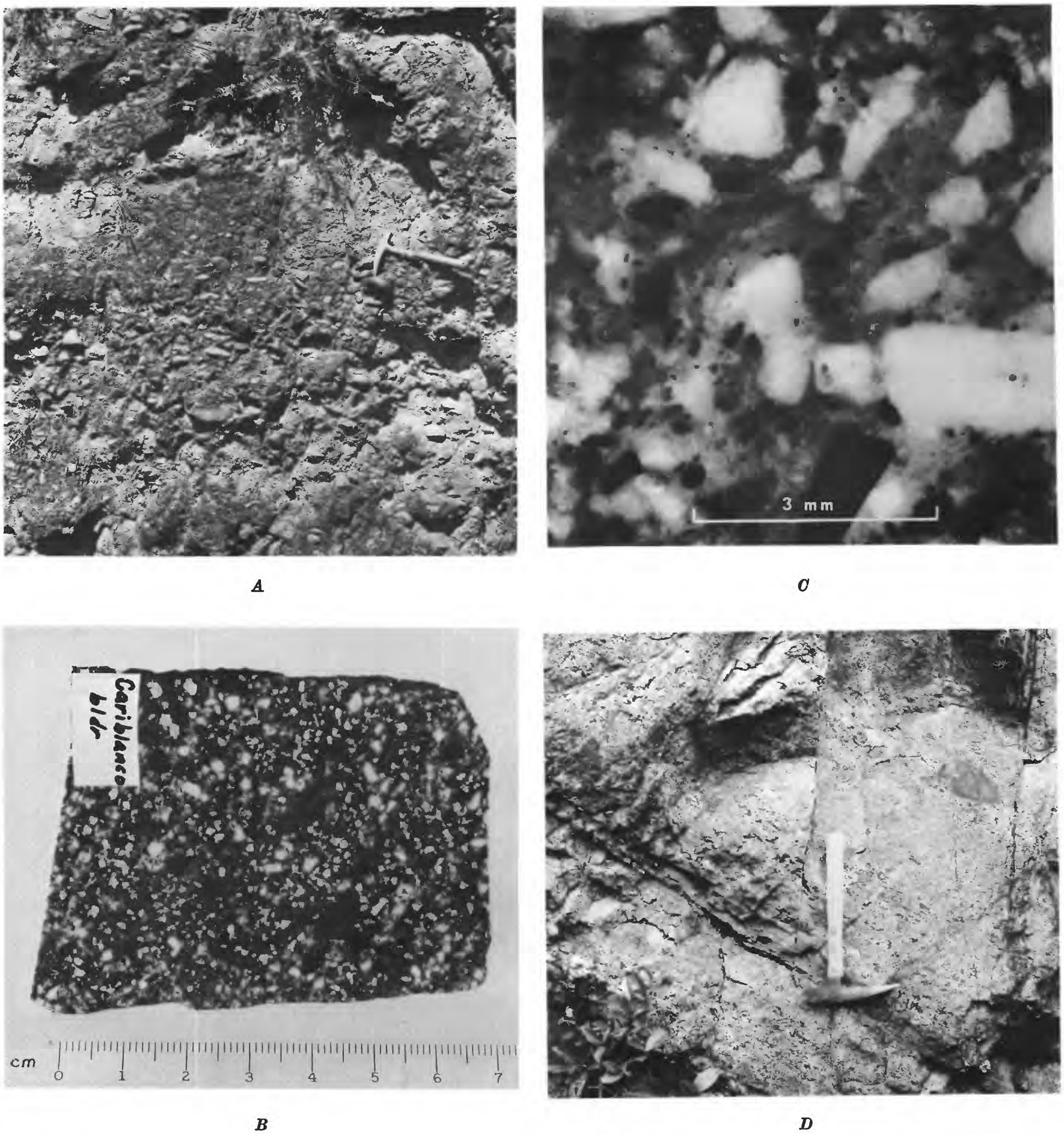


FIGURE 11.—Rocks of the Cariblanco Formation: *A*, Conglomerate of the Cariblanco Formation in roadcut along Highway 15 at the north edge of the Coamo area. Typical massive to thick-bedded marine conglomerate facies. *B*, Hand sample from a large well-rounded boulder of welded crystal-rich tuff; Cariblanco Formation. *C*, Polished surface of a crystal-rich welded tuff boulder in the Cariblanco Formation. Collapsed pumice structure can be seen near the center of the picture. *D*, Crystal tuff of Hacienda Larga Tuff Member with some gravel and interbedded tuffaceous mudstone. Along Highway 14 at north edge of Coamo quadrangle.

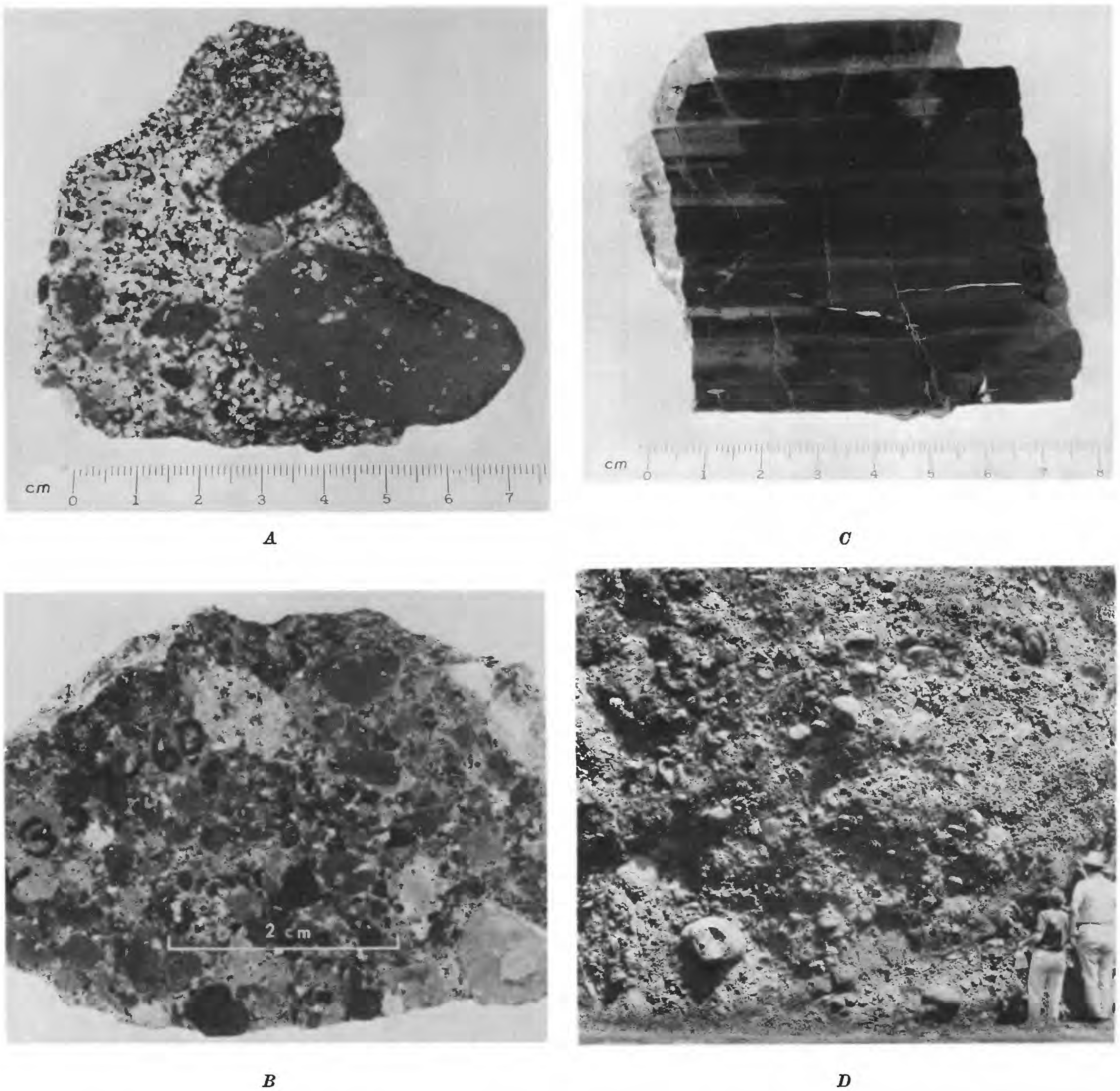


FIGURE 12.—Rocks of the Cariblanco Formation and Achiote Conglomerate: *A*, Conglomeratic crystal tuff from the northeast-central Coamo quadrangle. Well-rounded epiclastic andesite porphyry, similar to the Avispa Formation of north-central Puerto Rico, and pebble of tuff lie in a matrix of well-sorted crystal tuff of primary pyroclastic origin. *B*, Reworked tuff and lapilli tuff with minor admixture of reworked and primary(?) tuff. The many colors of clasts reflect varying degrees of oxidation and weathering prior to deposition. Upper part of Cariblanco Formation. *C*, Thin-bedded plankton-bearing mudstone, colored medium to dark gray by organic content. Many of these beds are graded. Cariblanco Formation, Salinas Training Area. *D*, Achiote Conglomerate along Highway 155 at the north edge of the Coamo area. Matrix of the conglomerate and prominent bed at lower right is grayish-red volcanic wacke. Probably a nonmarine fanglomerate.

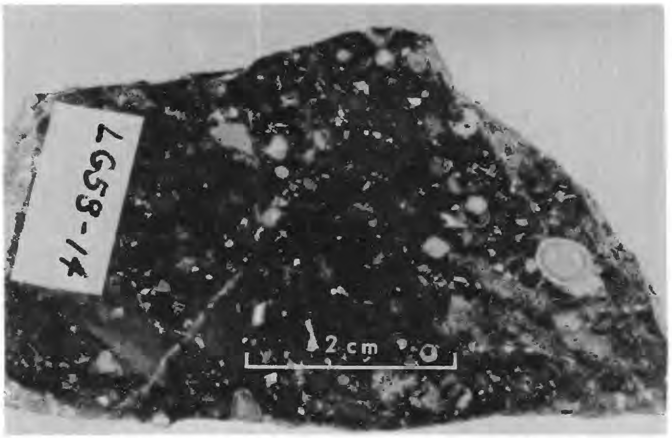


FIGURE 13.—Dark pebbly biomicritic limestone of the Jobo Dulce Limestone Member, Cariblanco Formation.

to the vitrophyre fragments described from the Frailes Formation near San Juan by Kaye (1959) and are also very similar to fragments from the Manicaboa Formation in the Ciales quadrangle described by Berryhill (1965), (2) plagioclase-clinopyroxene-phenocryst andesite, (3) hornblende-plagioclase-phenocryst dacite (?) having the hornblende partially replaced by quartz, chlorite, and epidote(?), (4) pumice and scoria, which may be tan, gray, or red, (5) microdiorite fragments, which may be sparsely amygdaloidal, composed of quartz and chlorite interstitial to an interpenetrating mass of twinned plagioclase crystals, (6) green chlorite after glass(?), (7) welded(?) tuff, (8) poorly sorted tuff, possibly a sillar(?), (9) crystal-vitric tuff, probably subaerial, (10) red aphanite, and (11) epidotized fragments.

In addition, fragments of pelecypods, corals, and calcareous algae are relatively common.

The crystal debris includes, in decreasing order of abundance, plagioclase, clinopyroxene, magnetite, rare quartz, and rare hornblende. Secondary minerals are rare to common laumontite, common albite, and common secondary quartz as veinlets and void fillings.

Mixed Primary and Reworked Pyroclastic Debris

Most of the coarse-grained volcaniclastic strata of the Cariblanco, both conglomeratic and nonconglomeratic, are made up of mixed primary crystal tuff (and perhaps vitric crystal tuff) with reworked coarse vitric crystal tuff and reworked lapilli tuff. The colors are intermediate in shades of dark greenish gray, dark gray, and olive gray in gross aspect. The primary ash is angular, and the reworked debris is subrounded and varicolored. Sorting is poorer in the mixture than in the pure end members. Nevertheless, fine tuff, silt, and clay are not abundant, and even the mixture is a moderately well sorted rock.

Petrographically, the only feature of note is that secondary laumontite is intermediate in abundance with respect to occurences in the primary and reworked end member components.

MUDSTONE, CHERT, AND TUFF

A variety of fine-grained generally tuffaceous mudstone is particularly common in the upper Cariblanco Formation in the northwestern part of the Coamo quadrangle. In the type area in the southeastern part of the quadrangle, mudstones are common in all but the lower 100 meters of the formation. Drab mudstone constitutes as much as 10 percent of the Cariblanco and is common to all parts of the formation. Is is more abundant, however, in the less conglomeratic sequence of southeastern Coamo quadrangle. The mudstones locally predominate in sequences several meters thick, but more commonly they are found alternating with greater amounts of tuff, rarely with conglomerate, and more rarely, perhaps, with thinly laminated dark- and light-gray chert. The mudstones vary from subfissile, graded, and thin-bedded shale to massive mudstone having a blocky to subconchoidal fracture. These rocks are rarely if ever conglomeratic. They are commonly calcareous, tuffaceous, and locally cherty. Epigenetic calcareous concretions are common in the mudstones of the Cariblanco in contrast to their absence in somewhat similar rocks of the underlying Robles Formation. Thinly laminated beds of chert are commonly found in the mudstones near the middle of the Cariblanco in the type area.

Radiolarian mudstones are common in southeastern outcrops (fig. 12*B*), but they also occur in the northwestern part of the Coamo quadrangle within a few kilometers of the red beds of the Achiote Conglomerate. Planktonic Foraminifera are very common in most mudstones, benthonic Foraminifera are common, and mollusks are rare. The mudstones contain as much as 3 percent very finely divided organic matter, but most probably have less than 1 percent. Locally, the mudstones contain abundant coalified woody fragments.

The mudstone, tuff, and chert are gradational with one another in all proportions and are interbedded in any combination. Bedding in the mudstones and tuffaceous mudstones varies in thickness from 1 mm laminae to beds as much as 1 meter thick. Cherts and cherty mudstones vary from about 1 to 5 cm in thickness. The very thin bedded and laminated rocks commonly are graded. Thick beds generally are mottled and streaked by darker clay-rich mud in lighter silty mud matrix; this fact suggests thixotropic disruption of a once more thinly bedded deposit. Most of the mudstones are medium gray to medium dark gray when fresh; on slight weathering they become olive gray. Cherts are light to dark gray and have a greasy luster on freshly broken surfaces. Mudstones and cherts are commonly interbedded with fine tuffs and tuffaceous sandstone and somewhat less commonly with conglomerate.

Clay minerals were not specifically identified in the mudstones, but a preliminary X-ray examination suggests that montmorillonite is not a major component of the clay fraction. The fine tuff and volcanic silt fraction constitutes as much as 20 percent of some rocks. All the tuffs, tuffaceous mudstones, and cherts are rich in planktonic Foraminifera and Radiolaria. In some of the thin graded beds, the Foraminifera (in part benthonic?) and Radiolaria are graded with the silt and clay. Some redistribution of fossils has undoubtedly occurred, and this will be an obstacle in estimating water depth by plankton-benthon ratios. In addition to varying amounts of silica, the cherty mudstones and mudstones commonly contain as much as 10 percent calcium carbonate and about 2 to 3 percent organic matter as very fine grained wisps, stylolitelike concentrations, and plant fragments. Pyrite cubes and irregular masses of pyrite constitute a few percent of most samples. Some foraminifera are filled with glauconite(?).

Calcareous Concretions

Calcareous concretions are a minor but widespread constituent of the Cariblanco mudstones. Some of these concretions have a septarian shrinkage-crack system which is partly filled with coarsely crystalline sparry calcite. In one locality just northeast of Cerro Santa Ana the septarian voids are filled with a light petroleum (Glover, 1957). The concretions have not been studied in detail, but they apparently constitute about 50 percent mudstone, which suggests that they formed during early diagenesis. Prior to the major episode of compaction, the enclosing mudstone would have contained approximately the same amount of water as the concretion now contains calcium carbonate (Pettijohn, 1957, p. 204).

LA GUABA LAVA MEMBER

The La Guaba Lava Member was named by Glover (1961a) for exposures just southwest of the small community of La Guaba in northeastern Coamo quadrangle. Outcrops of the member occur in several fault blocks in the northeastern part of the quadrangle and by their distribution suggest a northerly elongated body of lava. Another area of outcrop occurs a few kilometers east of Coamo along the western margin of the Los Panes intrusive. The lava is as much as 50 meters thick, and its base seems to lie about 100 meters above the base of the Cariblanco Formation.

The La Guaba is dark greenish gray to olive gray, very amygdaloidal, and finely porphyritic. It is commonly pillowed. Clinopyroxene is the only abundant phenocryst, and it constitutes as much as 30 percent of the lava. Cumulophyric aggregates of clinopyroxene are common. Plagioclase phenocrysts are rare. There are calcite pseudomorphs after large phenocrysts of orthopyroxene or olivine. The matrix is a pilotaxitic matte of plagioclase microlites with common clinopyroxene granules and about 3 percent opaque oxide, probably magnetite. Irregular patches of yellowish-green chlorite replace the groundmass. Amygdules compose about 20 percent of the rock. Most amygdules are calcite, but some are filled with quartz and have a rim of chlorite.

Clinopyroxene seems to be a high-calcium augite having a moderate green pleochroism. Optic axial angles ($2V_z$) determined on two crystals from a sample near La Guaba were 57°. Another sample from the outcrops near the west edge of the Los Panes intrusive contains augites with $2V_z$ measured to be 57°, 57°, and 57°. As with the lavas from the underlying Robles Formation, the optic axial angles seem to be so constant within an individual lava that they provide an identifying criterion useful in correlation where lavas are structurally displaced.

Plagioclase is too altered and fine grained for its original composition to be determined.

The La Guaba seems to have been a basalt originally.

JOBO DULCE AND PÍO JUAN LIMESTONE MEMBERS

Two limestone members in the upper 200 meters of the Cariblanco Formation were named by Glover (1961a). The Jobo Dulce Limestone Member occurs as discontinuous lenses in the northern part of the Coamo quadrangle about 200 meters below the top of the formation. It has a maximum thickness of about 50 meters.

The Pío Juan Limestone Member occurs only in the south-central part of the Coamo quadrangle about 100 meters below the top of the Cariblanco Formation. It may be as much as 30 meters thick.

All these limestones are medium-gray to greenish-gray medium- to thick-bedded rocks containing as much as 5 to 10 percent volcaniclastic material (fig. 12*D*). They are commonly interbedded with tuffaceous mudstones and occur in the nonconglomeratic or sparsely conglomeratic facies of the upper Cariblanco Formation.

The limestones are composed of 50 to 80 percent allochems (Folk, 1962, p. 63), including calcareous skeletal material, intraclasts, oolites, and pellets, in a matrix of partially recrystallized very fine grained lime mud (micrite). Skeletal material is the most abundant allochem in these limestones, or biomicrites according to the classification proposed by Folk. Moderately well rounded fragments of the red calcareous algae *Archaeolithothamnium*, intraclasts of biomicrite, mollusk fragments, and Foraminifera are particularly abundant in most outcrops. One sample from the Jobo Dulce Member in a structurally complex area in northwestern Coamo quadrangle is unusual in that it contains abundant oolites, algal(?)-coated volcanic grains, Foraminifera (including the very shallow water benthonic miliolids), and only minor mollusk debris, all in a partially recrystallized micritic matrix that composes as much as 40 percent of the sample. The oolites and other grains are very well sorted and are "floating" in the micrite.

In general, the allochems were derived from a high-energy environment, probably largely from the algal (*Lithothamnium*(?)) ridge on the front of a reef. The micritic matrix suggests final deposition in a low-energy environment probably below wave base seaward of the reef. The oolite from the Jobo Dulce of northwestern Coamo quadrangle might be a lagoonal deposit.

AGE

The age of the Cariblanco seems to be Santonian or possibly Santonian and early Campanian. Pessagno (1962) reports the following fossil lists from four localities in the Cariblanco as the formation is defined in this report (OP is a Pessagno collection locality; R, C, and A stand for rare, common, and abundant):

Collection OP–2099 Coamo quadrangle (Puerto Rico meter grid 164,800 N.; 22,437 E.):

Foraminifera:

Robulus sp. cf. *R. münsteri*	C
sp	C
Heterohelix sp. cf. *H. navarroensis*	R
Gyroidina globosa	C
Eponides sp	C
Chilostomelloides tubulosus	R
Praeglobotruncana crassa	C
sp	R
Globotruncana (*G.*) *fornicata*	A
lapparenti lapparenti	A
bulloides	R
coronata	R
sp. cf. *G. lapparenti tricarinata*	R
inornata	C
sp	R

Age: Santonian

Collection OP–2100 Coamo quadrangle (Puerto Rico meter grid 164,425 N.; 21,900 E.):

Foraminifera:

Gyroidina beisseli	R
Planomalina messinae messinae	R
Globotruncana (*G.*) *fornicata*	C
lapparenti group	R
inornata	R
sp	C

Age: Santonian

Collection OP–2102 Coamo quadrangle (Puerto Rico meter grid 164,290 N.; 22,150 E.):

Foraminifera:

Heterohelix sp	C
Planoglobulina glabrata	C

Age: late Santonian to early Campanian

Collection OP–2196 Río Descalabrado quadrangle (Puerto Rico meter grid 152,890 N.; 20,800 E.):

Foraminifera:

Lenticulina nuda	R
Heterohelix striata	C
Heterohelix sp	C
Planoglobulina glabrata	A
Praeglobotruncana sp	R
Globotruncana (*G.*) *fornicata*	A
lapparenti group	A
conica	R
sp	C

Age: Santonian

Upper Robles rocks have been dated as Santonian in age, and the lower part of the Maravillas Formation is Campanian. The youngest Cariblanco fauna recorded is only a few tens of meters below the top of the formation. Therefore, most of the Cariblanco is probably Santonian, but the uppermost part of the formation may be early Campanian in age.

ACHIOTE CONGLOMERATE

The Achiote Conglomerate was named by Mattson (1968) to include a conspicuous conglomerate with a red matrix in the Jayuya quadrangle; it is generally correlated with the Cariblanco Formation in the Coamo quadrangle. The Achiote Conglomerate in the Jayuya and Orocovis quadrangles comprises most of the rocks correlative with the Cariblanco Formation, but typical drab-matrix Cariblanco conglomerate occurs in the lower part of the sequence in both quadrangles.

The Achiote volcanic conglomerate has a red tuffaceous wacke matrix in the northwestern corner of the Río Descalabrado quadrangle. The matrix and interbedded wackes differ from typical drab Cariblanco in having a bright grayish-red (5*R* 4/2) hematite-bearing clay component which makes up as much as 15 percent of the rock. Tuffaceous wacke beds in the conglomerate are composed of subangular lithic and crystal fragments in a bright grayish-red clay matrix. The associated red conglomerate contains an assemblage of very well rounded gravel ranging from pebbles to boulders 1 meter in diameter in a matrix of red wacke. Pyroxene andesite porphyry and hornblende dacite welded(?) tuff are the principal gravel components at this locality; less common are pyroxene-phenocryst-rich basalt(?), textural variants of malachite-bearing altered porphyritic pyroxene andesite rock, and milk-white vein quartz. This assemblage of gravel is very similar to that common in the typical Cariblanco conglomerate in the type area. Bedding in the highway outcrop is very thick to massive and not graded.

The wacke has an overall grayish-red color imparted by a hematite-stained clay and silt fraction that constitutes 10 to 15 percent of the wacke. Larger fragments reach pebble size. They are all subangular and, together with the clay and silt fraction, compose a very poorly sorted rock.

Lithic, crystal, and vitric fragments are similar to the assortment in the reworked pyroclastic debris described above. Several fragments of slightly welded(?) vitric tuff have well-preserved (shard and vitric fragment) textures and are partially replaced by bright-green nontronite(?). Crystal fragments are plagioclase, hornblende, clinopyroxene, biotite, and quartz.

X-ray diffraction analyses and thin-section studies of the red clay matrix indicate that cryptocrystalline quartz is an abundant component. The clay mineral was not certainly identified, but it does not appear to be montmorillonite.

ACHIOTE CONGLOMERATE AND CARIBLANCO FORMATIONS, SOURCE AND CONDITIONS OF DEPOSITION

The sources of the Cariblanco-Achiote sequence were large subaerial dacitic to andesitic volcanoes 15 to 20 km. north of the Coamo area (fig. 10). The volcanoes were probably built upon a high area resulting from Río Orocovis deposition and perhaps to a lesser extent resulting from tectonic arching. Erosion of the cones and lesser erosion of the tectonic land produced subaerial coarse ill-sorted fanglomerate known as the Achiote Conglomerate in central Puerto Rico. The nonmarine red Achiote fanglomerate interfingers in the Coamo area with the thicker drab-colored conglomeratic Cariblanco Formation of marine origin. Contemporaneous eruptions in the source area added pyroclastic debris to the weathered subaerial fans as well as to the marine sediments offshore.

In the Cariblanco Formation conglomerates of submarine slide origin are interbedded with turbidites and dark plankton-bearing mudstones. Submarine slides transported boulders as much as 3.3 meters in diameter as far as 12 km south of the strand. A minimum unbroken slope of 1° would be necessary to propagate sliding once started; hence, reconstruction of this slope suggests that, in the southern part of the Coamo area, the water during this time was at least 300 meters deep. The interbedded dark-gray to dark-grayish-brown plankton-bearing mudstones indicate by their high content of carbonaceous material deposition under euxinic conditions, and it is suggested that the Cariblanco was deposited in a submarine graben or silled basin. The details of this paleogeographic reconstruction are discussed in the following sections.

SOURCE

Volcanic cones coeval with the deposition of the Achiote-Cariblanco sequence are believed to be the principal source of volcaniclastic rocks because the well-rounded gravel neoclasts are similar in composition to the primary tuff with which they are mixed. This is particularly well demonstrated by the petrographic similarity of the distinctive sanidine-bearing crystal tuff and the welded tuff gravel. Possibly as much as 10 percent of the sequence could have been eroded from older consolidated rocks, and to this extent, tectonically elevated terrane was a possible source of sediment.

Vent sites of the Cariblanco volcaniclastic rocks have not been identified, but are presumed to have been north of the Coamo area for the following reasons.

The nonmarine Achiote Conglomerate presumably lies nearer the volcanic source than does the Cariblanco, yet neither coarse near-vent volcanic rocks nor ventsites have been discovered in the Achiote. According to R. P. Briggs and P. H. Mattson (oral commun., 1964), the Achiote occurs as far north as central-western Orocovis quadrangle and northeast-central Jayuya quadrangle (see also north limit of Cariblanco-Achiote sequence, fig. 6). Near the southern margins of both these quadrangles, typical drab-matrix marine Cariblanco conglomerate interfingers with the Achiote. Therefore the general strike of the facies change, and probably the strike of the ancient strand, is easterly. The direction of abrupt thinning of Achiote is northerly, and the conglomerate in the marine Cariblanco increases in abundance toward the north. The data suggest that the volcanic source of the Achiote-Cariblanco sequence lay north of the present north limit of the Achiote Conglomerate.

Another and more speculative approach to the problem of locating the source area is an estimation of the distance from the source vent by measuring the coarseness of primary pyroclastic debris. The sizes of the largest ejecta found at varying distances from the source crater Soufrière, St. Vincent, British West Indies, were tabulated by Hay (1959). Fragments of nonvesicular rock as large as 38 mm in greatest diameter were found at distances of 17 and 15.3 km from Soufrière on the east and west coasts respectively. This rough method of determining distance from source would be affected by such variables as explosivity of the magma, ash flow versus vertical eruption, force of the prevailing winds, and human error in finding the largest ejecta. However, it may be used with caution to get a minimum source distance by (1) comparison of pyroclastic deposits representing approximately the same magmatic composition, and therefore approximately the same explosivity index, (2) restriction of use of the method to sizes of primary pyroclastic rocks coarser than about 2 mm, because the distribution of coarser sizes is much less affected by the wind, and (3) diligent search for the largest sizes at a given location.

Magmas from the Cariblanco vents varied in composition from dacite to andesite, whereas the magmas of St. Vincent are mostly andesitic. Presumably the more siliceous Cariblanco magma may have been slightly more explosive than Soufrière magma on the average. The maximum size of primary pyroclasts in the Cariblanco can only be judged within a couple of orders of magnitude from the writer's data. For pyroclasts from the northern margin of the Coamo quadrangle, about 10 mm would be a conservative estimate. If this errs on the conservative side by a factor of two, then ejecta 20 mm in diameter would still be judged to have fallen more than 17 km from their source vent, according to Hay's data from St. Vincent.

Most of the data evaluated above suggest that the principal sources of the Achiote-Cariblanco sequence were volcanic cones in the area of previous Robles-Río Orocovis volcanicity about 17 km north of the Coamo area. Perhaps the magmatic activity continued from the same reservoirs. The Cariblanco tuffs suggest by their high sanidine-quartz ratio a somewhat alkalic composition in common with the more basic Río Orocovis rocks.

SEDIMENTATION

The red Achiote Conglomerate appears to be principally a nonmarine fanglomerate. Much of the material in it probably originated from mass movement and sheetwash transport down the slopes of volcanoes. Hay (1959) has described similar material on the slopes of Soufrière, St. Vincent, British West Indies, which also has deep radially distributed valleys choked with coarse gravel. In the case of the Achiote, such material was probably mixed at the base of the cones and subsequently distributed southward as a subaerial fanglomerate deposit across the eroded tectonic land of central and northern Jayuya, Orocovis, and possibly Barranquitas quadrangles.

The Achiote is a prograding facies that advanced in a southerly direction. The sequence along Highway 155 in southeastern Orocovis and northeastern Río Descalabrado quadrangles has typical marine Cariblanco tuffaceous conglomerate at its base and bright-red nonmarine wacke conglomerate of the Achiote at its top. Through many oscillations the strand advanced southward a minimum distance of 2.2 km during this time. Eastward in southern Barranquitas quadrangle, the strand seems to have swung slightly north because only locally, as in the central southern part of the quadrangle, do red beds occur.

As the muddy gravels of the Achiote were dumped into the sea, they seem to have been subjected to sufficient winnowing to separate virtually all the clay- and silt-size particles. These fine materials were transported seaward to be deposited in part as turbidites and in part as a pelagic rain to form the bulk of the Cariblanco mudstones. If the Achiote mud was red at that time, the iron in it has subsequently been reduced in the environment of the Cariblanco marine mudstones. There is, of course, the possibility that the Achiote mud was brown and has since gained its red color by a diagenetic "aging" process, such as conversion of goethite to hematite.

The dispersal of coarse gravel presents a problem of transport. How were the well-rounded 3.3 meter boulders that occur in the coarse lower Cariblanco conglomerate of the Salinas Training Area moved a distance of at least 10 kilometers seaward of the strand? Finer gravel in the southernmost outcrops has been moved at least 15 km seaward. These conglomeratic strata are thick to massively bedded crudely graded or ungraded and generally have a moderately well sorted matrix of coarse volcaniclastic sand or fine breccia. They are also interbedded with very fine grained graded mudstones that contain abundant planktonic Foraminifera and Radiolaria.

The generation and propagation of turbidity currents probably depends in large part upon the thixotropic properties of the clay-size fraction. The resultant deposit is commonly poorly sorted at each level, and the coarsest clasts probably cannot exceed 10 cm in true turbidity-current deposits (Kuenen, 1956). Coarse boulder conglomerates and ungraded well-sorted sandstones, however, do occur interbedded with undoubted deep-water turbidites in the Ventura basin of California. Natland and Kuenen (1951) developed a strong case for submarine landslide emplacement of these sediments. For sliding of the Ventura basin conglomerates and well-sorted sandstones, Natland and Kuenen believed that slopes of a few degrees were reasonable on the basis of their depth range and horizontal distance data. Kuenen (1956) discussed the differences between submarine sliding and turbidity flow and concluded that a submarine slide halts suddenly, the entire mass stopping at the same moment. There would be little or no segregation of the larger clasts, so that grading should be crude or nonexistent. Submarine slides require a slope of 1° or more, and they probably cannot continue to travel very far on a horizontal floor.

The general absence of clay and silt in the matrix, the large size of many of the cobbles and boulders, the general lack of well-defined grading, and the association of the conglomerates with true turbidites are compelling evidence that the Cariblanco conglomerates were also transported mainly by submarine landslides.

An interesting corollary of the submarine-landslide theory is that slopes of at least 1° must have existed as unbroken features from the Santonian strand to the southern margin of the Coamo quadrangle in order to allow transport of the gravel found there. This slope imlies a minimum depth of water of about 170 meters in the southern area during early Cariblanco time. If the slope was as high as 3°, which seems likely, the water depth would be about 500 meters.

Thick-shelled macrofossils, characteristic of shallow and well-agitated water environments, are generally absent throughout most of the Cariblanco Formation in the Coamo area. Rare fragments of *Barrettia*(?), corals, and other presumably shallow-water inhabitants occur as well-rounded pebbles and cobbles in the conglomerates, and some of the coarse sandstones and reworked tuffs have an allochemical component of fragmented shell material from shallow-water organisms. However, this material was generated, fragmented, and rounded in the shoal areas near shore. During the deposition of the Cariblanco, it was intermittently swept seaward by turbidity currents and submarine landslides to the sites where it is now found.

It is difficult to evaluate the paucity of skeletal material in the lower Cariblanco in terms of growth conditions in the shoal areas. Both low rates of growth and high rates of deposition of volcaniclastic material could produce the ratios found in the Cariblanco. The postulated steep slope away from the strand suggests only a narrow belt of shoal water suitable for prolific growth of skeletal material, and the prograding of muddy Achiote gravels seaward suggests turbid rapidly changing conditions unfavorable for abundant organic growth in the narrow belt of shoal water that may have existed.

Euxinic conditions probably existed at times in the offshore waters below wave base. The dark mudstones are estimated to contain 1 to 3 percent finely divided organic matter plus common pyrite. There also seems to have been few bottom dwellers, perhaps because of the low oxygen content of the water.

Almy (1965) found evidence of a submerged carbonate bank of Santonian(?) to Maestrichtian age in southwestern Puerto Rico. The bank is believed to have formed on a horstlike east-trending structure, the northern slope of which appears to strike into the Coamo area near Isla Caja de Muertos. Perhaps some such feature produced a submerged graben during Cariblanco time, with a volcanic island to the north and a submerged bank to the south as shown in figure 10.

MARAVILLAS FORMATION

The Maravillas Formation was named and described in a report by Mattson (1967). In the Coamo area the formation consists of, from oldest to youngest, the Sabana Hoyos Limestone Member, the San Diego Member, the Santa Ana Limestone Member, and younger unnamed map units consisting of mudstone, fine- to coarse-grained pyroclastic rocks, limestone, and limestone-fragment wacke conglomerate.

The formation comprises rocks previously included by Glover (1961a) in the lower part of the Coamo Formation and, in the case of the basal Sabana Hoyos Limestone, previously included in the upper part of the Cariblanco Formation. Pessagno (1962) redefined the Cariblanco of Glover (1961a) to include rocks called Maravillas in this report.

The Maravillas is a heterogeneous formation comprising hornblende-augite andesite pyroclastic rocks and tuffaceous mudstone in approximately equal amounts. Less common are limestone (biomicrite) and limestone-boulder wacke conglomerate. The Maravillas contains more thick-bedded and massive pyroclastic rocks and much less conglomerate than does the Cariblanco Formation. It is much more heterogeneous than the overlying Coamo Formation (restricted).

The base of the formation in the Coamo area is placed at the base of the Sabana Hoyos Limestone or, where that is absent, at the base of the San Diego Member. To the north and northwest in the Orocovis and Jayuya quadrangles, the base of the marine Maravillas is placed at the top of the red nonmarine Achiote Conglomerate, and in these quadrangles the Maravillas probably includes at the base some rocks correlative with the upper Cariblanco of the type area. Correlative rocks in the north edge of the Coamo area are entirely marine, and a slightly different stratigraphic break was chosen for mapping purposes there.

The top of the formation is placed at a level where massive tuff breccia and tuff of the Coamo Formation constitute more than about 95 percent of the sequence. In general, this level is higher stratigraphically in the southern Coamo area than it is to the north.

SABANA HOYOS LIMESTONE MEMBER

The Sabana Hoyos Limestone Member was named by Glover (1961a) for outcrops in south-central Coamo quadrangle. In this original description it was included as the youngest member of the Cariblanco Formation, but it is herein treated as the oldest member of the Maravillas Formation. By this change, the Maravillas of the Coamo area is brought into better lithic and time correlation with the type section.

The limestone occurs as discontinuous lenses as much as 30 meters thick in the Coamo quadrangle. According to R. P. Briggs (oral commun., 1963), the limestone is more continuous, thicker, and more conspicuously stratified in the Orocovis quadrangle. In the Coamo area, the Sabana Hoyos is medium gray to greenish gray and medium to thick bedded. It contains varying amounts of volcaniclastic material and reaches a maximum of about 15 percent. In thin section, the limestone is seen to be a partially recrystallized biomicrite. Allochems include pellets, algae, molluscan fragments, and Foraminifera.

On the basis of macrofossil assemblages, the Sabana Hoyos has been dated in the Orocovis quadrangle as Campanian. It has not been dated in the Coamo quadrangle.

SAN DIEGO MEMBER

The San Diego Lapilli Tuff Member was named by Glover (1961a) for outcrops near the community of San Diego, northwestern Coamo quadrangle. The term "lapilli tuff" is not uniformly appropriate, and the name is herein changed to the San Diego Member.

The San Diego is composed mostly of greenish-gray lithic lapilli tuff (fig. 14) but crystal-vitric tuff and tuff breccia are common. The member rests conformably upon lenses of the Sabana Hoyos Limestone, or where that is absent, it overlies Cariblanco tuffaceous mudstone. Massive or thick-bedded rocks predominate in the San Diego.

Hornblende andesite constitutes the bulk of the pyroclastic debris, hornblende-augite andesite is very common, and augite andesite is rare to common in the upper part of the member. Accessory amounts of quartz are also common near the top of the member. Cognate hornblende diorite and microdiorite fragments petrographically identical to the Los Panes instrusive have been found in the San Diego. The largest block of andesite or microdiorite, about 2 meters in greatest diameter, was found in the vicinity of Cerro Santa Ana.

In the northwestern part of the Coamo quadrangle and adjacent parts of the Río Descalabrado quadrangle, the lower part of the San Diego contains much well-rounded gravel similar to that in the Cariblanco Formation.

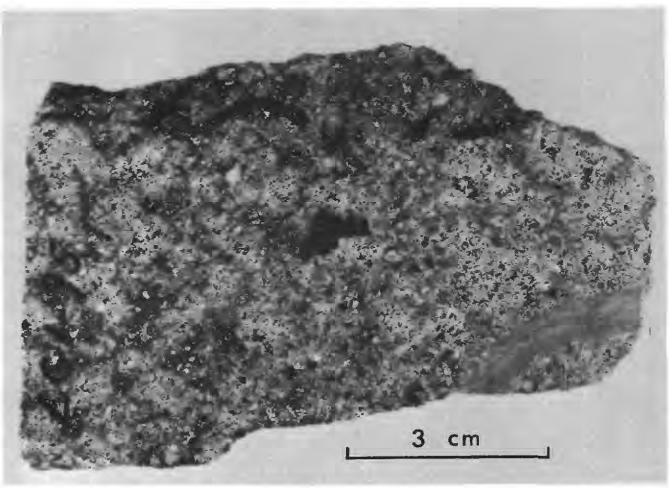
The San Diego varies in thickness from about 50 meters in southern Río Descalabrado quadrangle to more than 300 meters in southern Coamo quadrangle. In the northern part of the Coamo area, it is 130 to 230 meters thick. The member has also been mapped in the Jayuya and Orocovis quadrangles. Its base is well defined and is one of the most widespread isochronous surfaces in Puerto Rico.

SANTA ANA LIMESTONE MEMBER

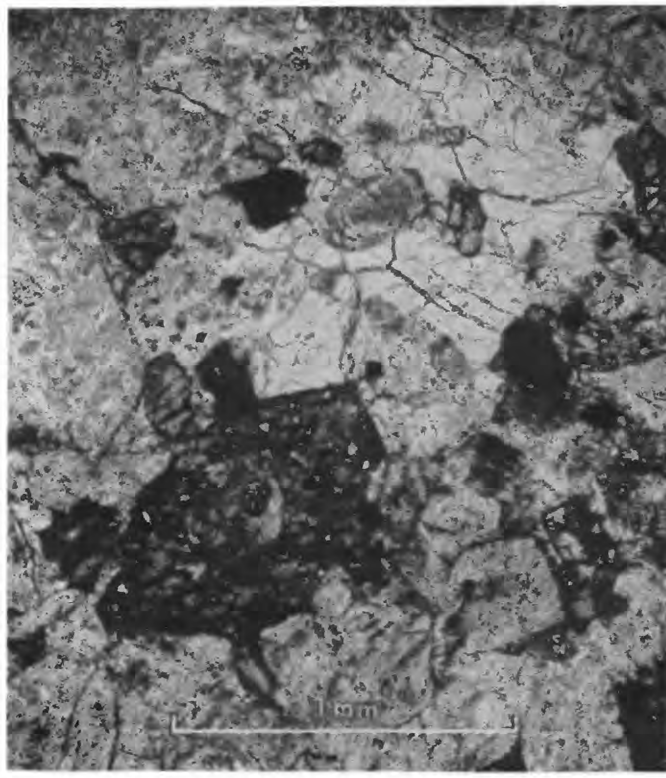
The Santa Ana Limestone Member was named in the Coamo quadrangle (Glover, 1961a) for limestone that caps and flanks Cerro Santa Ana just northeast of Coamo. In the type area, the limestone rests upon the San Diego Member or may be separated from it by a thin unit of tuffaceous mudstone. In the southwestern part of the Coamo quadrangle, two units of limestone are correlated with the Santa Ana. The two limestones are separated from the San Diego Member and from each other by 10 to 30 meters of tuffaceous mudstone. The member name is not extended into southern Río Descalabrado quadrangle, where many units of limestone are scattered throughout the vertical extent of the Maravillas Formation and into the upper part of the Cariblanco Formation. The Santa Ana Member extends into northeastern Río Descalabrado and southern Orocovis quadrangles.

At the type locality the Santa Ana is an impure skeletal limestone that grades laterally and vertically into limestone-fragment wacke conglomerate and tuffaceous mudstone. The limestone is a biomicrite with abundant mollusk fragments, sponges and sponge spicules, echinoid spines, calcareous algae, and Foraminifera. Mudstone interbeds contain abundant Radiolaria

A



B



C

D

FIGURE 14.—Rocks of the Maravillas Formation: *A*, Lapilli tuff from the San Diego Member. This rock has been rendered ash-gray in overall aspect by pervasive zeolitization but it mottled by pastel reds, brown, green, and yellow that are relict from the original differences in oxidation state of the fragments. *B*, Tuff from the Maravillas Formation. Light mottling due to abundance of secondary zeolite (laumontite) and albite. Large fragments are accidental clasts of deformed mudstone. *C*, Thin section of hornblende andesite tuff from the Maravillas. Note large patch of laumontite just above and to the right of the hornblende crystal. Murky appearance of feldspars due to replacement by an intimate mixture of albite and laumontite. *D*, Limestone fragments and (under the pencil) rudistid shell (*Barrettia*) in wacke conglomerate of the Maravillas Formation just east of Coamo on Highway 14.

and Foraminifera. Rudistids and other shallow-water pelecypods and corals are particicularly abundant as clasts in the associated wacke conglomerates.

In the southwestern Coamo quadrangle, limestone-boulder wacke conglomerate is at least as common as beds of biomicritic limestone, and both are interbedded with graded wackes. Quartz-bearing hornblende andesite pyroclastic debris is a common component of the Santa Ana and associated rocks.

Paleontological data are tabulated in stratigraphic sections (p. 36–47). Microfossils indicate that the Santa Ana and associated mudstones are Santonian to early Campanian in age, probably early Campanian; macrofossils indicate that these rocks are Campanian to Maestrichtian, possibly Maestrichtian.

UNNAMED MAP UNITS IN THE UPPER PART OF THE MARAVILLAS FORMATION

Tuffaceous mudstone and mudstone occur throughout the Maravillas above the San Diego Member. It is olive gray to dark gray when fresh. Bedding is thin to thick and commonly graded. Radiolaria, planktonic and (less commonly, perhaps) benthonic Foraminifera, sponge spicules, echinoid spines, and coalified plant debris abound in the mudstone. Mudstone is interleaved with beds of tuff, limestone, and wacke conglomerate.

TUFF, LAPILLI TUFF, AND TUFF BRECCIA

Pyroclastic rocks throughout the Maravillas are generally similar to those in the San Diego Member, but quartz-bearing tuffs are more common, and, locally, augite-andesite pyroclastic rocks predominate over hornblende andesite. Maravillas primary pyroclastic rocks are coarser than those in the underlying Cariblanco Formation and do not seem to contain sanidine or biotite as do the Cariblanco tuffs. Pyroclastic rocks in the Maravillas are commonly mottled by secondary zeolites (laumontite, analcime) and albite (fig. 14*B*, *C*).

LIMESTONE

Above the stratigraphic level of the Santa Ana Member, limestone is rare north of Coamo but becomes common south of Coamo. In the vicinity of Las Flores, in the southwestern part of the Coamo quadrangle, several lenses of limestone occur in the upper part of the Maravillas Formation. In southern Río Descalabrado quadrangle, limestone is very common in the Maravillas, and one unit is present at the top of the formation. The limestones are biomicrites similar to those of the Santa Ana. Dark biomicrite probably deposited in a euxinic environment is most common in southern Río Descalabrado quadrangle.

WACKE CONGLOMERATES

Wacke conglomerates are most closely associated with limestone units, but the conglomerate also occurs alone. Most rudistids and other large macrofossils in the formation have come from these conglomerates or from large blocks of limestone in the conglomerates (fig. 14*D*). Limestone debris and large macrofossils are also common as a conglomeratic phase at the base of massive pyroclastic units.

LIMESTONE AND BEDDED VOLCANICLASTIC SANDSTONE

An unnamed sequence of mixed limestone and calcareous volcaniclastic rocks occurs along the northern edge of the Coamo area where it supplants a sequence comprising the Santa Ana Limestone and volcaniclastic sandstone.

COMPOSITE STRATIGRAPHIC SECTIONS

The following section descriptions of the Maravillas Formation in the Coamo area have been compiled from the maps, field notes, sample descriptions, and fossil determinations. There are several reasons for presenting the data in this manner:

1. Except for the named members, few of the other map units can be recognized outside the areas of the composite sections.
2. Ages based on microfossils are at variance with ages based on macrofossils. The details of the relative stratigraphic positions of the fossil collections can be given in a section but may be obscured on a map of complicated structure and facies.
3. Lastly, some of the details of the structure and stratigraphy are imperfectly known, but descriptions of numbered map units provide a degree of objectivity that may allow the present work to serve as a basis for further refinement of this important fossiliferous formation.

Identifying letter symbols preceding fossil lists are:

1. USGS, N. F. Sohl (written commun., 1959–63).
2. OP, E. A. Pessagno, Jr. (1962).
3. JR, Jeremy Reiskind (unpub. data, 1961–63).
4. LG, Lynn Glover III (this paper).

Abundance code letters which follow some fossil names have the following meanings: R, rare; C, common; A, abundant.

Composite stratigraphic section 1 of the Maravillas Formation in the northeastern corner of the Rio Descalabrado quadrangle, Puerto Rico

[For distribution of units, see fig. 15]

	Thickness (meters)
Cretaceous—Coamo Formation (lower part):	
5. Lapilli tuff, tuff breccia, and minor amounts of tuffaceous mudstone, limestone, and limestone-pebble wacke conglomerate. Lapilli tuff and tuff breccia are hornblende andesite and, less commonly, pyroxene andesite. The rock type is very similar to the San Diego Member	100+

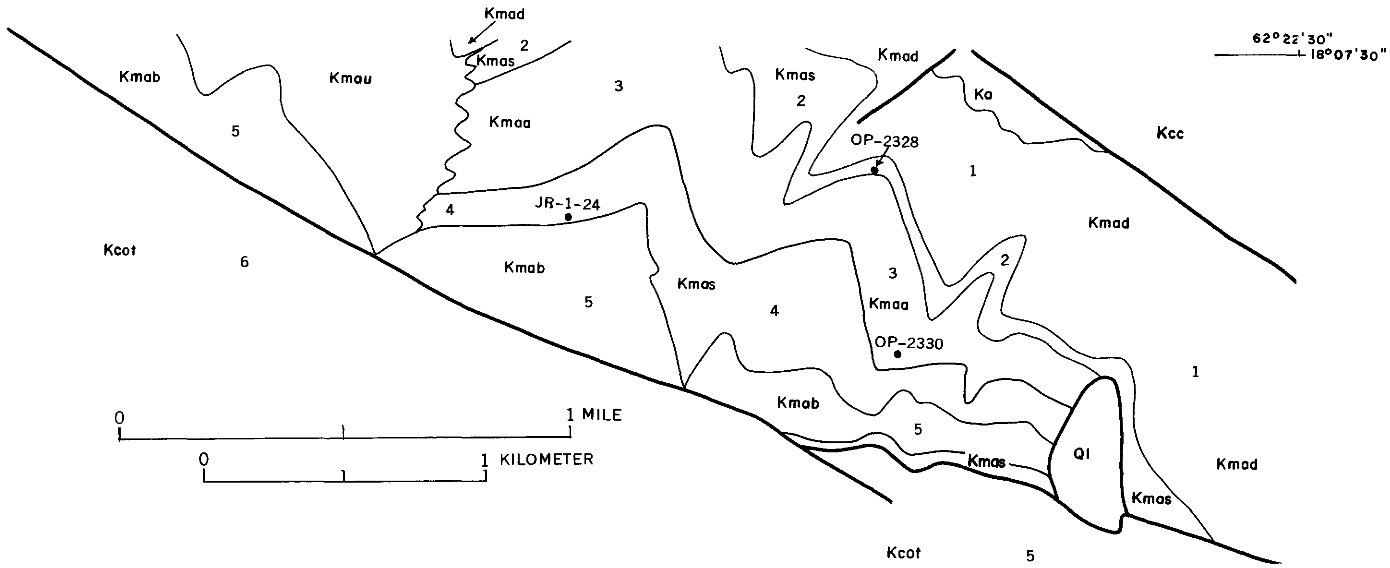


FIGURE 15.—Distribution of units described in composite stratigraphic section 1, northeastern Río Descalabrado quadrangle. Map symbols same as on plates 1, 2, and 4. Scale, 1:20,000.

Composite stratigraphic section 1 of the Maravillas Formation in the northeastern corner of the Rio Descalabrado quadrangle, Puerto Rico—Continued

Cretaceous—Maravillas Formation: *Thickness (meters)*

4. Tuffaceous mudstone, minor tuff, and limestone-pebble wacke conglomerate. Mudstones, thin- to medium-bedded; medium gray when fresh, commonly weathering to light olive gray; contain planktonic and benthonic Foraminifera, plant remains, and stringers of dark carbonaceous material. Fossil collection JR-1-24 from near top of unit includes the following Foraminifera:
   - *Anomalina henbesti*
   - *Bolivina watersi*
   - *Robulus münsteri*
   - *Globotruncana arca*
     - *lapparenti tricarinata*
     - *stuarti*
     - *stuarti stuartiformis*
     - *conica*

   Age: middle to late(?) Campanian 60

3. Santa Ana Limestone Member: Bioclastic limestone with tuffaceous mudstone interbeds; some limestone-pebble wacke conglomerate. Fossil collection OP-2330, near top of member:

Foraminifera:	
Marssonella oxycona	R
Lenticulina nuda	R
Globotruncana (G.) fornicata	C
Ostracodes	R
Radiolaria:	
Dictyomitra multicostata	C
Aulophacus gallowayi	R
Aulonia sphaerica	C

   Age: early Campanian 30–100

Composite stratigraphic section 1 of the Maravillas Formation in the northeastern corner of the Rio Descalabrado quadrangle, Puerto Rico—Continued

Cretaceous—Maravillas Formation—Continued *Thickness (meters)*

2. Tuffaceous mudstone and tuff; thin to thick bedded; dark gray to olive gray when slightly weathered. Mudstones contain abundant Radiolaria, planktonic Foraminifera, common sponge spicules and echinoid spines, and common coalified plant debris. Tuff is commonly thick bedded and comprises hornblende andesite and pyroxene andesite ash. Fossil collection OP-2328 from near top of unit includes Foraminifera identified in thin section as *Globotruncana lapparenti* group (common) of early Campanian age 55
1. San Diego Member: Andesitic lapilli tuff, less commonly tuff and tuff breccia; conglomeratic near base of member. Dominantly medium gray, but generally mottled by light gray, light olive gray, greenish gray, and grayish purple. Commonly thick bedded to massive, more rarely thin bedded. Rests conformably upon graded beds of reworked tuff at top of Cariblanco along Highway 155. Hornblende andesite is dominant, but hornblende-augite andesite is very common particularly near top of the member. Cognate fragments of hornblende diorite and microdiorite common. Laumontite, albite, and chlorite are abundant secondary minerals. Mottled appearance of much of the rock can be attributed in part to variation in abundance of zeolites and secondary albite ....

Total thickness of Maravillas Formation 400–450

Composite stratigraphic section 1 of the Maravillas Formation in the northeastern corner of the Rio Descalabrado quadrangle, Puerto Rico—Continued

	Thickness (meters)
Cretaceous—Cariblanco Formation:	
Andesitic tuff, reworked; thin to medium bedding, commonly graded: overlies Achiote Conglomerate	5–10

The geologic map of the Coamo area (pl. 2) and figure 16 show a structurally complex area of upper Cariblanco and lower Maravillas rocks several kilometers north of Coamo. The stratigraphic assingment of some map units is doubtful, and in this area the limestone mapped as Jobo Dulce Member of the Cariblanco Formation may actually be the Sabana Hoyos Member of the Maravillas. By such an interpretation the overlying conglomerate would be a conglomeratic phase of the basal San Diego Member and not Cariblanco conglomerate as it has been mapped.

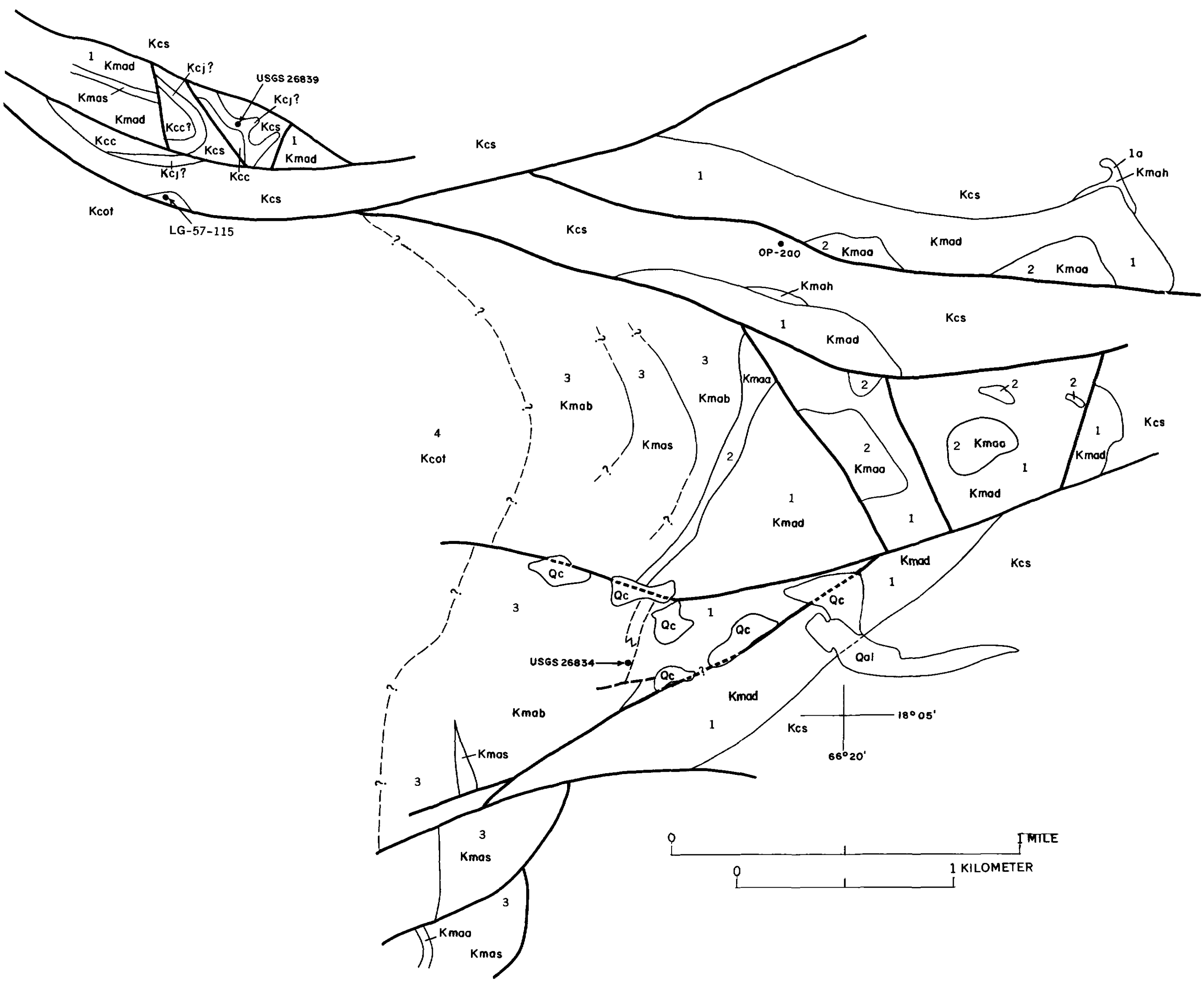


FIGURE 16.—Distribution of units described in composite stratigraphic section 2, western Coamo quadrangle. Map symbols same as on plates 1, 2, and 4. Scale, 1:20,000.

Three fossil collections (OP–200, USGS 26839, and LG–57–115) are shown in figure 16 but are not included in the following generalized stratigraphic section because structural complications cast doubt on their stratigraphic assignment. For reference the collections are listed below.

Fossil collection OP–200:

Foraminifera:

Guadryina cf. *G. pyramidata*	R
Clavulinoides sp. cf. *C. asper*	R
Marssonella oxycona	A
Dorothia retusa	R
Robulus sp. cf. *R. münsteri*	C
Lenticulina nuda	C
Lagena apiculata	C
sp	C
Heterohelix striata	A
ultimatumida	R
sp	C
Planoglobulina glabrata	A
Gyroidina beisseli	C
sp	C
Eponides sp	R
Praeglobotruncana gautierensis	R
Globotruncana (*G.*) *fornicata*	A
lapparenti group	C
lapparenti	A
stuarti stuartiformis	R
subspinosa	R
sp. aff. *G. repanda*	R
sp. aff. *G. ventricosa*	R
inornata	C

Ostracodes

Radiolaria:

Aulophacus lenticululatus	R
gallowayi	R
Aulonia sphaerica	R

Age: late Santonian to earliest Campanian

Fossil collection (USGS 26839) (LG–57–246):

- Algae
- Corals (abundant)
- Gastropoda:
  - *Turritella* sp.
  - *Actaeonella* sp.
- Pelecypoda:
  - Radiolitid fragments
  - *Barrettia*(?) sp. (fragment)
  - *Praebarrettia*(?) sp.
  - *Pecten* (*Neithea*) sp.
  - Ostreid
  - *Plicatula* sp.
  - *Trigonia* cf. *T. eufaulensis* Gabb
- Echinoid spine
- Vermes:
  - *Hamulus onyx* Mortan
- Age: late Campanian-Maestrichtian

Fossil collection LG–57–115:

- Pelecypoda:
  - *Durania*(?) sp.
- Corals
- Age: Late Cretaceous; post-Turonian

Composite stratigraphic section 2 of the Maravillas Formation in the northwestern quarter of the Coamo quadrangle, Puerto Rico

[For distribution of units, see fig. 16]

	Thickness (meters)
Cretaceous—Coamo Formation (lower part):	
4. Pyroxene andesite tuff breccia and lapilli tuff, commonly massive.	
Cretaceous—Maravillas Formation:	
3. Dominantly conglomeratic tuff and conglomeratic lapilli tuff; contains common tuffaceous mudstone which increases in abundance toward the south. Hornblende-augite andesite is about as abundant as augite andesite pyroclastic rocks. Tuffs contain as much as 1 percent quartz. Some conglomeratic beds contain rudistids and limestone clasts. Mudstone is plankton-bearing and tuffaceous. Minor analcime and common laumontite in addition to albite, chlorite, and quartz are the main secondary minerals. Fossil collection USGS 26834 (LG–56–23) at base of unit: Pelecypoda: *Barretia monilifera* Woodward (variety with wide-spaced moniliform rays) *Biradiolites cubensis* Douville Gastropoda: Large actaeonellid Age: Campanian to Maestrichtian	350
2. Santa Ana Limestone Member: Impure skeletal limestone, conformably overlies San Diego Member or intervening tuffaceous mudstone; grades laterally and vertically into limestone-fragment wacke conglomerate and plankton-bearing mudstone. Bedding varies from thin to thick. The limestones are biomiorites with abundant mollusk fragments, abundant whole sponges or sponge fragments, abundant sponge spicules and echinoid spines, calcareous red algae, and Foraminifera. In the bed of the Río Cuyón this limestone is interbedded with a mudstone containing abundant Radiolaria, planktonic Forminifera, and sponge spicules. The limestone-fragment wacke conglomerates comprise abundant angular to well-rounded fragments of limestone and rudistids in a coarse-grained commonly graded reworked tuff and tuffaceous wacke	0–50

Composite stratigraphic section 2 of the Maravillas Formation in the northwestern quarter of the Coamo quadrangle, Puerto Rico—Continued

Cretaceous—Maravillas Formation—Continued	Thickness (meters)
1. San Diego Member: Lapilli tuff abundant, tuff breccia and tuff common, all may be conglomeratic locally. Bedding is massive, less commonly somewhat poorly defined, graded medium to thick bedding occurs. The member rests conformably upon tuffaceous mudstone of the Cariblanco Formation except locally where thin lenses of Sabana Hoyos Limestone are in conformable contact with the San Diego. Medium-gray to greenish-gray colors are characteristic of the San Diego. Crystal tuffs and crystal-vitric tuffs are very abundant, vitric-crystal tuffs are rare. Hornblende and plagioclase, commonly with a small amount of augite, are the most frequent crystal components. More rarely augite-plagioclase crystal tuffs occur in the upper part of the member. At the top of the member 1 to 2 percent quartz occurs in the tuffs. Vitric-crystal ash is completely devitrified or replaced by secondary minerals. Rarely a small amount of allochems or sparry calcite cement occurs in the tuffs. Lapilli tuff and tuff breccia comprise dominately hornblende andesite, less commonly hornblende-augite andesite and augite andesite. Rarely blocks as large as 2 meters in diameter occur in the tuff breccia. Cognate and accidental fragments are locally common, and in the bed of the Río Cuyón from the lower part of the member, the following fragments were collected: (1) nonfoliated hornblendite, (2) a chloritized volcanic fragment, (3) coarsely crystalline augite andesite, (4) hornblende microdiorite, (5) a pink fragment of hornblende-plagioclase crystal tuff probably from the Cariblanco conglomerate, (6) chips of gray tuffaceous mudstone, and (7) a fragment of hornblende-plagioclase-biotite phenocryst andesite or dacite probably from the Cariblanco. Fragments of hornblende andesite and microdiorite petrographically identical to the Los Panes intrusive are very common. In the Río Cuyón outcrops, and locally near San Diego, small prehnite veins occur in the member, and actinolite replaces some of the matrix and cuts prehnite veinlets. Laumontite is more abundant than analcime. Calcite veinlets cut all the above. Elsewhere in the area of this section laumontite is the dominant zeolite, but minor amounts of analcime occur also. Albite, chlorite, and secondary quartz accompany many zeolite occurrences	130
1a. Sabana Hoyos Limestone Member: Limestone, a thin lens at the base of the San Diego Member northeast of Cerro Santa Ana	0–10
Total thickness of Maravillas Formation	550

Cretaceous—Cariblanco Formation (upper part):
Tuffaceous mudstone

Composite stratigraphic section 3 of the Maravillas Formation in the southwestern quarter of the Coamo quadrangle, Puerto Rico

[For distribution of units, see fig. 17]

Cretaceous—Coamo Formation (lower part):	
9. Pyroxene andesite tuff breccia and lapilli tuff; massive to thick bedded.	
Cretaceous—Maravillas Formation:	
8. Mudstone, commonly tuffaceous; limestone-gravel conglomerate with a very tuffaceous limestone matrix; some hornblende-andesite tuff and lapilli tuff	50
7. Abundant andesitic hornblende-plagioclase crystal tuff, common lapilli tuff, and less tuff breccia. Some augite andesite and hornblende-augite andesite lapilli tuff and tuff breccia. Mudstone and tuffaceous mudstone are interleaved with the pyroclastic rocks. Minor amounts of quartz occur in the tuffs. At one outcrop a 1½- by 4-inch fragment of hypidiomorphic granular diorite containing about 5 percent quartz with hornblende and plagioclase was found. The enclosing tuff contains hornblende, plagioclase, clinopyroxene, quartz, and allochems in a calcareous matrix. Secondary minerals are analcime or laumontite with albite, quartz, celadonite, chlorite, and calcite	150+
6 Mudstone and tuffaceous mudstone, thin- to thick-bedded, calcareous in part; lower contact is gradational by interleaving with underlying wacke conglomerate. Contains some beds of hornblende andesite tuff and and lapilli tuff and a few beds of impure limestone.	

Fossil collection OP–2:
Foraminifera:

Marssonella oxycona	R
Lenticulina sp	R
Nodosaria sp	R
Neoflabellina interpunctata	R
Planomalina messinae messinae	R
Globotruncana (G.) fornicata	A
lapparenti lapparenti	R
bulloides	A
stuarti stuartiformis	A
conica	R
sp. cf. *G. rosetta*	R

FIGURE 17.—Distribution of units described in composite stratigraphic section 3, southwestern Coamo quadrangle. Map symbols same as on plates 1, 2, and 4. Scale, 1:20,000.

Composite stratigraphic section 3 of the Maravillas Formation in the southwestern quarter of the Coamo quadrangle, Puerto Rico—Continued

Cretaceous—Maravillas Formation—Continued		Thickness (meters)
Radiolaria:		
Dictyomitra multicostata	R	
Age: early Campanian (base of the *Globotruncana fornicata-lapparenti-stuarti* assemblage zone, *Dictyomitra multicostata* zonale)		
Fossil collection OP–135:		
Foraminifera:		
Marssonella oxycona	R	
Dorothia bulletta	R	
sp	R	
Robulus sp. cf. *R. münsteri*	R	
Lenticulina sp. *L. praegautina*	R	
Lagena sp	R	
Neoflabellina interpunctata	R	
Gyroidina globosa	R	
Eponides sp	R	
Praeglobotruncana crassa	R	
Globotruncana (G.) fornicata	A	
lapparenti lapparenti	A	
bulloides	R	
sp. cf. *G. rosetta*	R	
cretacea (d'Orbigny)	R	
Ostracodes	C	
Radiolaria:		
Aulophacus lenticulatus	C	
gallowayi	C	
Dictyomitra multicostata	A	
Aulonia sphaerica	C	
Age: early Campanian		200

5. Heterogeneous wacke conglomerate, tuff, and lapilli tuff or tuff breccia; massive to indistinctly bedded in thick units. Heterogeneous wacke conglomerate consists of coarse gravel varying in roundness from angular to well rounded, and in size from pebbles to boulders 1 meter in diameter. The gravel is composed of abundant limestone clasts and mollusk-shell debris (particularly rudistids). One light-tan limestone cobble examined in thin section is a slightly recrystallized biomicrite. The cobble is in a matrix of reworked andesitic tuff composed chiefly of bright-green chloritized glass fragments, plagioclase crystals (andesine to labradorite An_{54}), minor altered mafic(?) minerals, and about 1 percent quartz crystals as embayed grains. Augite andesite prophyry gravel is common, and a single boulder of very fresh microgabbro was seen. The gabbro contained about 30 percent augite, 10 percent orthopyroxene(?) now largely replaced by chlorite, and 60 percent plagioclase (An_{60-71}). The conglomerate matrix makes up about 50 percent of the rock and is commonly a tuffaceous mudstone. Interbeds of hornblende and augite andesite tuff, and tuff breccia are interleaved with the conglomerate. Laumontite-albite-quartz(?)-chlorite is the common secondary mineral assemblage.

		Thickness (meters)
Fossil collection OP–24:		
Foraminifera:		
Robulus sp. cf. *R. münsteri*	R	
Lenticulina sp	C	
Gyroidina beisseli	C	
Allomorphina trochoides	C	
Globotruncana (G.) fornicata	A	
lapparenti lapparenti	A	
bulloides	C	
stuarti stuartiformis	R	
Planulina taylorensis	C	
Radiolaria:		
Aulophacus lenticululatus	C	
gallowayi	C	
Dictyomitra multicostata	A	
Aulonia sphaerica	A	
Age: early Campanian		
Fossil collection (USGS 21919) (LG–58–13):		
Pelecypoda:		
Idonearca sp.		
Plagioptychus sp.		
Corals		
Age: Late Cretaceous, probably Campanian-Maestrichtian		
Fossil collection USGS 27598 (LG–9–194):		
Pelecypoda:		
Durania sp.		
Barrettia sp.		
Radiolitid		
Thyrastylon cf. *T. adhaerens* (Whitfield)		
Actaeonella sp.		
Coral		
Algae		
Age: Maestrichtian		
Fossil collection LG–57–82:		
Small gregarious radiolitids (*Distefenella*)		
Age: Campanian-Maestrichtian		
Fossil collection (USGS 26835) (LG–57–55):		
Pelecypoda:		
Barrettia monilifera (Woodward)		
monilifera (Woodward) (variety with widely spaced moniliform rays)		
Durania cf. *D. nicholasi* (Whitfield)		
Titanosarcolites(?) sp.		
Caprinid		
Corals		
Age: Campanian-Maestrichtian		50

Composite stratigraphic section 3 of the Maravillas Formation in the southwestern quarter of the Coamo quadrangle, Puerto Rico—Continued

Cretaceous—Maravillas Formation—Continued	*Thickness (meters)*
4. Mudstone and tuffaceous mudstone, interleaved with a few beds of crystal tuff and lapilli tuff; minor limestone lenses. Mudstone is similar to that in unit 2. Some limestone lenses or wildflysch blocks(?) have small gregarious rudistids. Tuffs are hornblende and augite andesite and single quartz crystals of pyroclastic origin. Celadonite occurs as a secondary mineral with albite	200
3. Tuff breccia and lapilli tuff, conglomeratic; thick bedded to massive; quartz-bearing hornblende andesite and pyroxene andesite are common. Limestone rubble and (or) thin limestone lenses occur in a basal conglomeratic phase. Analcime and laumontite occur with quartz(?)-albite-chlorite as secondary mineral assemblages	100
2. Mudstone and tuffaceous mudstone are most abundant, tuff and lapilli tuff are common, limestone and limestone-pebble wacke conglomerate occur near the middle of the interval, and one thick bed of well-rounded volcanic conglomerate is present. Mudstone and tuffaceous mudstone are thin to thick bedded and weather to shades of brown. Radiolaria and Foraminifera are very common in some beds. Tuff and lapilli tuff are thin to thick bedded and are interleaved with the mudstone. Hornblende andesite similar to that in the San Diego Member is the most common type; however, quartz is more abundant than in the San Diego. One specimen of coarse vitric-crystal tuff contained nearly 5 percent quartz. Laumontite, albite, quartz(?), and chlorite are common secondary minerals. Limestone and limestone-gravel wacke conglomerate occur at two levels near the middle of the unit. The limestone-rich units are closely correlative with the Santa Ana Limestone. The limestones commonly contain abundant volcaniclastic debris and are indistinctly bedded. Limestone gravel in a wacke conglomerate is locally abundant. Many of the clasts are rounded fragments of mollusks and corals. A sample of light-grayish-tan limestone from the hill just southwest of the junction of Highways 14 and 153 appears in thin section to be a slightly recrystallized biomicrite. Calcareous algae, molluscan debris, and Foraminifera are the most abundant allochemical components. Among the Foraminifera, miliolids are very abundant. Quartz-bearing hornblende andesite fragments occur in the limestone. Volcanic conglomerate occurs as a prominent massive unit shown as Kmac on the Coamo geologic map. It contains well rounded cobbles of andesite and rarer cobbles and pebbles of coral or mollusk shell.	

Composite stratigraphic section 3 of the Maravillas Formation in the southwestern quarter of the Coamo quadrangle, Puerto Rico—Continued

Cretaceous—Maravillas Formation—Continued

Fossil collection OP–45:

Foraminifera:

Marssonella oxycona	R
Lenticulina sp	R
Guttulina sp. cf. *G. adhaerens*	R
Planoglobulina glabrata	R
Gyroidina globosa	R
Praeglobotruncana gautierensis	R
sp	C
Globotruncana (G.) fornicata	A
lapparenti lapparenti	R
bulloides	A
conica	A

Radiolaria:

Dictyomitra multicostata	C
Aulonia sphaerica	C

Age: early Campanian

Fossil collection OP–2614:

Foraminifera:

Pseudotextularia elegans	C
Heterohelix pulchra	C
Praeglobotruncana sp	R
Globotruncana (G.) fornicata	C
Globotruncana lapparenti lapparenti	C
sp	C

Radiolaria:

Aulophacus lenticululatus	C
gallowayi	R
Dictyomitra multicostata	R
Aulonai sphaerica	R

Age: early Campanian

Fossil collection JR–1–54:

Foraminifera:

Valvulineria allomorphinoides
Robulus münsteri
Saracenaria triangularis
Buliminella carseyae
Pleurostomella subnodosa
Globotruncana fornicata

Age: late Santonian to early Campanian

Fossil collection (USGS 26842) (LG–57–252):

Pelecypoda:

Titanosarcolites sp.
cf. *Durania*
Barrettia monilifera (Woodward)

Corals

Age: Maestrichtian

Fossil collection (USGS 26845) (LG–57–254):

Pelecypoda:

Actaeonella sp. (large)
Nerineid gastropod

Age: Campanian-Maestrichtian

Composite stratigraphic section 3 of the Maravillas Formation in the southwestern quarter of the Coamo quadrangle, Puerto Rico—Continued

	Thickness (meters)
Cretaceous—Maravillas Formation—Continued	
Fossil collection (USGS 26844) (LG–57–76):	
Pelecypoda:	
Vaccinites n. sp.	
Age: Maestrichtian	
Fossil collection (USGS 26843) (LG–57–251):	
Pelecypoda:	
Barrettia monilifera (Woodward)	
Radiolitid	
Thyrastylon sp.	
Corals	
Age: Maestrichtian	300
1. San Diego Member: Andesitic lapilli tuff is abundant, tuff breccia and tuff are common. The San Diego rests conformably upon tuffaceous mudstone of the Cariblanco Formation, or upon the lenticular Sabana Hoyos Limestone. Most of the rocks are massive, but medium- to thick-bedded lapilli tuff is common. Hornblende andesite containing about 30 percent phenocrysts is abundant; hornblende-augite andesite is common, and more rarely augite andesite occurs alone. Accidental fragments are common; some seen in thin section were chloritized pyroxenite, and sericitized fragments. Near the top of the member volcanic wackes occur which are interbedded with plankton-bearing claystone. Quartz occurs as a minor accessory near the top of the San Diego. Laumontite, albite, calcite, and chlorite are the most common secondary minerals	280–320
1a. Sabana Hoyos Limestone Member: Limestone, medium-gray to greenish-gray, medium- to thick-bedded. In thin section a biomicrite comprising pellets, algae, mollusk debris, and Foraminifera in a slightly recrystallized micrite matrix	0–30
Total thickness of the Maravillas Formation	1350–1400
Cretaceous—Cariblanco Formation (upper part):	
Tuffaceous mudstone	

Composite stratigraphic section 4 of the Maravillas Formation in the southern Rio Descalabrado quadrangle

[For distribution of units, see fig. 18. Data are from the notes and samples of P.H. Mattson and L. Glover, 1959–1960. Sample study is by Glover, 1963]

	Thickness (meters)
Cretaceous—Coamo Formation (lower part):	
18. Pyroxene andesite tuff breccia, minor hornblende andesite; massive.	
Cretaceous—Maravillas Formation:	
17. Mudstone and limestone, mudstone and basal limestone grade to thin limestone in a northerly direction. Mudstone is dark gray to brownish black; thin beds are finely laminated or contain wisps of disrupted fine laminae; Radiolaria and planktonic Foraminifera are abundant; some mudstones are free of the tuffaceous component; dark color caused by high content of carbonaceous organic matter. Limestones are medium-bedded (10 to 20 cm) medium-grained tuffaceous biomicrites; they commonly contain about 30 percent feldspathic tuff and a small amount of carbonaceous organic material; color is dark gray to brownish black speckled with light and dark volcaniclastic fragments	5–55
16. Andesite tuff breccia and lapilli tuff, thick-bedded to massive; some lapilli tuffs have bright-red oxidized matrix. Primary minerals are abundant plagioclase, common augite and hornblende. Secondary minerals are epidote-chlorite-quartz(?)-albite(?)-calcite and small patches of actinolite; plagioclase too altered to determine original composition; hornblende is locally replaced by chlorite with anomalous blue interference colors and by actinolite. Unit is locally cut by veins of calcite-quartz-epidote-chlorite-specular hematite (rare)	165
15. Dark limestone, in part conglomeratic; interbeds of dark mudstone; rudistid fragments in a few float blocks from the limestone; unit seems to exist as discontinuous lenses	0–5
14. Tuff breccia similar to unit 16 above	50
13. Limestone, 2 to 10 cm beds; medium grained and dark gray; a thin discontinuous unit	0–5

Composite stratigraphic section 4 of the Maravillas Formation in the southern Rio Descalabrado quadrangle—Continued

	Thickness (meters)
Cretaceous—Maravillas Formation—Continued	
12. Volcanic sandstone and dark mudstone; sandstone is fine grained and calcareous; mudstone is dark gray and medium bedded	15–30
11. Andesitic tuff breccia, lapilli tuff, and tuff (includes some crystal tuff); hornblende-augite andesite is abundant, hornblende-plagioclase-quartz (rare to common) crystal tuff of andesite or dacite composition occurs as minor(?) constituent of this interval	40
10. Mudstone interbedded with tuff; mudstone is dark gray, laminated, plankton-bearing; tuff is poorly sorted, medium grained, calcareous, and generally dark olive gray	80
9. Heterogeneous unit of coarse unsorted material; includes (1) hornblende-augite andesite tuff and tuff breccia, (2) tuffaceous quartz-bearing sandstone, (3) tuffaceous gray to medium-gray biomicrite and allochem-bearing tuff with plagioclase, augite, hornblende, and minor quartz (2 percent maximum), and (4) minor dark gray, laminated mudstone. A diorite float boulder 50×20×20 cm in diameter was found resting on the unit. The boulder may have been let down from a former cover of the mid-Tertiary Juana Díaz Formation, or equally likely may be an accidental or cognate clast deposited with the unit. The rock is a granitic-textured quartz-bearing hornblende diorite. Smaller fragments of similar rock are known from the Maravillas Formation in southwestern Coamo quadrangle	150
8. Mudstone, dark-gray to brownish-black; thinly laminated with carbonaceous organic-rich layers; somewhat tuffaceous in part; well-preserved planktonic Foraminifera and Radiolaria; somewhat cherty and (or) calcareous	45
7. Limestone, medium-grained, olive-gray; sponge spicule (15 percent) and echinoid spine (20 percent) biomicrite; spicules are siliceous and weather in relief; there is a fine-grained volcaniclastic component; some mudstone layers in the limestone	2
6. Mudstone, dark-gray to brownish-black; thinly laminated; similar to unit 8	145

Composite stratigraphic section 4 of the Maravillas Formation in the southern Rio Descalabrado quadrangle—Continued

	Thickness (meters)
Cretaceous—Maravillas Formation—Continued	
5. Limestone; dark-olive-gray biomicrite(?) with layers of mudstone	5
4. San Diego Member: Tuff breccia, lapilli tuff, and tuff; augite-hornblende andesite is the dominant constituent; a single cobble of greenish quartz-bearing volcanic sandstone float was found on the outcrop and probably came from the upper part of this unit; the unit is cut by quartz-calcite-epidote veins and in places is extensively epidotized	50+
Total thickness of Maravillas Formation	800
Cretaceous—Cariblanco Formation	
3. Mudstone, thin-bedded with streaks and blebs of disrupted dark organic-rich mudstone; some cherty and calcareous mudstone; unit is cut by quartz-calcite-epidote veins. Fossil collection OP–2196 (Santonian)	45
2. Limestone and conglomerate, medium- to thick-bedded, in part graded. Limestone, dark-olive-gray, volcaniclastic biomicrite; allochemical constituents comprise abundant pelecypod shell fragments, calcareous red algae (*Archaeolithothamnium*(?)), small gastropods, and benthonic and planktonic(?) Foraminifera, all in 15 to 25 percent micrite matrix. Volcaniclastic constituents include andesite fragments and plagioclase, hornblende, devitrified glass, and rare quartz. Conglomerate comprises pebbles of andesite and large rudistid(?) fragments in a biomicrite matrix	5–20
1. Volcanic sandstone, tuffaceous sandstone and tuff, mudstone, and minor pebble conglomerate (Kcs). Tuffs are commonly very feldspathic, less commonly vitric; relic plagioclase near An_{30}, biotite is common in some tuffs; augite is common and is locally replaced by chlorite; sanidine(?) may be present; quartz is rare. Volcanic sandstones and tuffaceous sandstones and conglomerate are probably reworked tuffaceous rocks of similar composition. Mudstones are dark-gray to dark-grayish-brown laminated tuffaceous planktonic Foraminifera- and radiolarian-bearing rocks similar to those in the Maravillas Formation	400

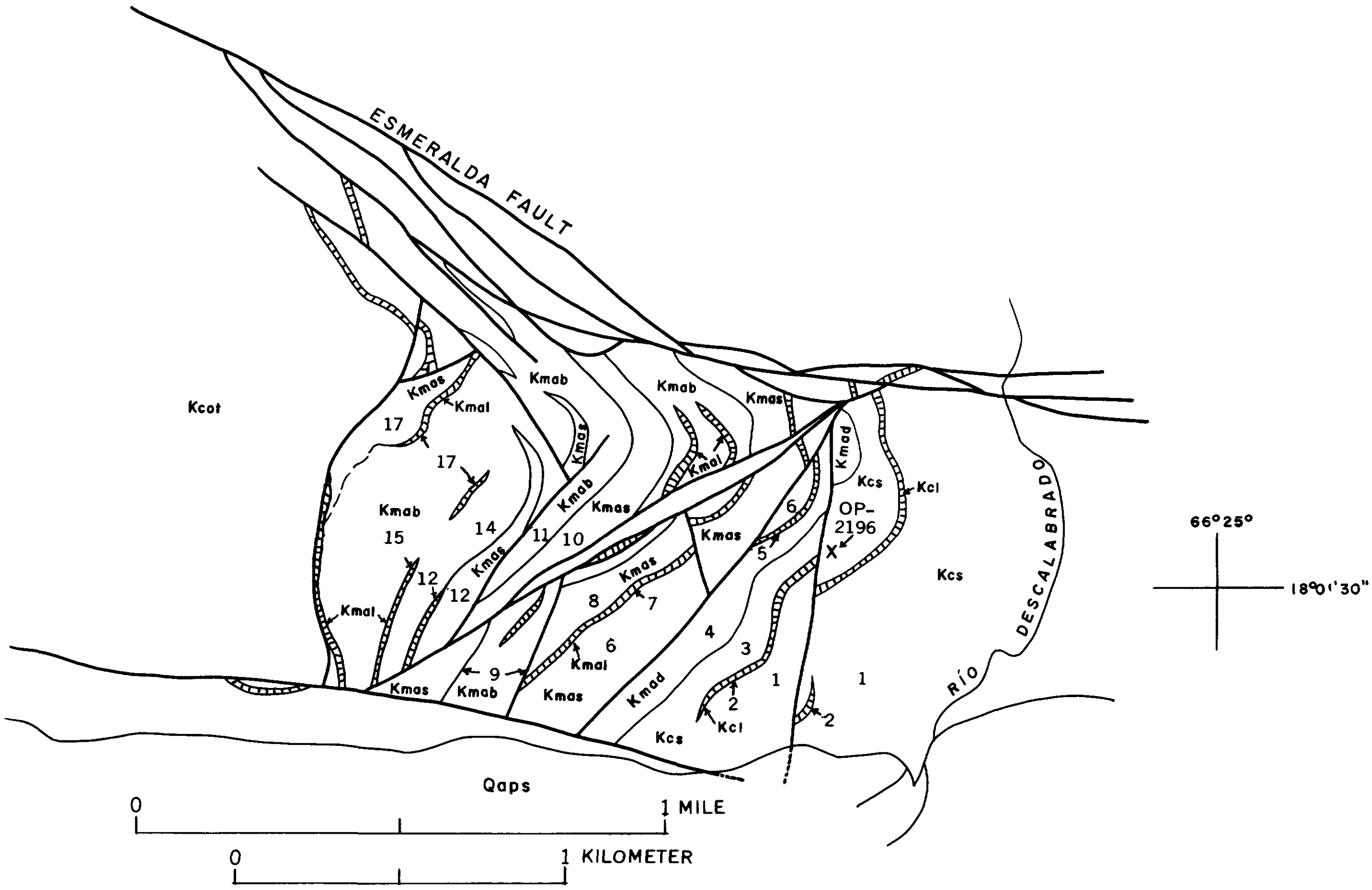


FIGURE 18.—Distribution of units described in composite stratigraphic section 4, south-central Río Descalabrado quadrangle. Map symbols same as on plates 1, 2, and 4. Scale 1: 20,000.

AGE

The age of the Maravillas Formation can be estimated from the fossil collections listed below. The ages of individual collections are tabulated according to their stratigraphic positions within the composite sections described above. Collection numbers preceded by OP– or JR– are generally Foraminifera; others are macrofossils. Inspection of the lists below indicates that if the rock units are correctly correlated, the two groups of fossils do not suggest the same age for the containing strata. This is particularly true of unit 2 in section 3, for which a late Santonian to early Campanian age is suggested by the microfossils and a Maestrichtian age, by the macrofossils.

At present the data suggest that the Maravillas is principally of Campanian age, and that it may contain rocks as old as Santonian and as young as Maestrichtian. It is also possible that some of the Maestrichtian collections represent parts of the younger Miramar Formation tectonically mixed in a thrust zone as postulated in figure 17 and on the geologic map (pl. 2).

Composite stratigraphic section 1 of the Maravillas Formation in the northeastern corner of the Río Descalabrado quadrangle, Puerto Rico

[For distribution of unit, see fig. 15]

*Stratigraphic unit**	*Fossil collection*	*Age*
4	JR–1–24	middle to late (?) Campanian.
3	OP–2330	early Campanian.
2	OP–2328	early Campanian.

*Numerals indicate relative age within a composite section; the numerals are not ntended to indicate correlation between sections.

Composite stratigraphic section 2 of the Maravillas Formation in the northwestern quarter of the Coamo quadrangle, Puerto Rico

[For distribution of unit, see fig. 16]

Stratigraphic unit	*Fossil collection*	*Age*
3	USGS 26834	Campanian to Maestrichtian.

Composite stratigraphic section 3 of the Maravillas Formation in the southwestern corner of the Coamo quadrangle, Puerto Rico

[For distribution of unit, see fig. 17]

Stratigraphic unit	*Fossil collection*	*Age*
6	OP–2	early Campanian.
6	OP–135	Do.
5	OP–24	Do.
5	USGS 21919	Probably Campanian to Maestrichtian.
5	USGS 27598	Maestrichtian.
5	LG–57–82	Campanian to Maestrichtian.
5	USGS 26835	Do.
2	OP–45	early Campanian.
2	OP–2614	Do.
2	JR–1–54	late Santonian to early Campanian.
2	USGS 26842	Maestrichtian.
2	USGS 26845	Campanian to Maestrichtian.
2	USGS 26844	Maestrichtian.
2	USGS 26843	Maestrichtian.

SOURCE AND CONDITIONS OF DEPOSITION

Toward the end of deposition of the Cariblanco Formation, two events occurred that markedly changed the sedimentary regime in the Coamo area. The first was regional subsidence and consequent inundation of the nonmarine Achiote fanglomerates to the north. Hence, the northern part of the Coamo area, which had begun to shoal into the zone of wave action, was again deeply submerged. The second event, which occurred somewhat later, was the eruption of large quantities of Maravillas pyroclastic rocks from newly established volcanic centers in south-central Puerto Rico. Intrusive breccias and dikes (p. 78) from one of the smaller centers are well displayed along Highway 14 in northern Coamo quadrangle. Other intrusive rocks which were emplaced at about this time and which may or may not have been at eruptive centers are the Los Panes in central Coamo quadrangle and the Quebrada Montería and Coamo Arriba intrusive bodies in southwestern Barranquitas quadrangle (Glover, 1961a; Briggs and Gelabert, 1962). All these contain rock petrographically identical to the Maravillas pyroclastic rocks. Structural relations of the intrusive rocks as shown on the geologic maps are compatible with this interpretation. Sedimentological relationships give some support in that the Maravillas is coarser and more massive in the Santa Ana area where it is closest to the apparent eruptive center along Highway 14. Maravillas sediments in the Coamo area were deposited below wave base. Judging from the widespread distribution of submarine slide material, the formation was deposited on slopes that exceeded 1°. The abundant dark organic-rich graded mudstones and biomicrites in south-central Río Descalabrado quadrangle suggest that there may have been a submerged sill to the south which caused restricted conditions in the deeper parts of the depositional area.

Sediments were transported into the depositional area in part by turbidity currents and submarine sliding. Perhaps an equal volume of material was contributed by air falls that rained into the sea. During rarer quiet intervals, the normal background pelagic sedimentation resulted in thin beds of plankton-bearing mudstone and claystone.

The abundance of rudistids and other large pelecypods and corals suggests that growth conditions were more favorable around the volcanic islands during Maravillas time than during the time when the prograding shore of the Achiote fanglomerate was moving southward. Doubtless an important factor was that the near-shore zones surrounding the small volcanic cones were less turbid than the shallow-water zone just seaward of the advancing Achiote fanglomerate.

Periodically the fringing reefs and shell-rich deposits were disrupted by earthquakes and volcanic eruptions and were carried to greater depths by slides and turbidity currents. Many of the coarse pyroclastic units have an ill-sorted basal conglomerate phase containing abundant limestone and pelecypod shell debris probably produced in this manner. Some of the large blocks of rudistid-bearing massive limestone, as well as blocks of bedded bioclastic limestone in southwestern Coamo quadrangle, may well have been transported by sliding from fringing reef deposits rather than having been deposited in place.

COAMO FORMATION

This formation was named by Glover (1961a) for a sequence in the vicinity of Coamo comprising coarse massive pyroclastic rocks which interfinger in the lower part of the sequence with mudstone, limestone, and wacke conglomerate. In this report the heterogeneous lower part of the sequence has been included in the Maravillas Formation, and the massive upper 70 percent of the sequence is restricted to the Coamo Formation as redefined by Mattson (1968).

The formation is widely distributed in the Coamo area (pl. 2), where it crops out in western Coamo quadrangle, in the northeastern half and south-central part of the Río Descalabrado quadrangle. The Coamo Formation interfingers with the upper part of the underlying Maravillas Formation toward the south. The top of the formation appears to be bounded by an unconformity; hence, the original thickness is unknown. At least 1,500 meters of Coamo rocks crop out in the area.

Massive dark-gray to reddish- and greenish-black rocks predominate in the formation (fig. 19*A*). Tuff breccia and lapilli tuff (fig. 19*B*) are abundant throughout the Coamo sequence. Lava breccia (fig. 19 *C*, *D*), lava, and agglomerate(?) are common in the lower part of the formation, particularly north and northeast of Coamo. Tuff is common but is much less abundant than the coarser pyroclastic rocks in the Coamo area. Angular blocks of andesite as large as 3 to 4 meters occur in some of the massive pyroclastic deposits. Wacke conglomerates with a red mudstone matrix are common in the upper part of the formation (fig. 20). Bedding is rarely observed in the north-central part of the Coamo area but is somewhat more common in the western and southern areas of outcrop.

Augite andesite makes up most of the clasts in the Coamo Formation. Hornblende andesite similar to that in the Maravillas Formation is present in abundance at the base of the Coamo in northeastern Río Descalabrado quadrangle. Southward, the top of the underlying Maravillas Formation is placed at higher stratigraphic levels as the percentage of bedded tuffaceous mudstone increases. Therefore, in this direction, most of the hornblende andesite pyroclastics are included in the Maravillas Formation. The top of the hornblende andesite, though not mapped, probably is an approximately isochronous surface in the Coamo and adjacent areas. Only one of more than 50 samples taken higher in the formation contained hornblende.

In the lower part of the Coamo augite phenocrysts constitute 15 to 20 percent of the rock but diminish to 5 percent or less in the upper part of the sequence. Most of the augite is fresh, and occurs as rounded phenocrysts (fig. 19*D*), which locally have concentric zones of impurities trapped during growth. Euhedral augite phenocrysts are very rare in the Coamo samp'es studied for this report. Augite(?) also occurs as an abundant constituent of the matrix.

Plagioclase phenocrysts constitute 25 to 60 percent of the rocks and are somewhat more abundant in the upper parts of the sequence. The phenocrysts are euhedral and zoned and have broad albite twins. Carlsbad-albite and pericline twins are common but much less abundant than simple albite twins. Compositions estimated by measuring albite-twin extinction angles range between An_{55} and An_{70}. Plagioclase of somewhat more sodic composition also occurs as an abundant constituent of the matrix.

An intergranular texture is characteristic of the augite andesite. The matrix minerals are pyroxene, plagioclase, and opaque oxides. Amygdules constitute as much as 15 to 20 percent of the andesite and are generally common throughout the Coamo.

AGE

A few fossils have been found in the Coamo Formation in the middle and upper parts of the sequence. Pessagno (1962) reported *Barrettia monilifera* from locality OP–2358 in the bed of the Río Toa Vaca a short distance north of Highway 150. The writer has seen *Barrettia* about 700 meters above the base of the Coamo in south-central Río Descalabrado quadrangle and rare indeterminate benthonic Foraminifera in the mud matrix of a volcanic breccia about 3 km west of Coamo.

The underlying Maravillas Formation is as young as Campanian and possibly as young as Maestrichtian. The unconformably overlying Miramar Formation is Maestrichtian in age. The Coamo Formation could therefore be of Campanian or Maestrichtian age or may range from Campanian to Maestrichtian in age.

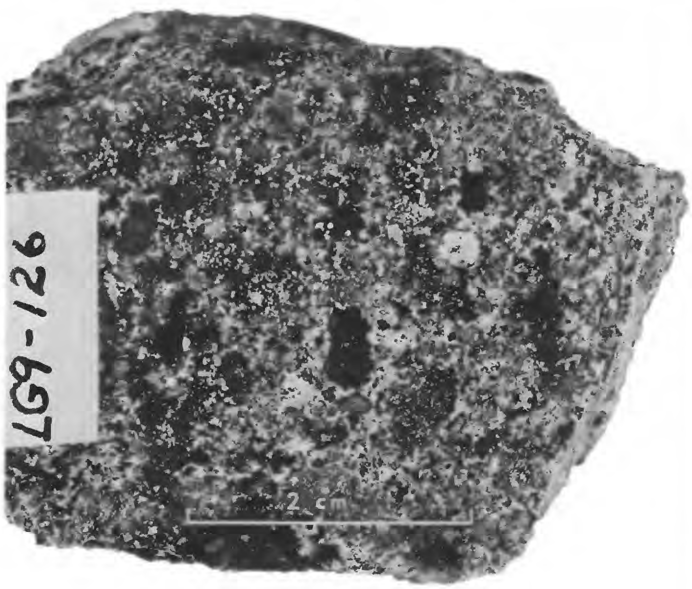
CONDITIONS OF DEPOSITION

The Coamo represents near-vent pyroclastic and effusive material. Many dikes and sills of augite andesite similar to that in the pyroclastic deposits occur in the northern and eastern areas of outcrop in the Coamo area and suggest by their abundance that the source vent or vents were nearby. The Zanja Blanca stock in northeastern Río Descalabrado quadrangle may mark the site of a major vent.

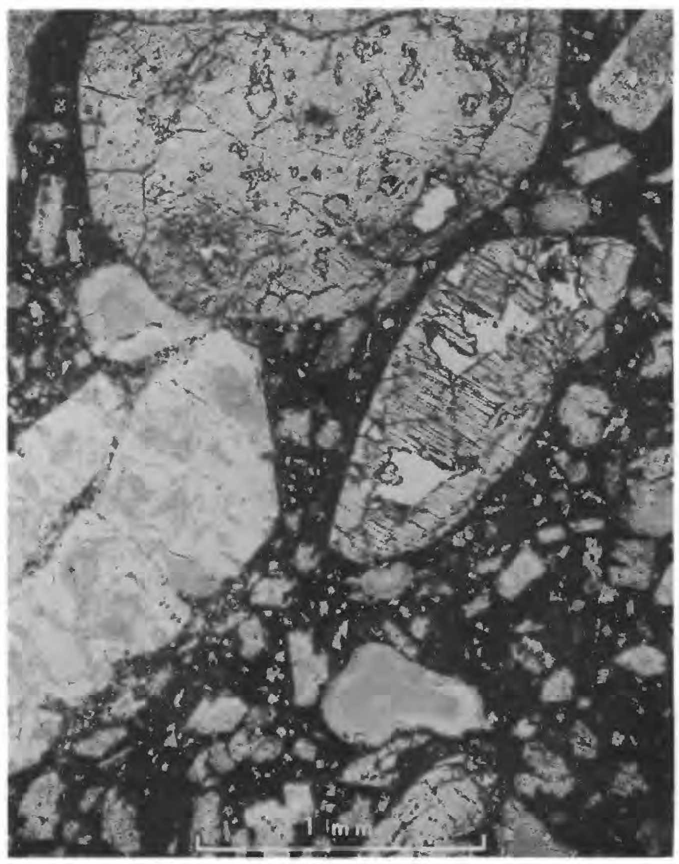
The fossils, though rare, indicate by their stratigraphic distribution that much of the Coamo in the area was deposited in a marine environment. The rare to common red-matrix wacke conglomerates, however, may imply oxidation in a subaerial environment. Their presence in the Coamo suggests near-shore and possibly nonmarine deposition.

A

C



B



D

FIGURE 19.—Rocks of the Coamo Formation: *A*, Typical massive Coamo Formation along Highway 155 north of Coamo. Outcrop is principally pyroxene andesite lava breccia. *B*, Lapilli tuff from the Coamo Formation southeast of Juana Díaz. Rock is poorly sorted feldspathic augite andesite. Light mottling due to prehnite and quartz filling amygdules and interstices and replacing the andesite. *C*, Lava breccia from the Coamo Formation northwest of Coamo. Lighter colored fragments of pyroxene andesite in an igneous matrix of the same general composition. Note dark anhedral augite phenocrysts and scattered amygdules of zeolite. *D*, Thin section of pyroxene andesite lava (LG–1–117), above. The lava had two pyroxenes; a large prismatic euhedral orthopyroxene (?) at the left is now replaced by chlorite and large anhedral (resorbed) augite phenocrysts are at top of photograph. Matrix comprises albitized labradorite, augite, and opaque oxides. Secondary minerals are chlorite and analcime (in amygdules and matrix) albite, calcite, and quartz.

FIGURE 20.—Reworked pyroclastic breccia with red argillaceous matrix; probably a mudflow deposit of weathered ash and gravel. Coamo Formation along Highway 155 just west of Coamo.

CUYÓN FORMATION

The Cuyón Formation was named by Glover (1967) for outcrops along Highway 162 just south of the headwaters of the Río Cuyón in northwestern Cayey quadrangle. These rocks were previously included in the Robles Formation by Berryhill and Glover (1960).

The Cuyón is a heterogeneous formation comprising, from the base upward (1) reddish-gray volcaniclastic rocks, (2) drab reworked tuff with lenses of conglomerate, and (3) limestone. The formation is about 75 meters thick and crops out over an area of about 0.5 sq km. An igneous rock, probably a sill, overlies the limestone that forms the youngest part of the formation exposed in the area; downdip to the west, younger parts of the formation are cut out by a fault. The lower contact has not been observed because of brush and soil cover, but the Maestrichtian age of the formation and apparent absence of several older formations below it suggest that the contact is an unconformity.

The basal reddish- to purplish-gray volcaniclastic rock is obscurely stratified in thin to medium-thick beds. The rock is poorly sorted and contains more than 10 percent fine red silt and clay. Most of the rock is medium to coarse sand of weathered volcanic fragments, and there is a minor amount of very well rounded chert and andesite pebbles. The red unit weathers easily and has not yielded fresh material for study.

Approximately the middle third of the outcropping Cuyón Formation is composed of drab thin- to thick-bedded reworked tuff with lenses of volcanic conglomerate. This is overlain by hard bluish-gray fossiliferous limestone in thin to medium-thick beds interleaved with volcanic sandstone. The northwestern part of the limestone unit has been converted to a skarn by contact metamorphism near the Cuyón intrusive.

The genesis of the basal reddish rock is uncertain from the data at hand. The rock seems to be principally reworked pyroclastic debris deposited in a nonmarine to shallow marine environment. It is similar to rocks in the largely nonmarine Pozas Formation (Berryhill, 1965) of north-central Puerto Rico and to parts of the Miramar Formation of the Coamo area.

AGE

Following are fossil collections made over a period of 8 years from a single locality in the limestone. (Locality: Highway 162, in roadcut 0.7 km NW of intersection of Highways 162 and 1. Puerto Rico meter grid 173,525 N.; 29,970 E.)

Collection 4 (H. L. Berryhill and Lynn Glover): "Detrital limestone composed of partially recrystallized fragments of corals, 'stromatoporids,' and indeterminable molluscs. Only a broken specimen of a specifically indeterminable *Ostrea* could be identified." (N. F. Sohl, written commun., 1957).

Collection USGS 27595 (P. H. Mattson); identifications by N. F. Sohl (written commun., Jan. 7, 1957):

Barrettia sp.
Sauvagesia sp.
Antillocaprina sp.

"In addition there are cross sections of a nerineid gastropod, several pelecypods, a few corals and algae exposed in cut sections. . . . As far as I can recall this is the first *Sauvagesia* from the island but the genus is a long ranging Upper Cretaceous form and of not much help. . . . Age—probably Campanian to Maestrichtian . . ." (N. F. Sohl, written commun., 1960).

Collection USGS 26825 (H. L. Berryhill and Lynn Glover); identifications by N. F. Sohl (written commun., May 18, 1960):

Gastropoda:
- Gerithid, large
- Nerineid, small
- Turriculate molds
- Trochoid molds

Pelecypoda:
- *Trigonia*(?) sp.
- Caprinid fragments—abundant, probably related to *Plagioptychus.*
- Radiolitids—no good cross sections seen; may be a Biradiolitid.

Collection LG-4-196 (Lynn Glover); identifications by E. A. Pessagno (written commun., 1965):

Foraminifera:

Globotruncana stuarti s. s. (de Lapparent)	C
stuartiformis Dalbiez	R
gansseri Bolli	R
contusa s. s. (Cushman)	C
Abathomphalus mayaroensis (Bolli)?	R
Pseudotextularia elegans (Rezhak)?	R

"Stratigraphic determination: Late Maestrichtian/Late Navarroan. *G. contusa—stuartiformis* Assemblage Zone: Upper part of *G. gansseri* Subzone to lower part of *A. mayaroensis* Subzone. Preservation of microfossils poor. . ." (E.A. Pessagno, written commun., 1965).

On the basis of macrofossils studied by Sohl, the age appears to be Campanian to Maestrichtian. According to Pessagno the microfossil assemblage is late Maestrichtian.

The absence of the Cariblanco, Maravillas, and Coamo Formations below the unconformity and the possible Maestrichtian age of the limestone suggest that the Cuyón correlates with the Miramar Formation.

CONDITIONS OF DEPOSITION

The Cuyón Formation probably is a transgressive sequence that begins with a nonmarine volcaniclastic deposit laid down upon a surface of unconformity and that ends with a shallow-water fossiliferous marine limestone.

LATE CRETACEOUS AND EARLY TERTIARY—JACAGUAS GROUP

The Jacaguas Group was named by Pessagno (1961) after the Río Jacaguas near the town of Juana Díaz, west edge of the Río Descalabrado quadrangle. The group has been redefined by Glover and Mattson (1967). Pessagno (1960b) divided the group into two laterally interfingering formations, the western Augustinillo Formation and the eastern Naranjo Formation. All the post-Coamo and pre-middle Tertiary rocks of the Coamo area thus were incorporated into the Naranjo Formation which he subdivided into the following four members: (1) The Miramar Member, (2) the Coamo Springs Limestone Member, (3) the Río Descalabrado Member, and (4) the Guayo Conglomeratic Sandstone Member. Pessagno considered the group to be of early middle Eocene age.

In this report the Jacaguas Group is recognized as comprising all the rocks between the Coamo and Cuyón Formations and the megabreccia and the Juana Díaz Formation in the Coamo area. It is bounded at its base and top by unconformities and is of Maestrichtian to early middle Eocene age. Abundant dacitic quartz-phenocryst-bearing volcaniclastic rocks are probably most characteristic of the group. Of all the rocks in south-central and southeastern Puerto Rico, only Formation A of the Lower Cretaceous pre-Robles sequence contains similar rocks in comparable abundance.

In this report on the Coamo area, the Naranjo Formation is not recognized and the Jacaguas Group is divided into the Miramar, Raspaldo, and Los Puertos Formations, the Cuevas Limestone, and the Río Descalabrado and Guayo Formations as shown on plate 3. In the course of the present study it was discovered that the Jacaguas Group is intensively deformed by gravity gliding. Many units are repeated at the surface several times; rocks of Paleocene age rest upon middle Eocene rocks with a megabreccia of Santonian to Eocene rocks in between, and some large glide sheets are overturned. Because Pessagno's stratigraphy assumed an essentially southward-dipping monoclinal structure for the Jacaguas Group, it differs considerably from the stratigraphic interpretation presented here. Wherever practical this report uses the earlier names, though most are redefined or changed in stratigraphic rank.

MIRAMAR FORMATION

Pessagno (1960b) named the Miramar Member of the Naranjo Formation for outcrops at the base of cliffs about 0.65 km southeast of Hacienda Miramar in southeastern Jayuya quadrangle. At the type locality the Miramar consists of coarse red volcanic wacke conglomerate overlain by the Cuevas Limestone and is in unconformable contact with the underlying Cariblanco Formation (Mattson, written commun., 1962). Pesagno included all rocks between the limestone and the unconformity in the Miramar; thus the tuff breccia at Los Puertos in southeastern Río Descalabrado quadrangle, as well as the thin-bedded brown tuffs and mudstones southeast of Río Jueyes in the Coamo quadrangle, was included. Pessagno considered the Miramar on negative evidence to be early middle Eocene in age. Mattson thought it might be late Paleocene or early Eocene on the basis of some poor specimens of *Globorotalia velascoensis* identified by Otto Renz.

In the Coamo area, the Miramar is considered to be a formation and is restricted to the red generally conglomeratic volcaniclastic rocks (fig. 21*A*) at the base of the Jacaguas Group.

The Miramar crops out in only two places in the Coamo quadrangle: (1) East-southeast of the village of Río Jueyes where it was mapped as Coamo breccia by Glover (1961), and (2) in several small outcrops (not shown on the 1961 map) along the bed of the Río Jueyes about 0.5 km south of the Río Jueyes water gap through the Cuevas Limestone.

In the first area, east-southeast of Río Jueyes, massive grayish-red wacke conglomerate forms most of the outcropping Miramar. The gravel component is principally of cobble size, though a few boulders more than 3 meters in diameter were found. The boulders are of andesite, various kinds of volcanic breccia, and minor limestone. Rudistids and other large pelecypods are a common constituent. The matrix varies from mudstone to tuffaceous mudstone to unsorted breccia. Beta-quartz crystals of volcanic origin are a common minor constituent of the matrix, which seems to range in composition from feldspathic andesite to dacite. Thin-bedded mudstone is a minor constituent of the Miramar in this area, where it occurs interbedded with red breccias. The thickness of the formation in this area cannot be estimated.

In the second area, south of the Río Jueyes water gap, the Miramar consists of grayish-red volcanic wacke conglomerate and grayish-red to drab reworked crystal-vitric tuff. As is characteristic of the Miramar in the Coamo area, these rocks also contain oysters, abundant hematite-red clay, and abundant plagioclase, common quartz, and common biotite crystals in the sand-size fraction. The thickness here also is unknown.

In the Río Descalabrado quadrangle, the Miramar Formation crops out only in the deformed strata south of Cerro de las Cuevas. It is generally grayish red and much less commonly olive gray. Thick-bedded or massive conglomerate composes most of the formation. The finer mudstones and reworked tuffs are thin to thick bedded. Oyster beds, channeling, minor crossbedding, and common but small thin magnetite concentrations are characteristic sedimentary features. Graded bedding is rare to common.

The conglomerate consists of subrounded to well-rounded gravel in a well-sorted to poorly sorted volcaniclastic matrix. Cobbles and pebbles are most common, but locally the gravel is as coarse as small boulders about half a meter in diameter. The gravel is composed mostly of feldspathic andesite and a small amount of limestone and calcareous mudstone. The matrix is generally a reworked crystal-vitric tuff with abundant plagioclase crystals and a trace to 25 percent beta-quartz crystals. From a trace to about 20 percent red mud is present.

The reworked tuffs are similar to the matrix of the conglomerates, and in addition to the plagioclase, quartz, magnetite and red clay, accessory amounts of the following also occur: Biotite (trace to 10 percent), a trace of hornblende, montmorillonite after glass, fragments of plagioclase-rich andesite, fragments of epidote of accidental pyroclastic origin, and chlorite in the matrix and in vesicles. Secondary minerals (fig. 21*B*) include abundant laumontite filling interstices in the rock and replacing plagioclase, common secondary albite, rare to common(?) heulandite(?), abundant secondary calcite, rare malachite, and rare celadonite(?).

OYSTER-BEARING LIMESTONE

An unnamed thick-bedded to massive limestone with abundant oysters, grown one upon another, occurs as thin unmapped lenses in the Miramar and as a mapped unit found near the top of the formation in the Río Descalabrado quadrangle. Yellowish-gray micrite with Foraminifera and algae commonly occurs between the oyster shells which form the bulk of the limestone. The reeflike mass generally is about 7 or 8 meters thick. In and just below the upper oyster limestone at many localities, one finds rudistids, radiolitids, and other pelecypods. Very little reworking is indicated by the condition of the shells. One specimen of *Barrettia* has a large part of its outer shell layer still intact.

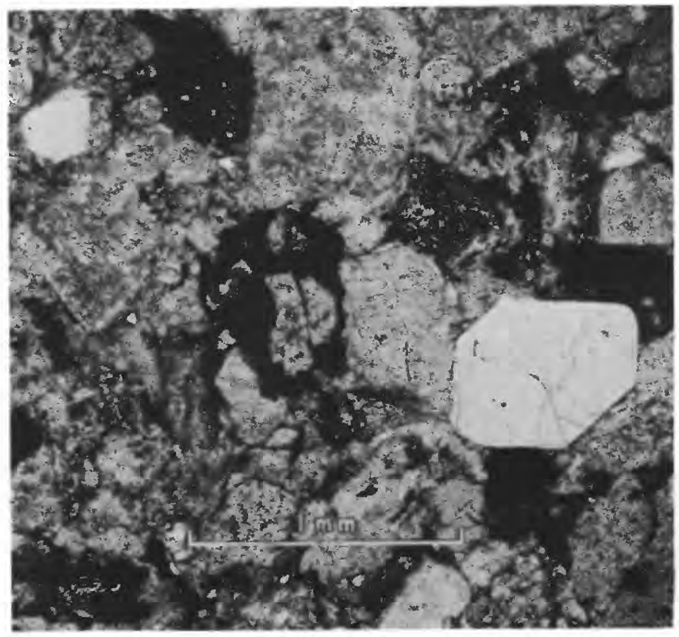
CONTACT RELATIONS AND THICKNESS

In the Río Descalabrado quadrangle, the basal contact of the Miramar is believed to be faulted everywhere. In the area just west of Cuatro Calles, the Miramar is probably in fault contact with the underlying Coamo Formation, but it is uncertain whether much of the section is missing. Possibly the contact there is a surface of unconformity along which gliding has taken place.

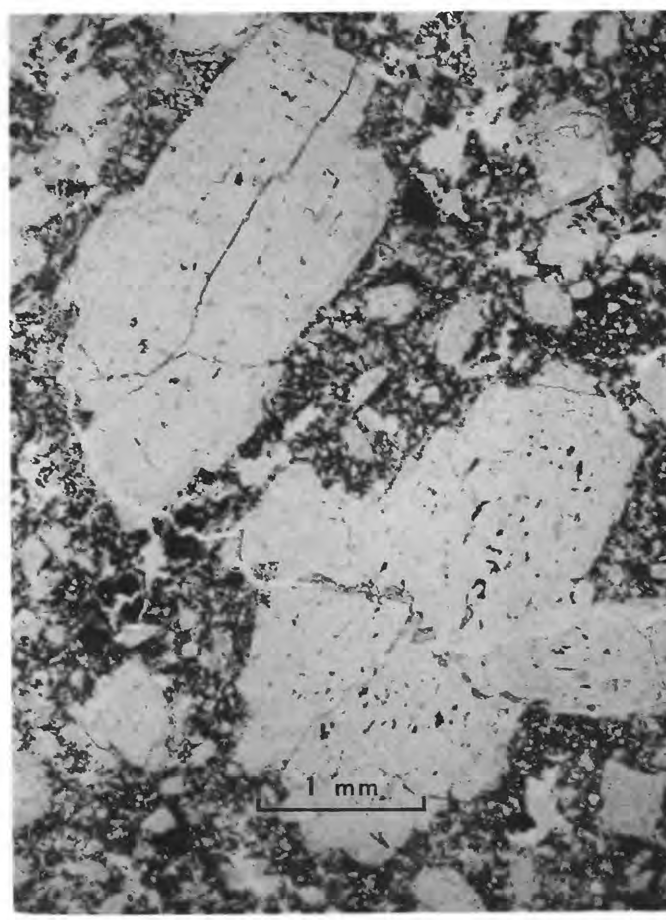
The upper contact is also generally faulted, but just north of Cuatro Calles, the oyster limestone at the top of the Miramar Formation seems to be conformably overlain by the Raspaldo Formation of Paleocene and early Eocene age.

Because of structural complications, the thickness of the Miramar is difficult to estimate. North of Cuatro

A



B



C

FIGURE 21.—Rocks of the Miramar and Los Puertos Formations: *A*, Reworked lapilli tuff from the Miramar Formation. Rock is grayish red, mottled white by zeolites. Fragments are subrounded and there is little clay- or silt-size material. Voids between fragments are filled with laumontite. *B*, Dacite tuff from the Miramar Formation. Quartz crystals and altered plagioclase and lithic fragments. Section shows typical zeolitic alteration of coarse feldspathic tuffs. Only quartz remains of the primary minerals. The remainder of the rock is composed of laumontite, albite, quartz, and clay minerals. *C*, Los Puertos Formation. Typical feldspathic andesite of the massive tuff breccia facies. Sample LG–9–91, at Los Puertos.

Calles, along the headwaters of the Río Cañas, about 700 meters of the conglomeratic formation seems to be exposed. This estimate assumes no duplication by faulting and negligible initial dip. Both assumptions may be somewhat in error, and in addition the section is incomplete. To the northwest, Mattson (1966) found that the Miramar varied greatly in thickness because it was deposited on an erosion surface of considerable relief. Prior to faulting, similar relations probably existed in the Coamo area.

The stratigraphic position of the Miramar seems well established by its locally conformable relationship beneath the Paleocene Raspaldo Formation of Paleocene and early Eocene age. The validity of this relationship is strengthened by the Maestrichtian fossils from the Miramar identified by Norman F. Sohl. The unfaulted basal contact will probably not be found in the Coamo area, but the age, distribution, and sedimentary facies strongly suggest that the Miramar rests unconformably upon older rocks throughout south-central Puerto Rico.

AGE

The following fossil collections were identified by Norman F. Sohl of the U.S. Geological Survey.

Miramar Formation (east-southeast of Río Jueyes, Coamo quadrangle:
  Collection LG–57–258 (USGS 26836), Puerto Rico meter grid 165,550N.; 20,350E.:
    Pelecypoda:
      Barrettia monilifera Woodward
        gigas Chubb?
      Durania cf. *D. nicholasi* (Whitfield)
      Titanosarcolites sp.
      Antillocaprina? cubensis (Douville)
      Parastroma sanchezi
      Thyrastylon adhaerens (Whitfield)
      Caprinid indet.
    Corals
    Age: Maestrichtian
  Collection LG–57–255 (USGS 26846), Puerto Rico meter grid 163,700N.; 21,025E.:
    Pelecypoda:
      Titanosarcolites cf. *T. giganteus* (Whitfield)
      Durania cf. *D. nicholasi* (Whitfield)
      Hippurites (*Orbignya?*) sp.
      Thyrastylon sp.
      Caprinid indet.
    Corals
    Age: Maestrichtian
  Collection LG–9–114 (USGS 27593), Puerto Rico meter grid 19,100N.; 167,604E.:
    Pelecypoda:
      Praebarrettia coralli (Palmer)
      Barrettia monilifera Woodward
      Durania nicholasi (Whitfield)?
      Antillocaprina? sp (fragments)
      Titanosarcolites? sp. (fragments)
      Plagioptychus sp.
      Thyrastylon cf. *T. coryi* (Trechmann)
    Age: Probably Maestrichtian
Miramar Formation, Río Descalabrado quadrangle:
  Collection LG–9–8 (Cenozoic colln. 21917), Puerto Rico meter grid 23,700N.; 149,050E.:
    Pelecypoda:
      Titanosarcolites giganteus (Whitfield)
    Age: Maestrichtian
  Collection LG–9–9 (Cenozoic colln. 21918), Puerto Rico meter grid 23,775N.; 14,905E.:
    Pelecypoda:
      Ostrea (*Lopha?*) sp.
    Age: Indeterminate
  Collection PM–9–27 (USGS 27604), Puerto Rico meter grid 21,585N.; 154,430E.:
    Algae
    Corals
    Gastropoda:
      Nerinea? sp.
      Turriculate gastropod indet.
    Pelecypoda:
      Thyrastylon adhaerens (Whitfield)
    Age: Maestrichtian?
Miramar Formation, Río Descalabrado quadrangle—Continued
  Collection PM–253 (USGS 27594), Puerto Rico meter grid 21,585N.; 154,370E.:
    Pelecypoda:
      Durania nicholasi (Whitfield)
      Durania? sp.
    Age: Probably Campanian-Maestrichtian
  Collection LG–9–171 (USGS 27597), Puerto Rico meter grid 23,500N.; 150,750E.:
    Pelecypoda:
      Antillocaprina occidentalis (Trechmann)?
      Durania nicholasi (Whitfield)
      Pironea? or *Praebarrettia* sp.
      Barrettia monilifera Woodward
      Thyrastylon cf. T. adhaerens (Whiltfield)?
      Ostrea sp.
    Gastropoda:
      Turriculate gastropod
    Age: Maestrichtian
  Collection PM–9–232 (USGS 27599), Puerto Rico meter grid 23,490N.; 151,350E.:
    Pelecypoda:
      Antillocaprina? sp.
      Thyrastylon or *Biradiolites*
      Radiolitid fragments, indet.
    Algae?
    Age: Campanian-Maestrichtian

Judging from these collections, the age of the Miramar Formation is Maestrichtian in the Coamo area, elsewhere ranging into the Tertiary to the northwest.

The Miramar is correlative in age and similar in many aspects of composition to the San Germán Formation (Mattson, 1960) of the Mayagüez area in southwestern Puerto Rico. Both the Miramar and the San Germán formations apparently rest unconformably upon older rocks.

CONDITIONS OF DEPOSITION

As elsewhere in the Coamo area, an abundance of red clay suggests derivation from a deeply weathered subarerial source. The Miramar is the initial deposit laid down on a folded, intruded, and deeply eroded Late Cretaceous surface. Nevertheless, the abundance of slightly reworked ash of dacitic composition shows that most of the formation is composed of coeval pyroclastic debris rather than epiclastic material from older formations.

Much as the Achiote Conglomerate, the Miramar seems to be a subaerial fanglomorate and shallow-water marine deposit. It is not found north of the Río Jueyes fault where the younger Cuevas Limestone overlaps older rocks. The restored stratigraphic relations are shown on the structural cross sections (pl. 4). The Miramar is probably overlapped by the Los Puertos and Cuevas Formations along a scarp of the Late Cretaceous Río Jueyes fault.

LOS PUERTOS FORMATION

Massive tuff breccia and conglomeratic breccia and tuff southeast of Los Puertos, in the southeastern part of the Río Descalabrado quadrangle, was named by Glover and Mattson (1967, p. 36–37) the Los Puertos Formation. At the type locality, the base of the formation is concealed by faulting, and the top is disconformably overlain by the Cuevas Limestone. Along the west side of the Coamo River valley, about 350 meters of Los Puertos crops out between the Río Jueyes fault on the north and the Cuevas Limestone to the south.

At the type locality, the formation comprises grayish-red-purple to pale-brown somewhat reworked tuff breccia, lapilli tuff, and minor tuff. Conglomeratic units are less abundant. The formation is typically massive or thick bedded. Fragments are feldspathic andesite (fig. 21*C*), and pyroxene- and hornblende-bearing andesite set in a finer matrix of similar material, which commonly has a component of red mud. Fragments of limestone are rare. Locally allochem-bearing reworked dacitic tuff with quartz crystals occurs interbedded with the massive andesitic units. Interbeds of graded fine-grained tuffaceous mudstones contain many coalified wood fragments as well as planktonic Foraminifera of Paleocene age.

The Los Puertos has been mapped just north of the fault at Los Puertos as a succession of intricately deformed glide sheets comprising similar coarse pyroclastic rocks, tuffaceous mudstones, and, in addition, a lens of medium-bedded gray fine-grained limestone.

The formation has also been mapped at the base of the Cuevas Limestone as far west as the Río Descalabrado. West of the river, the geologic map does not indicate the Los Puertos beneath the structurally lowest and northernmost outcrops of the Cuevas Limestone. This is because the massive Los Puertos is very similar to the older feldspathic andesites of the Coamo Formation, and wherever the finer dacitic interbeds were not seen, it was difficult or impossible to separate the two formations in the field. The writer considers it possible that the Los Puertos does extend toward the northwest beneath the Cuevas Limestone, and that it is separated from the Coamo Formation by an obscure unconformity.

East of the Río Coamo in southwestern Coamo quadrangle, the Los Puertos is finer grained and somewhat more conglomeratic. Thick-bedded and massive conglomeratic reworked tuff and lapilli tuff are characteristic. The gravel fraction consists mostly of small pebbles, but cobble-bearing beds are common, and more rarely one finds boulders. The gravel is composed of well-rounded andesite, limestone, and very well rounded fragments of rudistids (especially *Barrettia*) reworked from Cretaceous strata. The matrix is reworked tuff made up of abundant plagioclase, common chloritized vitric clasts, common to rare quartz, rare augite and hornblende, and rare biotite, along with varying small amounts of coalified woody material and allochems. Interbedded with the coarse conglomeratic tuff generally are thin beds of tuffaceous mudstone containing planktonic Foraminifera.

This conglomeratic facies is intermediate in position and texture between the coarse angular tuff breccia of the type area and the thin- to medium-bedded tuffaceous Raspaldo Formation with which it interfingers toward the east. Because of its massive to thick-bedded nature and limited distribution in outcrop, it is herein included with the Los Puertos Formation.

AGE

An interbed of tuffaceous mudstone just north of Cerro de las Cuevas along the west side of the Río Coamo contains the following foraminiferal assemblage, according to Jeremy Reiskind (written commun., 1962).

Collection JR—2–31, Puerto Rico meter grid 158,400 N.; 21,800 E.:
Globigerina daubjergensis
triloculinoides (abundant)
Globorotalia pseudobulloides (abundant)
compressa
Age: early Paleocene (*Globorotalia trinidadensis* zone of Bolli, (1957))

CONDITIONS OF DEPOSITION

The facies changes from the thin-bedded tuffs of the Raspaldo Formation near Río Jueyes on the east to the Los Puertos conglomeratic tuff and lapilli tuff east of the Río Coamo and finally to the tuff breccia and lapilli tuff of the Los Puertos west of the Río Coamo indicate that the local center of Paleocene volcanism lay north or northwest of Los Puertos. Rocks of similar age south of the Los Puertos area are also of the thin-bedded and fine-grained facies of the Raspaldo Formation.

The very well rounded rudistid fragments seem to have been reworked from the Miramar Formation or possibly from the Maravillas Formation. Such shallow-water fossils are commonly found in the Coamo area only where they have been reworked and transported from coeval high-energy environments to low-energy environments of deposition, and therefore nearly all rudistids show some rounding. The high degree of rounding shown by the Los Puertos fossils, however, is rare. Reworking from older formations is suggested by the occurrence of a Paleocene planktonic fauna in the formation. Thus, the rudistids are here considered to be an epiclastic contribution from Cretaceous rocks. Nevertheless, additional work may show that some

Cretaceous(?) rudistids and Paleocene(?) Foraminifera overlapped in time in the Coamo area.

The Los Puertos seems to be entirely marine and largely deposited below wave base by ash falls, turbidity currents, and possibly submarine sliding.

RASPALDO FORMATION

The Raspaldo Formation was named by Glover and Mattson (1967, p. 37) for a sequence of dominantly thin-bedded volcaniclastic rocks north of Cerro Raspaldo in central-southern Coamo quadrangle. These rocks were mapped as part of the Coamo Formation by Glover (1961a) and were thought to be of Cretaceous age because of the rudistids they contain.

RASPALDO FORMATION IN THE TYPE AREA

The base of the formation is not exposed in the Coamo quadrangle. In the type area, the oldest beds are in fault contact with the Miramar Formation south of the Río Jueyes fault. Phenomena along the fault, discussed in connection with gravity sliding (p. 87), indicate that parts of both formations were plastic or even fluid at the time of faulting. The structural cross sections (pl. 4) indicate that a large part of the basal Raspaldo Formation may have been faulted from its type area. The top of the Raspaldo is probably in disconformable contact with the Cuevas Limestone just below the crest of Cerro Raspaldo. The contact, however, was not seen because of talus cover. The Raspaldo grades westward along strike into the conglomeratic tuffs of the Los Puertos Formation.

Contact relations and structure of the Raspaldo are such that an exact thickness is impossible to measure. The minimum thickness exposed in the type area is estimated to be 600 meters.

In the type area the Raspaldo Formation is principally composed of tuffaceous mudstone, mudstone, and tuff. Less common are tuffaceous conglomerate, siliceous argillite, and very fine grained vitric tuff. The fine-grained rocks are light olive gray, yellowish gray, and moderate yellowish brown after slight weathering, and the coarse-grained rocks are similarly colored but are generally speckled with olive green, brown, and red. Rarely does one find pale-bluish-green vitric tuff.

Graded bedding is abundant (fig. 22*A*), and small-scale crossbedding (fig. 22*B*) is common.

The mudstones and tuffaceous mudstones are thin- to medium-bedded rocks similar to those in the Maravillas Formation. In general they tend to be lighter colored and less well indurated, and they probably contain a more felsic mineral suite than similar rocks of the Upper Cretaceous sequence.

The tuffs are thin to medium bedded, commonly reworked, and in graded beds. They are felsic rocks containing abundant plagioclase and 5 to 20 percent crystals of quartz. Felsic vitric-crystal fragments (plagioclase phenocrysts An_{30-52}) are common to abundant in the coarser tuffs and lapilli tuffs. Magnetite-rich layers are common and biotite crystals are rare. Allochems including pelecypod shell fragments, calcareous red algae, and Foraminifera are mixed through the reworked tuffs and are involved in the grading.

The tuffaceous conglomerate and conglomeratic tuff is similar in matrix to the tuff described above, but contains well-rounded cobbles of dacite, andesite, and limestone. Well-rounded fragments of *Barrettia* and other large rudistids are rare to common constituents of the gravel. Some of the conglomerate is a veritable wildflysch of Cretaceous conglomerate, tuff breccia, and limestone blocks in a matrix of felsic reworked tuff. Some of the conglomerates are turbidites; others, such as the wildflysch are ungraded and probably resulted from submarine sliding.

Minor amounts of hard thin- to medium-bedded laminated siliceous argillite possibly resulted from the alteration of a very fine grained vitric tuff. When somewhat weathered, these rocks are grayish dusky yellow. Quartz, minor plagioclase, and a clay mineral were identified by X-ray diffraction as the principal minerals of the argillite.

AGE

Two fossil collections from the Raspaldo Formation type area were studied by Reiskind (1962). The first, JR–1–48, is near the base of the outcropping sequence just east of Río Jeuyes. The second, LG–1–51, is from near the top of the Raspaldo just north of the southern end of Cerro Raspaldo. The fossils were recovered from mudstones that are interbedded with rudistid-cobble-bearing conglomerate at both localities. Although the rudistids have probably been reworked from older formations, the possibility that they were merely redeposited from a coeval habitat of higher energy cannot completely be discounted. With this qualification, the age herein accepted is that indicated by the Foraminifera. The numbers in the fossil list refer to the number of specimens identified.

Collection JR–1–48, Puerto Rico meter grid 163,700 N.; 20,800E.:

Bulimina petroleana	A
Gyroidina beisseli	
Eponides bronnimanni	C
Globigerina triloculinoides	A
Globigerinoides daubjergensis	C
Globorotalia compressa	R
pseudobulloides	A
Cibicides praecursorius	A

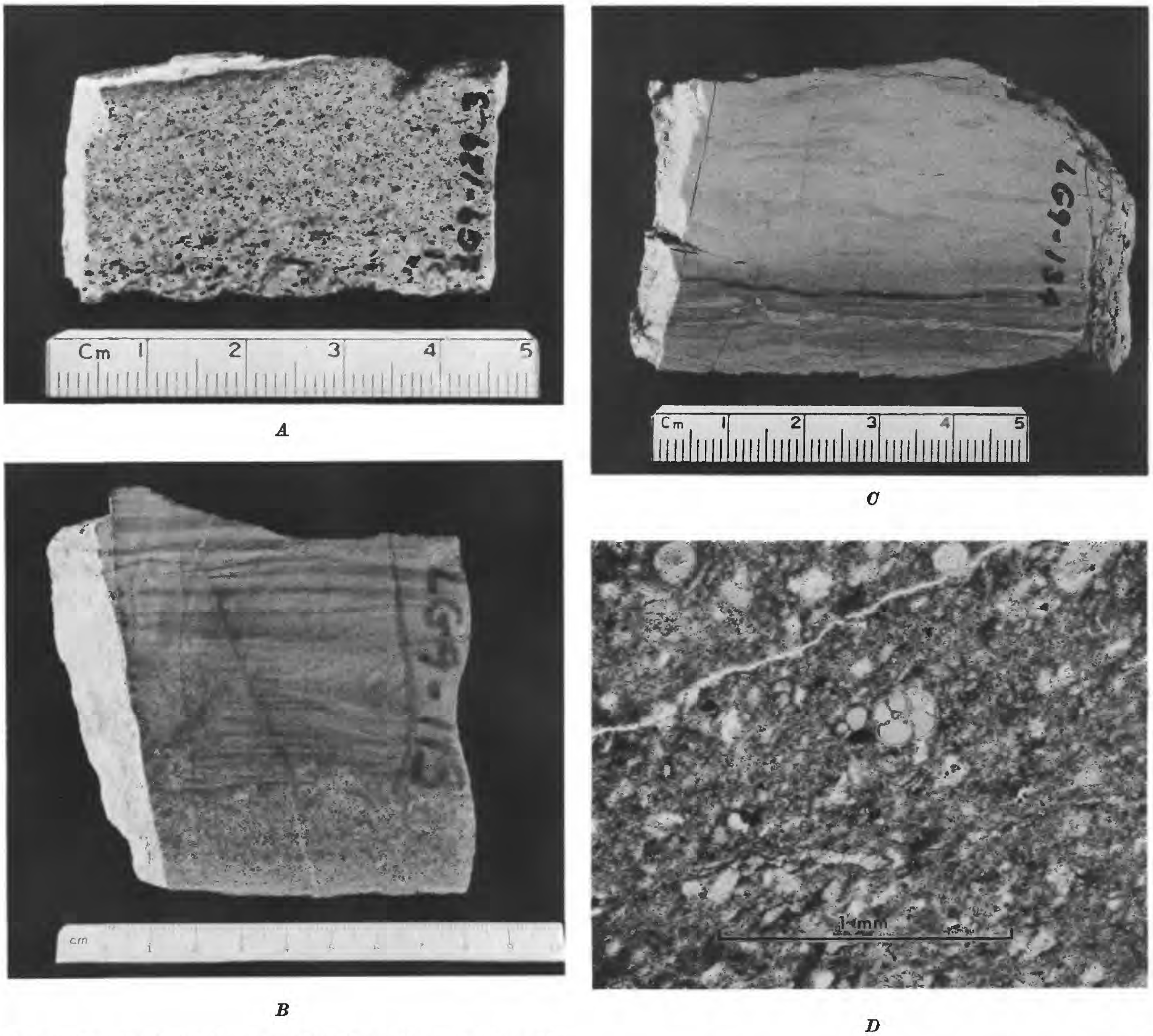


FIGURE 22.—Rocks of the Raspaldo Formation: *A*, Raspaldo Formation near Cuatro Calles, Río Descalabrado quadrangle. Dacite quartz-plagioclase crystal-vitric tuff showing graded bedding. Dark fragments are accidental pieces of older volcanics and vitric fragments replaced by celadonite. *B*, Raspaldo Formation, south edge of Coamo quadrangle. Small-scale crossbedding from top of a graded bed of reworked dacite tuff. *C*, Raspaldo Formation at Cuatro Calles, Río Descalabrado quadrangle. Tuffaceous mudstone showing wisp structure probably formed by thixotropic disruption of bedding. *D*, Raspaldo Formation, sample LG–9–134–2 from Cuatro Calles, Río Descalabrado quadrangle. Same as *C*. Thin section, analyzer out. Planktonic Foraminifera in tuffaceous mudstone.

Collection LG-1-51, Puerto Rico meter grid 166,100 N.; 18,800 E.:

Robulus discrepans	3
Globulina prisca	1
Sigmomorphina semitecta var. *terquemiana*	1
Chiloguembelina sp	3
Bulimina petroleana	A
Bulimina (Desinobulimina) quadrate	4
(Desinobulimina) suteri	1
Gyroidina globosa	a few
beisseli?	
Eponides bronnimanni	C
Globigerina triloculinoides	A
Globigerinoides daubjergensis	C
Globorotalia compressa	R
pseudobulloides	A
Anomalina praespissiformis	A
Cibicides praecursorius	A

On the basis of these two collections Reiskind (written commun., 1962) concluded that the enclosing beds were of early Paleocene age (". . . Danian, probably late Danian . . .")

RASPALDO FORMATION IN THE RÍO DESCALABRADO QUADRANGLE

The Raspaldo crops out in south-central Río Descalabrado quadrangle in what seems to be a single allochthonous block which was subsequently broken by the west-northwest-trending Las Ollas fault. The base of the Raspaldo is in contact with the oyster-bearing limestone of the Maestrichtian Miramar Formation. This contact between the massive or thick-bedded Miramar and the generally thin-bedded Raspaldo is a marked physical discontinuity; hence it is usually but not always a surface of detachment. Because of erosion, the upper contact of the formation is not exposed in the Río Descalabrado quadrangle.

Tuffs and mudstones (figs. 22*A*, *C*; 23*A*) predominate in these outcrops of the Raspaldo. Less common are intraformational conglomerates (fig. 24*A*) and breccia conglomerates, lithified foraminiferal ooze, and thin extensive beds of limestone. In general, the Raspaldo Formation is a markedly thin- to medium-bedded unit, with abundant graded bedding and common small-scale crossbedding and primary slump features.

Crystal-vitric tuffs (fig. 23*B*) are olive gray to light olive gray speckled with a small amount of bright green and reddish brown. Some are pale yellowish brown and light reddish brown. These rocks are common in graded thin- to medium-bedded units with small-scale crossbedding and soft-sediment deformation features. Crystal-vitric tuffs are medium to coarse grained with angular to subrounded fragments. The degree of roundness attributable to reworking varies considerably, but the composition is relatively constant. The amount of allochemical material in the tuffs seems to increase with increasing degree of muddiness. Primary crystalline debris includes a maximum of 30 percent plagioclase (generally fresh but locally replaced by analcime), 1 to 10 percent quartz, common magnetite, rare clinopyroxene, rare hornblende, rare biotite, a single crystal of sanidine(?) (in a tuff slide from the Río Descalabrado outcrops), and some felsic porphry fragments. Accidental pyroclastic or epiclastic epidote occurs in two samples. Vitric constituents are common as pieces of reddish-brown scoria and vitric fragments altered to smectite (probably montmorillonite), nontronite, and nontronitic montmorillonite(?), celadonite, analcime (fig. 23 *C*, *D*), albite, quartz, and calcite. Allochemical constituents, principally mollusk and algal debris, are common.

The vitric and vitric-crystal tuffs are generally thick bedded to massive. Locally, as in the banks of the Río Cañas south of Highway 14, the vitric tuffs are also thin- to medium-bedded and rarely show grading and small-scale crossbedding. Shard structures are in places very well preserved. Vitric tuffs are very pale bluish green to light greenish gray overall and are mottled white in detail. Less common are olive-gray to olive-green vitric tuffs. Coarse-grained vitric tuffs in thin section generally show vesicular glass altered to as much as 40 to 50 percent analcime, 40 percent smectite, and about 10 percent other material, including pyroclastic crystals of plagioclase and quartz and secondary quartz (fig. 23 *B*, *C*). The plagioclase crystals are generally fresh or moderately replaced by analcime. Calcite cement is common, and in some rocks calcite replaces the alteration products of glass. Some very fine grained vitric tuffs are known from X-ray diffraction analysis to be composed principally of albite, quartz, smectite, and calcite. In such cases, the lack of zeolite development may be due in part to extremely low permeability to water.

Mudstone (fig. 22*C*, *D*) probably is the third most abundant rock type in the Raspaldo Formation of the Río Descalabrado quadrangle. Upon moderate weathering these rocks vary widely in color from brownish gray to light olive gray or yellowish gray. Less commonly they are brownish black to dusky red, grayish red, or even pale red. The mudstones are thin to thick bedded and break with a subchoncoidal fracture. Rarely are they thinly laminated or subfissile shales. In thin section they are seen to contain Foraminifera (largely planktonic forms) and a small amount of ash in a clay-or fine silt-size recrystallized matrix. The fine fraction probably represents a mixture of vitric ash and pelagic clay, but the glass is now altered and there is no practical way to determine the original proportions of these materials. By X-ray diffraction analysis, most of these rocks are composed of albite, quartz, calcite, smectite, and, in two samples, heulandite and laumontite, respectively.

Intraformational breccias and breccia conglomerates (fig. 24*A*) constitute a minor but distinctive rock type. These thick-bedded to massive rocks are very coarse, containing blocks as large as half a meter in greatest diameter. They are varicolored in tones of olive gray, light bluish green, and light gray. Imperfect grading occurs locally, but the subrounded to angular blocks are poorly sorted and occur in an unsorted matrix of similar but finer material. All the blocks are of rock types found elsewhere in the Raspaldo Formation in well-bedded units. They include green vitric tuff and grayish-green silicified tuff, brownish-gray tuffaceous mudstone, and lumps of bluish-green celadonite-bearing(?) clay. The matrix contains all the above, plus crystals of quartz and plagioclase in an unsorted mudstone. Locally, large irregular fractures are filled with white colloform quartz. An articulated pelecypod was found in the matrix at one locality. These breccias probably originated as submarine fault scarp talus following periods of intermittent faulting.

Lithified plankton ooze (foraminiferal biomicrite) with partially recrystallized micrite matrix and planktonic Foraminifera tests is a rare rock type in the formation.

Limestone (Trl) makes up less than 5 percent of the Raspaldo Formation. It consists of light-olive-gray to medium-light-gray biomicrite and occurs as units commonly about 3 meters thick. As shown on the geologic map (pl. 2), this limestone occurs at two and possibly three stratigraphic levels. It is medium to thick bedded, rarely massive. Some allochems are in the size range of fine pebbles. The allochemical constituents of the biomicrite are principally fragments of calcareous red algae, mollusc shell, echinoid spines, Foraminifera, and sponge spicules. There are rare to common pebbles of red and green volcanic rocks and crystals of plagioclase and quartz. Celadonite is a common replacement of glass fragments. In places the fine micrite matrix contains enough green clay to color the limestone.

The partial thickness of the Raspaldo Formation as exposed in the south limb of the syncline through Cuatro Calles is estimated to be about 400 meters.

AGE

The age estimate of the Raspaldo Formation in the Río Descalabrado quadrangle is based upon its conformable relationship to the underlying Miramar Formation of Maestrichtian age, and upon two collections of Foraminifera from the youngest(?) part of the outcropping Raspaldo just east of Cuatro Calles. According to Jeremy Reiskind (written commun., 1962), the two collections contain the following Foraminifera:

Collection JR–2–13, Puerto Rico meter grid 151,250 N.; 22,950 E.:

Globigerina triloculinoides	A
soldadoenis	
Globorotalia aequa	A
velascoensis	A
apanthesma	

Age: latest Paleocene (*Globorotalia velascoensis* zone of Bolli, 1957)

Collection JR–2–14, Puerto Rico meter grid 151,320 N.; 22,930 E.:

Globigerina triloculinoides	A
soldadoensis	
Globorotalia aequa	A
wilcoxensis	
elongata (two poor specimens)	

Age: earliest Eocene (*Globorotalia rex* zone of Bolli, 1957).

Reiskind noted that in both collections *Globigerina triloculinoides* may be *G. inaequispira*. The two species are very similar except for surface ornamentation which is poorly preserved in the specimens he observed.

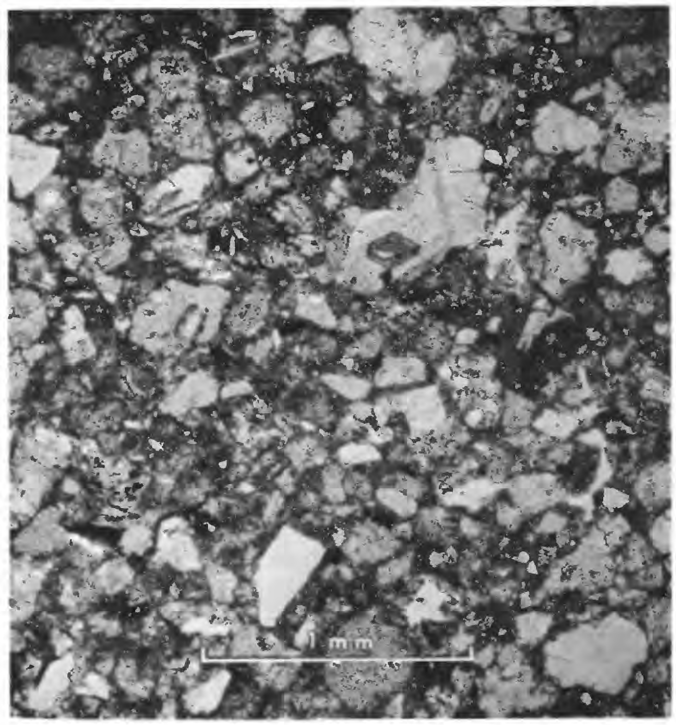
From these data it is concluded that the Raspaldo Formation of the Río Descalabrado quadrangle probably ranges in age from Maestrichtian(?) to earliest Eocene.

SUMMARY AND CONDITIONS OF DEPOSITION

The differences between the Raspaldo Formation of the Coamo and Río Descalabrado quadrangles are herein attributed to minor facies variation in a homotaxial unit. Because of structural deformation it is not possible to demonstrate beyond all doubt that homotaxis is justified, but the stratigraphic, lithologic, structural, and paleontologic data are compelling evidence.

The Raspaldo is principally a sequence of thin- to medium-bedded tuffs and mudstones deposited by ash falls, turbidity currents, mudslides, and pelagic sedimentation below wave base and probably under open-sea conditions. It grades westward and northward(?) into the coarse volcanic breccias of the Los Puertos Formation in southeastern Río Descalabrado quadrangle. The eruptive source of both formations may have lain northwest of the Río Descalabrado quadrangle.

A



B

FIGURE 23.—Rocks of the Raspaldo Formation: *A*, Raspaldo Formation near Cuatro Calles, Río Descalabrado quadrangle. Interbedded crystal-vitric tuffs and tuffaceous mudstone. *B*, Raspaldo Formation, sample LG–9–112–1, just north of Río Jueyes, Coamo quadrangle. Typical quartz-hornblende-plagioclase crystal-vitric tuff of dacitic composition. *C*, Raspaldo Formation, dacite crystal-vitric tuff, plane-polarized light. Sample LG–9–130–3, just south of Cuatro Calles, Río Descalabrado quadrangle. Fresh quartz and plagioclase crystal in vitric ash largely replaced by analcime (clear) and montmorillonite (light gray). *D*, Same; Raspaldo Formation sample LG–9–130–3 (crossed nicols). Note almost complete extinction of originally vitric groundmass because of replacement by the isotropic zeolite analcime.

The eruptive mechanism seems to have rather efficiently fractionated the pyroclastic debris according to composition. The quartz-poor coarse andesitic material of the Los Puertos grades laterally imperceptibly into the quartz-rich finer grained dacitic material of the Raspaldo Formation. The continuous gradient in particle size and composition suggests that perhaps both andesite and dacite were erupted from the same source area, but that the dacitic eruptions were more explosive, resulting in finer material deposited at greater distances from the vent.

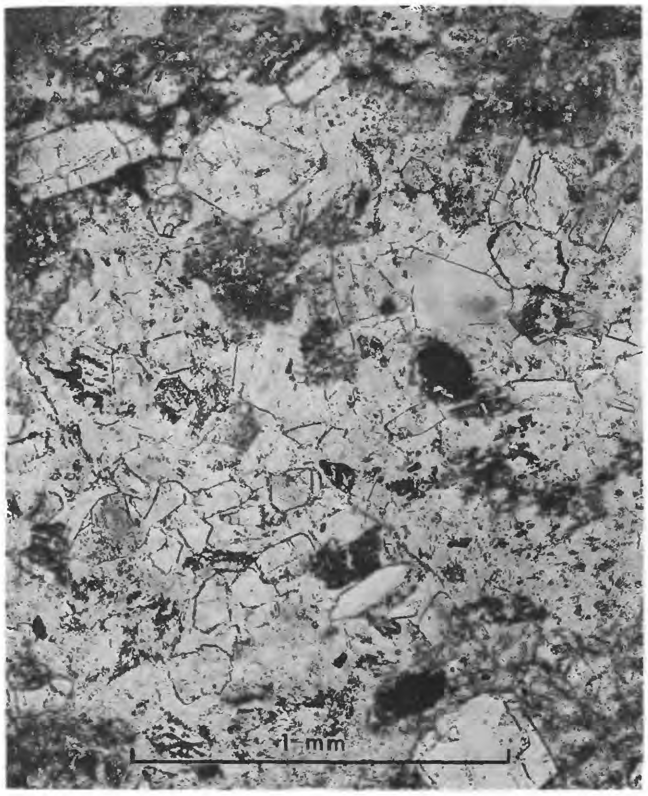
CUEVAS LIMESTONE

The Cuevas Limestone was named by Glover (1961a) for outcrops on Cerro de las Cuevas (fig. 25) in southwestern Coamo quadrangle. The Cuevas is almost synonymous with the Coamo Springs Limestone series of Hodge (1920, p. 153). Hodge (p. 153, 162) referred to the "Coamo Springs group," "Coamo Springs limestone series," and "Coamo Springs formation" as a body of interbedded tuff and limestone that grades upward and downward into tuff. According to Hodge (p. 153), "This series is named from a thermal spring located in the Coamo River Water Gap." These springs were known then as now Baños de Coamo (Coamo baths) and this name is shown on Hodge's map.

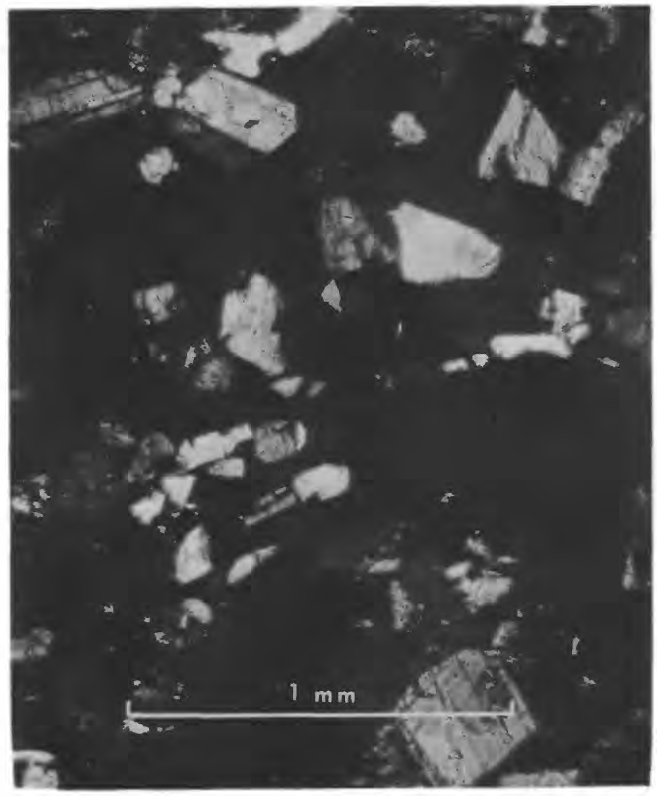
Pessagno (1960b) chose Coamo Springs Limestone as the variant to revive and considered it a member of his Naranjo Formation. The Baños are located about three-fourths of a mile from the nearest outcrop of the limestone, and in the absence of a type area designated by Hodge, Pessagno chose the northwestern end of Cerro de las Cuevas, Río Descalabrado quadrangle. Pessagno (p. 77) also extended the names to lenses of limestone "throughout the Descalabrado member" (Miramar, Raspaldo, and Río Descalabrado Formations of this report).

In this report, the name Cuevas Limestone is continued because:

1. Hodge's names varied in his report, were incorrectly translated from the Spanish, and, according to the modern Stratigraphic Code (American Commis-



C



D

sion on Stratigraphic Nomenclature, 1961, Article 12d), should not be translated. To the writer's knowledge, "Coamo Springs" is not a recognized geographic entity.

2. Over much of the area of outcrop, fully half the rock included by Hodge and Pessagno in the "Coamo Springs" is volcaniclastic rock belonging to other formations. Neither recognized that the sequence was one of repetition by gravity gliding. Thus, under the modern stratigraphic code, extensive redefinition of the formation would make it necessary to choose another name anyway.

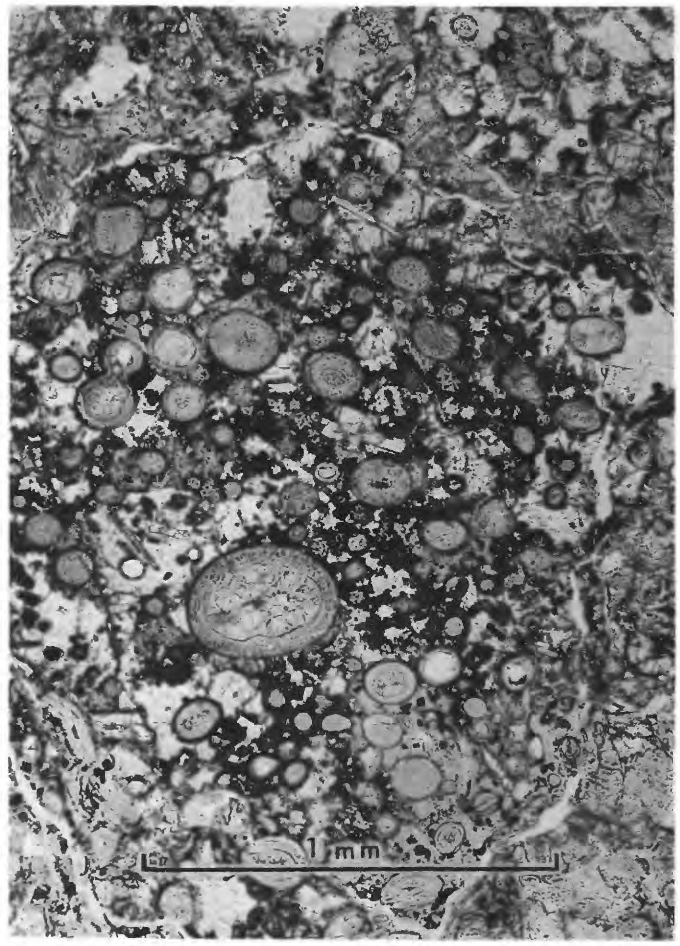
The Cuevas Limestone is a resistant formation that forms the summit of Cerro de las Cuevas and its extensions Cerro Raspaldo and Cerro Modesto in southern Coamo and northern Salinas quadrangles. The limestone is about 35 meters thick over most of the area. Previous estimates by Hodge (800 meters), Pessagno (0–1,200 meters), and the writer (100 meters) were in error because the structure was imperfectly known. The limestone rests disconformably upon the Raspaldo Formation and Los Puertos Formation in the Coamo quadrangle, and upon the Los Puertos and Coamo(?) Formations in the Río Descalabrado quadrangle. In the lower limestone quarry on the Camino Naranjo in west-central Río Descalabrado quadrangle, the quarrying operation penetrated the full thickness of the limestone. In 1961, it could be clearly seen that the limestone in the quarry was in depositional contact with the underlying tuff breccia of the Coamo Formation (fig. 26*A*). Elsewhere the contact is generally sheared, deeply weathered, or covered by talus. The upper contact is also a common locus of shearing, but in many localities the movement was along the bedding plane and the displacement probably was not large. The Cuevas is overlain by tuffs of the Río Descalabrado Formation.

The Cuevas is commonly thick bedded or massive, less commonly thin to medium bedded. In two outcrops near the Río Descalabrado water gap, north-dipping crossbedding occurs in the limestone.

A coarse-grained breccia of algal fragments in a matrix of algal sand and micrite is the dominant lithology of thet Cuevas Limestone (fig. 26*A*, *B*). The fragments range from algal heads 5 to 8 cm in diameter (fig. 27*A*, *B*) to sand-sized fragments. The average size is nearer 5 mm in the coarse facies and 1 mm in the fine facies. In general, the fragments are angular to subrounded and show more than one generation of algal coating and breakage.

A

B



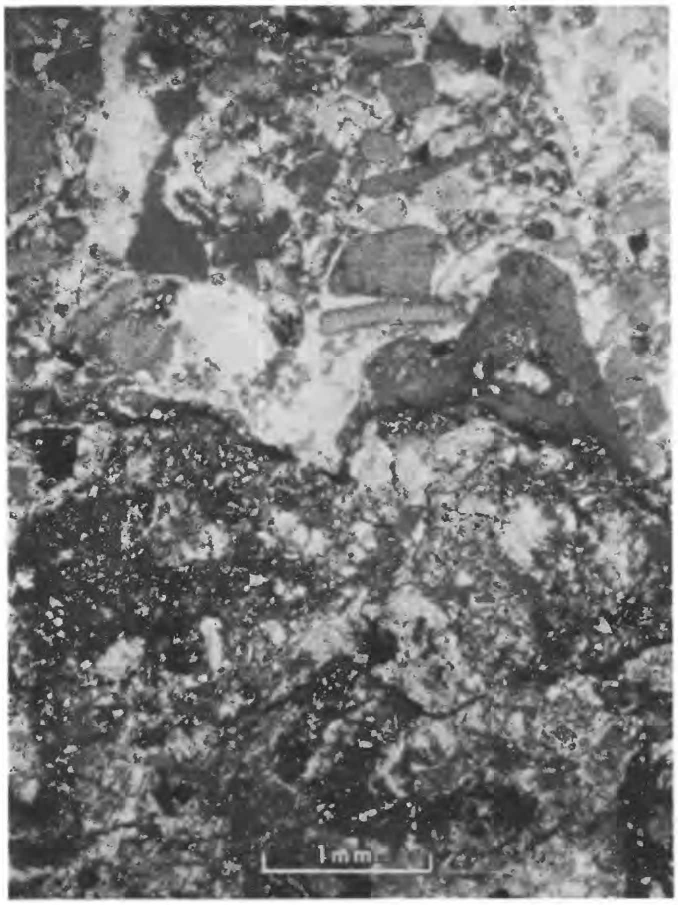
C

FIGURE 24.—Rocks of the Raspaldo Formation: *A*, Raspaldo Formation near Cuatro Calles, Río Descalabrado quadrangle. Intraformational conglomerate probably generated by slumping from submarine fault scarps. *B*, Raspaldo Formation near Cuatro Calles, Río Descalabrado quadrangle. Crossbedding in deep-water marine pumice tuff. Tree root covers part of outcrop in upper left corner of photograph. *C*, Raspaldo Formation near Cautro Calles, Rio Descalabrado quadrangle. Thin section of vitric-crystal pumice tuff from crossbedded unit shown in *B*. Analcime (white) and montmorillonite (medium-gray), replacing groundmass and filling vesicles. Quartz and plagioclase phenocrysts are unaltered.

The coarse-grained facies in the Río Descalabrado quadrangle contains rare large algal heads, algal balls or oncolites (fig. 27*C*), rare oyster fragments, rare corals, rare gastropods, and rare Foraminifera. Locally, it also contains 10 to 15 percent red mud reworked from older formations which lie disconformably beneath it. Late algal growths with very delicate wispy forms preserved are common in this area. The red limestone is common in the vicinity of the Río Descalabrado water gap. The color of the coarse Cuevas in the Río Descalabrado quadrangle varies between nearly white (dominant) and grayish red mottled in white. The coarse-grained facies in the Coamo quadrangle contains more Foraminifera, and no large coralline algal heads were found. As noted by Pessagno (1961), the fragments are much more rounded, and no wispy filaments of algae projecting into the fine-grained matrix were noted. In this area, the impure coarse-grained facies is light tan, reflecting the color of epiclastic material eroded from the underlying Raspaldo Formation with which it is probably in disconformable contact.

A fine-grained facies of the Cuevas interbedded with the coarser material is common throughout the area of outcrop. Algal fragments about 1 to 2 mm in diameter in a fine micrite matrix (fig. 27*B*) are predominant, but Foraminifera (especially miliolids) and echinoid spines are common to abundant and a few small gastropods and corals occur.

FIGURE 25.—Cuevas Limestone (white) forming a dip slope on Cerro de las Cuevas just north of Juana Díaz, Río Descalabrado quadrangle.



A

B

C

FIGURE 26.—Cuevas Limestone: *A*, Thin section (analyzer in) showing Cuevas Limestone in unconformable contact with the volcanic rocks of the Coamo Formation. The Cuevas is of Eocene age and the Coamo, of Cretaceous, hence the section shows the systemic boundary. Note the calcareous algal colony in growth position upon a small rise of andesite within the Coamo. *B*, Red-matrix facies of the Cuevas Limestone, Río Descalabrado water gap along Highway 14. Calcareous algal fragments lie in an impure matrix of calcareous sand and epiclastic red mud eroded from the underlying Coamo Formation. *C*, Pure facies of the Cuevas Limestone; biomicrite principally of encrusting calcareous algae in a fine calcareous silt. Cerro de las Cuevas, southern Coamo quadrangle.

Locally a basal impure facies contains pebbles of the underlying formations, quartz sand, and concentrations of magnetite.

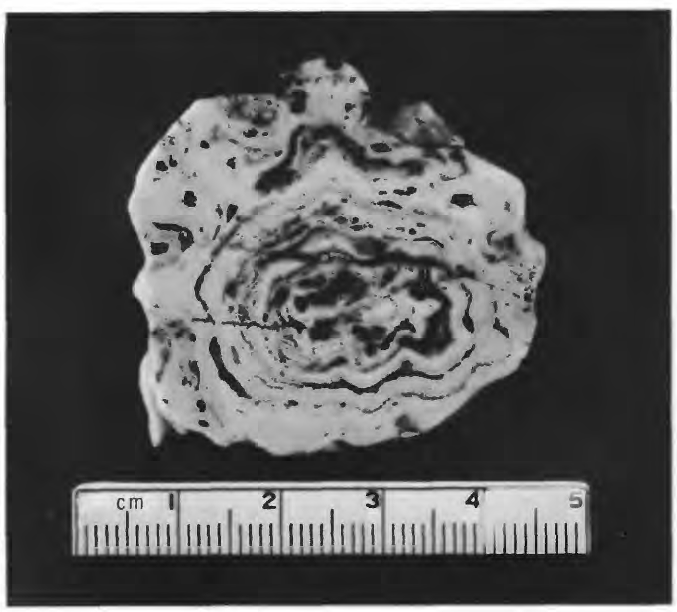
Most of the algae belong to the genus *Archaeolithothamnium* according to Johnson (Pessagno, 1960b, p. 77). Other algae are *Lithophyllum* and *Lithothamnium* (Pessagno, 1960b, p. 78). According to Johnson (1954, p. 15–16), *Archaeolithothamnium* ranges from Late Cretaceous to Holocene, having reached its zenith during the Eocene. Today it is only known from tropical and subtropical seas.

AGE

The age of the Cuevas Limestone cannot be closely estimated from the fossils thus far recovered. Pessagno (1960b, p. 77) believed the limestone to be Eocene on the basis of a microfauna "recovered from a marly lens" in the limestone, and early middle Eocene on the basis of a supposed interfingering of the limestone with the Río Descalabrado Formation of this report. According to the present structural and stratigraphic interpretation, the fauna Pessagno referred to were collected from a younger formation that does not interfinger with the limestone in the area of this report.

A

B



C

FIGURE 27.—Cuevas Limestone: *A*, Polished section through a head of branching coralline calcareous algae. Note stratification of calcareous sand and silt in the opening between algal fronds. Orientation of the stratification in some cavities is at right angles to that of others. This head probably rolled loose in a zone of high wave energy and was partially filled at different times and in different positions. *B*, Thin section of Cuevas Limestone (analyzer out) from Cerro de las Cuevas. Large fragments of *Archaeolithothamnium* in a poorly sorted matrix of similar material ranging in size to fine silt or clay. Clear areas of spar resulted from partial recrystallization of the fine fraction. *C*, Oncolite from the Cuevas Limestone on Cerro de las Cuevas, southeastern Río Descalabrado quadrangle. These subspherical bodies of concentric shells of calcareous algae presumably originate in an environment of high wave energy where they can be frequently turned.

The age can best be estimated from the following observations:

1. The Cuevas rests disconformably on Paleocene formations and by inference rested disconformably (?) prior to erosion upon the upper Paleocene-lower Eocene Raspaldo Formation of south-central Río Descalabrado quadrangle.
2. The Cuevas is overlain conformably by lower middle Eocene rocks.

The age suggested by this data is Paleocene to early middle Eocene, possibly early Eocene to early middle Eocene.

CONDITIONS OF DEPOSITION

Pessagno's interpretation of the limestone as a shallow neritic deposit is undoubtedly correct. Johnson (1961, p. 25) noted, "The greatest development of the coralline algae extends from low tide level down to depths of 30 to 70 feet (10 to 23 meters), depending on local conditions." According to Johnson (p. 26), encrusting types grow at all depths, but branching forms grow only close to the surface. The branching forms are most plentiful between tide level and 30 meters, and none have been found at depths greater than 80 meters. Among the encrusting forms, thick crusts indicate shallow water, thin crusts deeper water.

As the early middle(?) Eocene sea transgressed upon the truncated volcanic rocks that formed the early Río Jueyes fault-line scarp, a variety of calcareous algae dominated by the genus *Archaeolithothamnium* flourished in the shallow tropical water at the edge of the submerged scarp. It is uncertain whether reeflike masses of algae ever existed. The coarse-grained facies in central Río Descalabrado quadrangle might well have originated essentially in place by the local growth and occasional breakup of branching headlike masses, and as encrustations upon previously fragmented pieces of algae. Some of the large algal heads show several periods of solution and growth. Geopetal structures in them show filling at several orientations of the specimen; this fact suggests that under the high-energy conditions of very shallow water, heads as large as 8 cm in diameter were moved. Lack of sorting and grading and preservation of algal filaments and delicate encrustations which could not have traveled far suggest that the Cuevas in Río Descalabrado quadrangle grew locally. The better rounding of algal fragments, lack of growth in place, and better sorting of the limestone in the Coamo quadrangle imply greater transportation. The locus of most abundant growth seems to have been in central Río Descalabrado quadrangle where outcrops expose rocks formed near the old scarp.

As the sea became deeper in the Coamo area, the blanket of Cuevas Limestone was succeeded by the deeper water Río Descalabrado Formation.

RÍO DESCALABRADO FORMATION

In the Coamo area, the Río Descalabrado Formation comprises a sequence of well-bedded dacitic tuffs and mudstones overlying the Cuevas Limestone.

Hodge (1920, p. 161) named the "Río Descalabrados Series" to include "all the strata of the older series occurring above the Coamo Springs Limestone [Cuevas Limestone]." The series was named for outcrops along the Río Descalabrado between the Cuevas Limestone and the alluvial-plain deposits to the south as shown on the geologic map of the Coamo area. In addition to the post-Cuevas middle Eocene rocks, Hodge inadvertently included a preponderance of Cretaceous and Paleocene rocks, but his meaning is clear.

Pessagno (1960b, p. 78) recognized the Cretaceous rocks south of the Esmeralda fault and excluded them from the sequence. He considered the "Río Descalabrado" to be a member of his Naranjo Formation and amended the type area to include "rocks west and northwest of Las Ollas." Pessagno did not recognize the complex structure of the rocks north of the Esmeralda fault and also included Paleocene and Cretaceous(?) rocks in the member.

Glover and Mattson (1967, p. A38) changed the name to Río Descalabrado Formation. The type area was further restricted to include only post-Cuevas rocks similar to those that crop out along the Río Descalabrado between Cerro de las Cuevas and the Cañas Arriba fault 0.7 mile to the south. In the Coamo area, the formation crops out only along the southern flank of Cerro de las Cuevas.

The basal contact of the Río Descalabrado with the Cuevas Limestone is sharp, but because it marks a strong physical discontinuity, it is also a locus of shearing. At most outcrops the amount of movement is very difficult to judge.

The upper contact of the Río Descalabrado is everywhere bounded by a fault in the Coamo area. The minimum exposed thickness of the formation is 500 meters.

Thin- to medium-bedded tuffs and mudstones that characterize the Río Descalabrado seem to grade westward into thick-bedded and massive conglomeratic tuff northeast of Poblado Guayabal. This conglomeratic facies is the Guayo conglomeratic sandstone member of Pessagno's Naranjo Formation (Pessagno, 1960b, p. 85). The interfingering relationship was postulated by Pessagno and it seems to be borne out in the outcrops northeast of Poblado Guayabal. The field relationships are not conclusive, however, and a fault may separate the two facies.

Vitric-crystal, crystal-vitric, and vitric tuffs, tuffaceous mudstone, and mudstone in subequal proportions form the bulk of the Río Descalabrado Formation. In addition, tuffaceous arenites and planktonic and other limestones make up less than 10 percent of the rocks. These lithologies and their characteristic sedimentary structures are described below.

LITHOLOGY

CRYSTAL-VITRIC TUFFS

The crystal-vitric tuffs are generally thick-bedded, rarely thin bedded. Graded bedding is common, small-scale crossbedding is rare. Some beds are laminated. Graded beds commonly have planktonic mudstone tops. Some grading according to fragment density was noted where dark minerals (especially magnetite) are concentrated near the base of a graded bed. Crystal-vitric tuffs are commonly greenish gray to light olive gray overall; in detail they may be speckled in orange, hematite red, green, white, and gray.

Primary crystal components are: 5 to 30 percent plagioclase (An_{37-50}), fresh zoned euhedral crystals and crystal fragments; 2 to 10 percent bipyramidal quartz crystals, often partially embayed by resorption; 2 to 20 percent magnetite, commonly concentrated into thin laminae; and rare biotite.

Felsite porphyry fragments and red scoria are common. Accidental and (or) epiclastic epidote grains are rare. Allochems include a variety of shell and algal fragments.

Secondary minerals include green clay (smectite) after glass fragments. It is soft and greasy to the touch, and in many coarse particles a good lineation relict from long tube structure of pumice is evident. Analcime occurs as replacement patches in the fine fraction interstitial to crystals. In one area, analcime was observed in contact with quartz, albite, calcite, and clay or chlorite. There is limited replacement of plagioclase by analcime. Salmon-pink clinoptilolite and heulandite commonly replace shards. Calcite occurs as cement and in replacement patches. Quartz and albite replace groundmass. Chlorite is rare or absent in many samples.

VITRIC-CRYSTAL TUFFS

Bedding and other sedimentary structures of the vitric-crystal tuffs are similar to those of the crystal-rich variety. Because of the abundance of altered glass, the color varies between pale blue green and light blue green, and the rocks are speckled by the nonvitric constituents. Extensive alteration to analcime and calcite in some tuffs locally produced hard very light gray rocks.

Primary minerals include 2 to 20 percent fresh plagioclase, 1 to 10 percent quartz, rare sanidine (?), 1 to 3 percent magnetite, rare clinopyroxene, and rare biotite. Rare fragments of felsite porphyry with a quartz-albite matrix were observed. Glass fragments (entirely replaced) are abundant. Epiclastic, accidental, and allochemical constituents are rare or absent.

Secondary minerals include abundant green clay (smectite) surrounding shardlike bodies of clinoptilolite and heulandite. This clay colors the rock pale blue green. Analcime may form as much as 30 percent of some rocks. In one quartz-rich specimen, abundant analcime and calcite replacement resulted in a very compact fine-grained rock superficially resembling a calcareous quartzite. Clinoptilolite and heulandite replace shards and form salmon-pink micronodules in the rock (fig. 28*A*, *B*). Calcite occurs as cement and replacement mineral. Quartz and albite replace the fine-grained groundmass locally.

VITRIC TUFF AND TUFFACEOUS MUDSTONE

Vitric tuff and tuffaceous mudstone are commonly medium bedded to massive; they are locally thin bedded where they occur as mudstone tops on graded beds of reworked tuff. Pencil fracture is rare to common, but most break with a subconchoidal fracture. The rocks are pale bluish green to greenish gray when fresh and weather to light yellowish brown or light olive gray. Extensive alteration to analcime produces a rock that may be nearly white.

In hand specimen, the rock appears as fine-grained vitric tuff or mudstone with rare to common crystals of plagioclase and quartz. Shard structure is preserved in some, but the development of secondary minerals has completely obliterated such structures in others. By X-ray diffraction analysis the clay mineral was determined to be smectite, probably celadonite-montmorillonite. The diffraction patterns indicate that quartz, analcime, and albite are abundant minerals, and that clinoptilolite and (or) heulandite occur in less abundance. Some calcite is generally present.

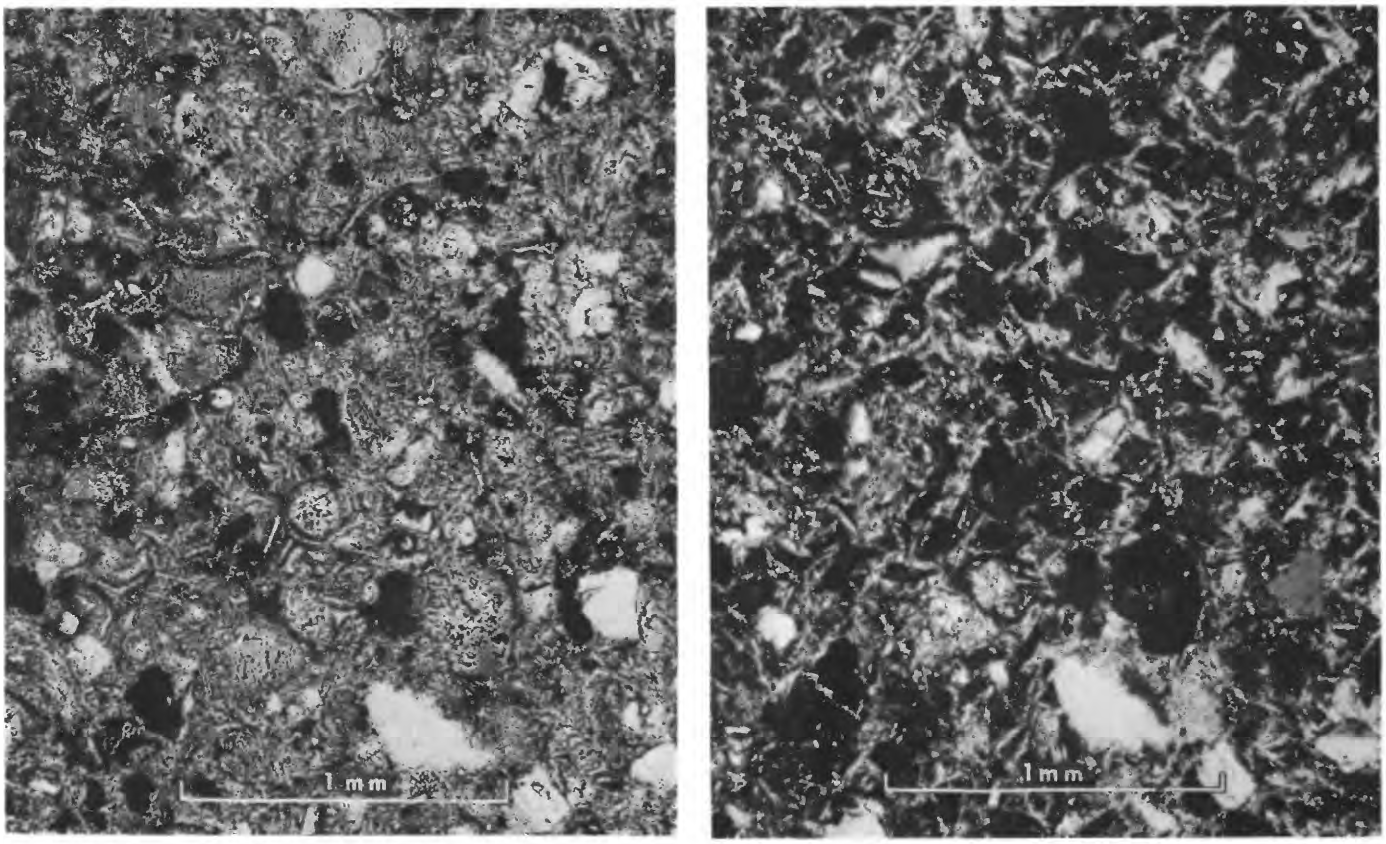
TUFFACEOUS ARENITES

Tuffaceous arenites are medium to thick bedded and commonly conglomeratic. All occur in the lower part of the Río Descalabrado, and most lie immediately above the Cuevas Limestone. They are dominantly grayish red, less commonly grayish tan and light olive gray.

The epiclastic constituents comprise well-rounded pebbles and sand grains of red and greenish-gray andesite and small amounts of red clay. Allochemical constituents are common fragments of calcareous algae, gastropod and pelecypod shell debris, large Foraminifera, echinoid spines, and sponge spicules. Pyroclastic constituents include plagioclase, quartz, and green clay after vitric fragments. Rare grains of clinopyroxene and hornblende are either pyroclastic or epiclastic.

MUDSTONES AND TUFFACEOUS MUDSTONES WITH PLANKTON

Mudstones and tuffaceous mudstones with plankton are thin to medium bedded and light olive gray, light grayish green, and yellowish brown. They principally are composed of clay, altered fine vitric ash, and plankton (Radiolaria and Foraminifera). Less common are plagioclase and rare quartz crystals. Generally there is a small amount of carbonaceous material. All the specimens examined were very poorly sorted and showed no evidence of grading.



A B

FIGURE 28.—Rocks of the Río Descalabrado and Guayo Formations: *A*, Thin section of pale-blue-green vitric-crystal tuff speckled with moderate reddish-orange zeolite. Shard structure clearly evident; shards replaced by clinoptilolite and heulandite (both clear) and rimmed by montmorillonite with celadonite. Quartz, magnetite, plagioclase, and biotite crystals constitute about 15 percent of the rock. Río Descalabrado Formation, bed of the Río Jueyes, Río Descalabrado quadrangle (analyzer out). *B*, Same as *A*, analyzer in. Shards (dark) replaced by low-birefringent zeolite, rims and interstices (light) filled and replaced by montmorillonite. *C*, Dacite block from the Guayo Formation, just north of Juana Díaz *D*, Thin section of dacite block shown in *C*. Note embayed quartz phenocryst, hornblende largely altered to opaque iron oxides, chlorite, and pyroxene, and fresh plagioclase phenocrysts.

PLANKTONIC LIMESTONES (BIOMICRITE)

Thin-bedded, partially laminated equivalents of planktonic oozes are rare to common in the Río Descalabrado Formation. They are light gray to light olive gray on slight weathering. They consist principally of planktonic Foraminifera, fine lime mud (micrite) Radiolaria, and clay in order of decreasing abundance of constituents.

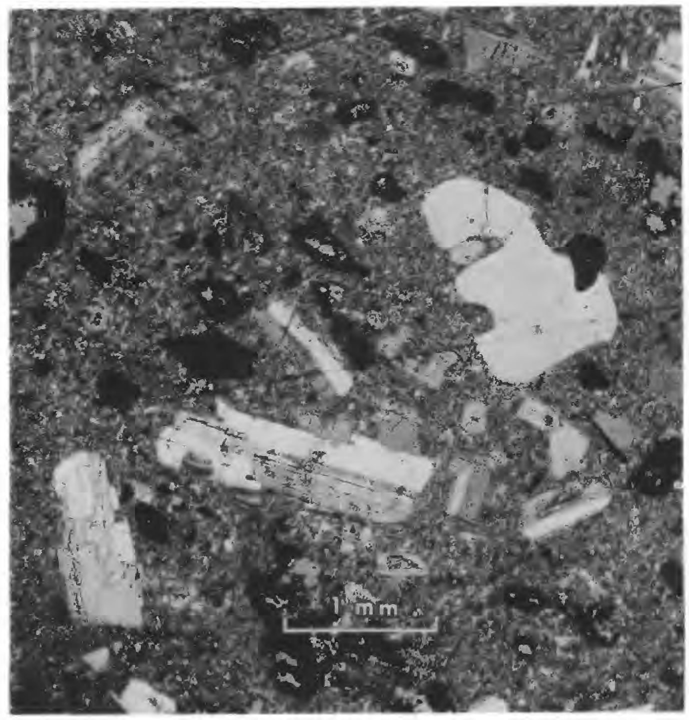
UNNAMED LIMESTONES SHOWN ON THE GEOLOGIC MAP

Limestone occurs at least at two stratigraphic levels in the Río Descalabrado Formation in the Río Descalabrado quadrangle. These limestones are shown on the geologic map of the Coamo area as Tdl. The units are seldom more than 5 meters thick. Bedding is medium to thick bedded and has a tendency to be laminated in some outcrops. The rocks are light to medium olive gray, weathering to yellowish brown and tan.

Biomicrite commonly contains abundant calcareous algae and large Foraminifera. Minor constituents are echinoid spines and small Foraminifera (especially miliolids). This type is especially common west of the Río Descalabrado. Elsewhere, very fine grained biomicrite is found. Varying amounts of tuff occur in the limestone.

In the west-central Río Descalabrado quadrangle, these limestones were variously included as contiguous parts of the Coamo Springs or as lenses of Coamo Springs Limestone in the Río Descalabrado Member of Pessagno (1960b).

C



D

AGE

Pessagno's (1961, p. 352) fossil localities 103, 104, 154, 155, 222, 228, 229, 241, 242, 2172, 2269 are all within the Río Descalabrado Formation as herein restricted. The last named locality is not shown on the 1961 locality map, but Pessagno (1960b) shows it to be about 1.7 miles west-southwest of locality 103. On the geologic map, locality 2269 is in the Río Descalabrado Formation at the headwaters of the Río Cañas just south of the Cuevas Limestone.

All the faunas diagnostic of the *Hantkenina aragonensis* assemblage zone as shown on Pessagno's Chart 1 (table 3 of this report) clearly fall in the Río Descalabrado Formation of this report. The Río Descalabrado is therefore considered to be earliest middle Eocene in the Coamo area.

It is interesting that all the faunas in this chart diagnostic of the next younger *Globigerapsis kugleri* assemblage zone (early middle Eocene) were taken from localities in Pessagno's Augustinillo Formation west of the Coamo area.

CONDITIONS OF DEPOSITION

The Río Descalabrado was deposited in deeper water than was the underlying Cuevas Limestone. As the sea continued to become deeper in the Coamo area, prolific algal growth was inhibited, and only the products of volcanism combined with a minor amount of epiclastic debris accumulated. At first, epiclastic debris was contributed in large amounts from a subaerial source as the sea transgressed. Hence, tuffaceous arenites commonly occur in the Río Descalabrado just above the Cuevas. Later this contribution diminished, and tuffs, mudstones, and some limestone accumulated in relatively deep water, certainly below wave base. The faunas as reported by Pessagno are overwhelmingly planktonic and also attest to deep water and considerable distances to shore. The thin limestone with abundant calcareous algae may be the debris from algal banks (similar to the Cuevas Limestone) that migrated shoreward to the north(?) and northwest(?) as the sea in the Coamo area became deeper.

GUAYO FORMATION

The Guayo Formation comprises principally thick-bedded and massive conglomeratic tuff.

Pessagno (1960b, p. 85) first proposed the name "Guayo conglomeratic sandstone" for a member of his Naranjo Formation. He designated the type locality as, ". . . OP 2396, located in the bed of the Río Guayo (Ponce quadrangle, NE.; opposite kilometer post K2Hl on the road to Collores.)." According to his description,

At the type locality the conglomeratic sandstone contains varicolored well-rounded pebbles and boulders mostly between 1 inch and 1 foot in diameter . . . However, some boulders occur that are 4 feet . . . or more in diameter. About half of the fragments between 0.06 inches and 1 inch in diameter . . . are angular. There are many fragments of sedimentary rocks such as green si'tstones and pyroc'astic rocks such as crystal tuffs. Some interbedded medium-gray calcilutites, identical to those of the Collores member, are present at the type locality. A characteristic feature of the Guayo conglomeratic sandstone is the large number of pebbles and boulders that are intraformational in origin.

The tuffaceous sandstone which constitutes 70 to 85 percent of the rock consists almost entirely of angular to subangular feldspathic and lithic fragments. Often broken microfossils such as *Discocyclina* and *Operculinoides* and present.

In the western part of the Río Descalabrado quadrangle, Pessagno included all the Miramar Formation of this report as the correlative of the Guayo type sequence. His meaning is clear, however, and the name is retained but amended to Guayo Formation (Glover and Mattson, 1967, p. 38–39). In this report the Guayo Formation is included in the Jacaguas Group.

In the Río Descalabrado quadrangle, the contact relations are either faulted or uncertain. Pessagno thought the Guayo interfingered with rocks herein considered part of the Río Descalabrado Formation and this may be true. From structural relations in section B–B′ (pl. 4), it may also be a facies of the Raspaldo Formation. The thickness is unknown but exceeds 200 meters.

TABLE 3.—*List of early middle Eocene microfauna from the Río Descalabrado Formation, Río Descalabrado quadrangle. Partial contents of a chart for the Jacaguas Group by Pessagno (1961, Chart I, p. 354).*

Microfaunal lists: Jacaguas Group, modified to show only lists from localities in Río Descalabrado Formation of Glover (this report).
Ha: *Hantkenina aragonensis* assemblage zone.
ts: Identification in thin section.
Key: A, abundant; C, common; R, rare.

Microfaunal list	Fossil locality												
	103-B Ha	104 Ha	154-A Ha	154-C Ha	154-D Ha	155 Ha	222 ts	228-B Ha	229 Ha	241 ts	242 Ha	2269 Ha	2172 Ha
Textularia sp				R									
Clavulinoides sp												R	
Textulariella sp									R				
Coskinolina sp										C			
Robulus sp	R		R	R									
Dentalina				C									
Lagena sp. cf. *L. nuttalli*				R									
sp						R					R	R	
Operculinoides sp							C			C			
Bulimina sp				R									
Ellipsoidina abbreviata										R			
Ellipsoglandulina sp												R	
Eponides sp		R	R	R	R				C				
Gyroidina sp. aff. *G. jarvisi*					R								
sp			R	C					C				
Globorotalites kochi	R									R			
Amphistegina sp							C			C			
Globigerina boweri			C	C	C				C		C		C
turgida	A		C	A		C		C	A		R		
sp. cf. *G. turgida*		R									R		C
sp. aff. *G. boweri*	R	R	C		C			R					
sp	C		C		C	C		C				C	
Globigerapsis index			?		?				C			C	
sp				?									
"*Globigerinoides*" *higginsi*												C	
Globorotalia densa	A	C	A	A	A				A		A	A	
broedermanni	A			R	C				C		R	C	
spinulosa	R												
aragonensis												R	
pseudomayeri													A
sp												C	A
Anomalina sp	R		R	R								R	
Cibicides micrus									R				
Discocyclina sp							C			C			
Milliolids							R					C	
Ostracodes				R									
Phacodiscus (?) sp												C	

LITHOLOGY

Conglomeratic tuff, tuff, and minor mudstone are found in the Guayo Formation.

CONGLOMERATIC TUFF

The conglomeratic tuff is thick-bedded to massive rock interbedded with tuff and plankton-bearing mudstones. It is light medium gray to grayish brown overall, speckled with white, red, green, and dark-gray fragments.

In 1961, excellent fresh outcrops of the conglomeratic Guayo existed in the new roadcuts at Poblado La Loma just west of the central-western margin of the Río Descalabrado quadrangle. The conglomerate includes fragments of dacite, green vitric tuff, and limestone in a matrix of dacite tuff. Sorting is extremely poor, and the bimodal nature of the rock is not always apparent.

The dacite blocks and cobbles (fig. 28 *C, D*) are angular to well rounded and consist of about 40 percent phenocrysts and 60 percent pilotaxitic to fine granular matrix. Phenocrysts include 30 percent cumulophyric plagioclase (An_{50} cores, zoned to oligoclase?), 10 to 15 percent partially resorbed hornblende, and 10 to 15 percent quartz as rounded to euhedral bipyramids. The groundmass is locally altered to quartz-albite-celadonite.

The vitric fragments are altered to a very fine grained mixture of quartz, albite, analcime, smectite (nontronitic montmorillonite?), and mordenite or clinoptilolite. Shard structure is commonly displayed in thin section.

Limestone fragments include angular to subrounded chunks of algal biomicrite similar to the Cuevas Limestone. One of these fragments is 45 cm long and 10 cm thick; others are elliptical and reach diameters of about 30 cm. In other cobbles, allochems include algal fragments, corals, gastropods, pelecypods, oysters and large Foraminifera. A few large coral cobbles were found.

The matrix is dacitic ash which has been slightly rounded and sorted. Primary minerals include plagioclase (An_{55-37}), quartz, rare hornblende, and clinopyroxene. Vitric fragments and fragments of felsitic porphyry are common. Accidental(?) fragments include epidote grains, epidotized fragments, and fragments of strongly recrystallized limestone. Allochems include algae, large and small Foraminifera, and pelecypod fragments. Secondary minerals are green nontronitic montmorillonite(?) after glass, celadonite after glass, zeolites replacing glass, calcite, quartz, and albite.

Crystal-vitric, vitric-crystal, and vitric tuffs (fig. 29) occur in the Guayo Formation. They are thin-bedded to massive rocks. Graded and laminated bedding are common, and primary slump structures are very common. Some beds grade into brown mudstones at their tops.

Primary crystal components include 0 to 30 percent(?) plagioclase (An_{35}, zoned to more sodic; also zoned crystals with cores An_{45}) poikilitically including apatite crystals, common quartz, common magnetite, 0 to 10 percent hornblende, 0 to 3 percent nonpleochroic clinopyroxene and rare biotite. Accidental fragments of epidote are rare. Fragments of glass are altered to pale-bluish-green smectite and zeolites (mordenite or clinoptilolite); secondary quartz and albite are present. Allochems include algae and large Foraminifera.

Locally there are fine vitric tuffs and vitric lapilli tuffs generally altered to smectite, zeolite, quartz, and albite.

MUDSTONES

Thin- to medium-bedded mudstone, commonly with disrupted laminae, is common in the Guayo Formation. These rocks range in color from pale olive to yellowish gray and medium gray.

Most of the samples examined consist of tuffaceous recrystallized micrite containing common to abundant plankton (Foraminifera and Radiolaria).

FIGURE 29.—Dacite crystal-vitric tuff from the Guayo Formation; same locality as figure 28C. Such tuff forms matrix of tuff breccia as well as thick graded beds in the sequence.

AGE AND CONDITIONS OF DEPOSITION

The age of the Guayo Formation at present can only be estimated from its probable interfingering with the lower middle Eocene Río Descalabrado Formation.

The moderately poor sorting (clasts finer than 2 mm are absent), thick bedding, and preponderance of only slightly rounded ash in the Guayo Formation suggest that it was deposited by submarine pyroclastic flows and slides. The large dacite fragments could have been picked up on the flanks of the cone by turbulent ash flows or perhaps more likely were incorporated during phreatic explosions. The green vitric tuff is also a Jacaguas Group rock type that could have been torn from the throat of a volcano during eruption or may have been picked up on the surface by the turbulent ash flows. The angular and recrystallized limestone clasts may have originated similarly, although the well-rounded ones probably were picked up outside the volcano. Some rounding of the ash fraction may have occurred during transport as pyroclastic flow or slide. Some undoubtedly occurred in high-energy environments during temporary deposition prior to redistribution by incorporation in later pyroclastic flows and submarine slides.

Interbedded turbidites of poorly sorted but graded tuff and tuffaceous mudstone and interbeds of plankton-rich mudstone indicate that the Guayo Formation was deposited in a marine environment below wave base.

The debris was probably erupted from submarine dacitic volcanoes somewhere in southern Jayuya and Adjuntas quadrangles (P. H. Mattson, oral commun., 1964).

MEGABRECCIA

A giant breccia or chaos (Noble, 1941) occurs between some of the large allochthonous plates of the Jacaguas Group along the belt of outcrop in the vicinity of Cerro de las Cuevas.

The megabreccia is widely distributed through the area of outcrop of the Jacaguas Group in the Río Descalabrado quadrangle, and it probably includes part of the complexly faulted Robles Formation mapped in the southwestern corner of the Coamo quadrangle (Glover, 1961a). The outcrop width of the megabreccia averages about 0.7 km but locally it is as much as 2 km. The thickness is difficult to estimate but probably ranges from 0 to 130 meters. Individual blocks in the chaos may be more than a kilometer in greatest dimension. The upper and lower boundaries of the megabreccia are not always clearly defined, because in many localities glide surfaces simply diminish in number and intensity of deformation into the larger allochthonous plates.

Blocks of older Cretaceous formations commonly occur between allochthonous plates of the Maestrichtian-middle Eocene Jacaguas Group. Some of the larger subdivisions of the megabreccia are shown on the geologic map and are described here.

Pyroxene andesite lava, Kcof, occurs west of the Río Descalabrado. Phenocrysts of plagioclase and augite constitute about 20 to 30 percent of the lava, and plagioclase is commonly about twice as abundant as augite. The groundmass is pilotaxitic to intergranular. Amygdules are elongate and filled with calcite or chlorite and quartz. More rarely some highly silicified lava occurs. The lava is not foliated, but contains secondary quartz-albite-epidote-chlorite assemblages and is therefore of greenschist grade.

Pyroxene andesite and basalt(?), Kcof, similar to the Cotorra Tuff (R. P. Briggs, unpub. data) occur south of the Esmeralda fault in southeastern Río Descalabrado quadrangle. In this area, augite-phenocryst lava with a pilotaxitic groundmass rich in pyroxene needles is most common. Associated fragments are textural variants of the same general rock type or more rarely are hornblende andesite. Interstratified(?) with the lavas are thin to massive units of volcanic sandstone of the same composition, as well as minor amounts of radiolarian chert. Quartz-albite-epidote-chlorite secondary mineral assemblages indicate the greenschist grade of metamorphism.

Eastward, the Lapa and Las Tetas Lava Members, where exposed south of the Esmeralda fault, are also probably in part allochthonous. Quartz-albite-epidote-chlorite secondary minerals are common except at the easternmost outcrop north of Salinas where quartz-albite-prehnite-chlorite occurs.

Tuff breccia, Kcot, in the Coamo Formation, occurs in the megabreccia along the Río Descalabrado at Las Ollas and also north of Cuatro Calles. The tuff breccia at Las Ollas may be essentially autochthonous.

Just west of Lago Coamo in southeastern Río Descalabrado quadrangle is a detached plate of Cariblanco(?), Kcs, rocks. Thin- to medium-bedded plankton-bearing dark tuffaceous mudstone is the dominant rock type. Locally, the mudstones are cherty or calcareous, and dark organic-rich laminae reveal soft-sediment disruption. Calcareous concretions, typical of this facies of the Cariblanco, also occur in the mudstones.

Undifferentiated megabreccia, B, is a chaotic mixture of many rock types representing the entire stratigraphic sequence from the Robles through the Río Descalabrado Formations. Fragments of the Miramar Formation are abundantly represented in the breccia.

MIDDLE TERTIARY ROCKS

In the southwestern part of the Coamo area, a sequence of rocks comprising coarse conglomerate grading upward into nearly pure limestone rests with conspicuous unconformity upon the folded and faulted rocks of the older volcanic sequence.

JUANA DÍAZ FORMATION

The basal epiclastic and conglomeratic part of the mid-Tertiary sequence is the Juana Díaz Formation. It crops out near the town of that name at the southwestern edge of the Coamo area. Hubbard (1920) formally proposed acceptance of Berkey's (1915) informal use of the locality name as "Juana Díaz shale." Maury (1929) called it the Juana Díaz Formation, and this name has been continued in general use. The Juana Díaz was mapped and described by Zapp and others (1948), and in their report there is a good account of the earlier work.

In the outcrops east of Juana Díaz, the lower part of the formation consists of coarse bouldery conglomerate having a poorly sorted matrix and an intact framework. The pebbles, cobbles, and boulders are very well rounded and include a wide assortment of pre-middle Tertiary rocks apparently derived from formations in the western Coamo area. Specifically, boulders of Cuevas Limestone, cobbles of well-rounded rudistids (probably from the Miramar Formation), cobbles of pyroxene andesite from the Coamo Formation, and pebbles of dacite from the lower Tertiary sequence can easily be recognized. A few cobbles of diorite suggest a source for some of the material as far north as the Utuado batholith in central Puerto Rico. The largest boulder recorded was a well-rounded piece of the Cuevas Limestone about a meter in diameter.

Higher in the section, the conglomerate becomes finer and is interleaved with calcareous lithic arenite and a small amount of limestone. The arenite is medium gray to greenish gray, weathering to yellowish gray. Typically the arenite is composed of about 60 percent to 70 percent terrigenous material consisting of weathered feldspar, quartz, pyroxene, hornblende, epidote, opaque oxides, and rock fragments (both volcanic rock and older limestone). The rest of the rock is recrystallized calcite commonly containing about 5 percent dolomite rhombs. Calcite replaces most mineral and rock fragments to the extent that serrate grain boundaries are common.

The arenite is medium to thick bedded, and surfaces of stratification commonly are undulatory and indistinct. The conglomerate is thick bedded or massive.

Assuming, from the data shown on the map, an average dip of 15° SW., there would be about 600 meters of Juana Díaz in the area. This figure is close to the 655 meters reported by Zapp and others (1948). However, it seems reasonable that initial dips in the coarser parts of the sequence would be high, and this figure probably represents a maximum thickness.

AGE AND CONDITIONS OF DEPOSITION

The following are new fossil collections herein reported from the Juana Díaz Formation in and just west of the Coamo area.

Collection LG-59-7 (Lynn Glover):
- Locality: Río Descalabrado quadrangle, SW. Puerto Rico meter grid 146,000 N.; 24,250 E.
- Stratigraphic level: Near middle of the formation.
- Fossil: *Antiguastrea cellulosa* (Duncan).
- Age: According to J. W. Wells (written commun., 1961), a widespread and characteristic species in the upper Oligocene of the Caribbean and adjacent areas.
- Paleontologist: J. W. Wells.

Collection BC-566, BC-566a (H. L. Berryhill):
- Locality: Central Aguirre quadrangle, Puerto Rico meter grid 174,600 No.; 137,600 E.
- Stratigraphic level: lower Juana Díaz.
- Fossils: *Antiguastrea cellulosa* (Duncan)
  Hydnophora sp.
- Age: According to J. W. Wells (written commun., 1961), the first occurs only in the West Indian Oligocene; *Hydnophora* is known only from the Eocene and Oligocene of the same area.
- Paleontologist: J. W. Wells.

Collection Po 35-1 (USGS f35139) (P. H. Mattson):
- Locality: Ponce quadrangle, SW., Puerto Rico meter grid 134,720 No.; 22,110 E.
- Stratigraphic level: Near middle of Juana Díaz Formation.
- Fossils: *Nummulites dia*
  Lepidocyclina canellei
  giraudi
  yurnagunensis
  undosa
- Age: lower Oligocene. According to K. N. Sachs, Jr. (written commun., 1963), this assignment is based on the above association coupled with the absence of both *Heterostegina* and *Miogypsina*, which are characteristic of upper Oligocene and Miocene deposits. Furthermore, the definite early Oligocene age of Po 35-3, which is about 20 meters above this sample, is additional evidence.
- Paleontologist: K. N. Sachs, Jr.

Collection Po 35-3 (USGS f35138) (P. H. Mattson):
- Locality: Ponce quadrangle, SW. Puerto Rico meter grid 134,700 No.; 22,100 E.
- Stratigraphic level: Near middle of Juana Díaz Formation.
- Fossils: *Lepidocyclina canellei*
  Nummulites dia
  Abundant small Foraminifera (see report by Ruth Todd below).

Collections (all samples collected by P. H. Mattson, 1963):
- Po 35-1 (U.S.G.S. f35139) Ponce quadrangle, Puerto Rico meter grid 134,720 N.; 22,110 E.
- Po 35-3 (U.S.G.S. f35138) Ponce quadrangle, Puerto Rico meter grid 134,700 N.; 22,100 E.
- Pe 46-1 (U.S.G.S. f35141) Peñuelas quadrangle, Puerto Rico meter grid 130,240 N.; 22,910 E.

Stratigraphic level: Po 35-1, -2, -3 near middle of Juana Díaz, Pe 46-1 near the base of the Juana Díaz.

Fossils: Only planktonic species are recorded below. In all four samples Miss Todd found a total of 143 species.

	Collections			
	35-1	*35-2*	*35-3*	*46-1*
Cassigerinella chipolensis (Cushman and Ponton)	--	--	R	R
Chiloguembelina cubensis (Palmer)	--	--	C	C
Globigerina ampliapertura Bolli	R	R	R	R
ampliapertura cancellata Pessagno	--	--	R	R
angustiumbilicata Bolli	--	--	R	R
foliata Bolli	R	R	R	R
obesa (Bolli)	--	--	R	---
sellii (Borsetti)	--	--	R	R
opima Bolli	--	--	R	R
parva Bolli	R	R	R	R
gortanii (Borsetti)	--	--	R	R
venezuelana Hedberg (includes *G. rohri* as synonym)	C	C	A	A
yeguaensis Weinzierl and Applin	R	R	R	---

Age: According to Ruth Todd (written commun., 1963): "Age can be most reliably interpreted from planktonic species because, in general, they have briefer ranges than do benthonic species. Speaking only of the two richer samples, the determination of early Oligocene age is made on the basis of the overlapping ranges of *Cassigerinella chipolensis* and *Chiloguembelina cubensis*, the former ranging from the Miocene downward no lower than the Oligocene (Lattorfian to Rupelian, the *Globigerina sellii* zone of Blow and Banner in Eames and others [1962, fig. 20]) and the latter ranging from the Eocene upward no higher than the two lower zones of the Oligocene (the *Globigerina ampliapertura* and *Globorotalia opima opima* zones of Bolli [1957, p. 100] as indicated by Beckmann [1957, fig. 16]).

"In addition to those two planktonic species, several of the globigerinids are reported to have even more narrowly restricted stratigraphic ranges in various parts of the world. They confirm the early Oligocene age that is indicated by the overlapping ranges discussed above. Listed in decreasing order of their frequency, they are *Globigerina ampliapertura, G. parva, G. opima, G. angustiumbilicata, G. sellii,* and *G. gortanii.* In this group greater reliance should be placed on the species that occur with greater frequency. The remaining planktonic species include *Globigerina venezuelana,* occurring in greater numbers than all the other globigerinids combined, but this species has little value as an age indicator, for it ranges from Eocene to Miocene (or even higher if it proves to be a synonym of *Globigerina conglomerata*

Collections—Continued

Age—Continued

Schwager, as now seems likely). The three additional species, *G. foliata*, *G. obesa*, and *G. yeguaensis*, are all rare. The first two are reported to range no lower than Miocene in the West Indies (Bolli, 1957, text fig. 18) and the third one no higher than Rupelian in East Africa (Blow and Banner, in Eames and others, 1962, text fig. 20).

"The globigerinids from the Juana Díaz Formation (two samples from Ponce quadrangle and one from Peñuelas quadrangle) were described by Pessagno (1963). The present globigerinid assemblage, although richer by several species, is quite similar to that already described, and some of the discrepancies are undoubtedly a result of different identification of nondistinctive species.

"In summary, the age of samples Po 35–3 and Po 46–1 seems to fall somewhere within the zones of *Globigerina sellii* (regarded as Lattorfian to Rupelian by Blow and Banner [in Eames and others, 1962, text fig. 20]) and *Globigerina ampliapertura* and *Globorotalia opima opima* (regarded as lower Oligocene by Bolli [1957, text fig. 18] and as lower Aquitanian [lower Vicksburgian] by Blow and Banner [in Eames and others, 1962, text fig. 20])."

Paleontologist: Ruth Todd.

Wells, Sachs, and Todd seem to be in general agreement that the Juana Díaz correlates with the classical Oligocene formations of the Caribbean and Gulf regions. Some conflict of opinion may exist for the middle Juana Díaz coral (LG–59–7) which was considered by Wells to be late Oligocene, whereas Sachs and Todd considered the middle Juana Díaz Foraminifera (Po 35–1, –2, –3) and the lower Juana Díaz Foraminifera (Po 46–1) to be of early Oligocene age. The localities are widely separated geographically, however, and the Juana Díaz may, as a basal clastic facies of the mid-Tertiary sequence, be strongly overlapping and be of younger age in the eastern outcrops.

In submitting her report, Miss Todd referred briefly to the Oligocene problem in the Cariblanco area. Eames and others (1962) have challenged the existence of Oligocene rocks in the region. They claim that the early transatlantic correlations by Conrad, Maury, and Vaughan were founded on insufficient or mistaken evidence, and they consider the Juana Díaz to be of early Miocene Aquitanian age. Gordon (1961) also considers the Juana Díaz to be entirely Aquitanian, principally on the basis of the occurrence of *Globoquadrina altispira altispira* (Cushman and Jarvis) which he reports as occurring from near the base of the Juana Díaz Formation to the top of the lower Ponce limestone. To the writer's knowledge, *Globoquadrina* has not been reported in any of the more recent literature dealing with the Juana Díaz, and Gordon's fossil localities are not known. Pessagno (1963a) reported on planktonic Foraminifera from three localities in the upper part of the Juana Díaz, and concluded that, regardless of where the Oligocene-Miocene boundary is placed, Gordon's Juana Díaz assemblage is in conflict with his placement. Pessagno believed that the planktonic assemblages at the three localities he described were older than the assemblage cited by Gordon and that much of the Juana Díaz falls within the *Globigerina ampliapertura* and *Globorotalia opima opima* assemblage zones (early Miocene Aquitanian or Vicksburgian according to Blow and Banner [in Eames and others, 1962]; or early Oligocene according to Bolli [1957]).

On the basis of the microfaunas, the Juana Díaz is Oligocene, possibly in large part of early Oligocene age, if the Oligocene is represented in the classical sequence of Trinidad as shown by Bolli (1957). However, if the Trinidad sequence is lower Miocene, as Eames and others (1962) maintain, then the Juana Díaz also is Miocene.

The Juana Díaz Formation apparently is a shallow-water transgressive largely epiclastic facies deposited upon erosional topography of considerable local relief.

PONCE LIMESTONE

The Ponce Limestone is a sequence of soft to moderately hard rocks that rests conformably upon the epiclastic Juana Díaz Formation with gradational contact. The general character of the limestone and the history of the name and subdivisions are well described by Zapp, Bergquist, and Thomas (1948) thus:

Mitchell (1922), following the suggestions of Berkey (1915) and Hubbard (1920), applied the name Ponce to the limestones of the south coast, considering the type locality to be the area northwest and west of Ponce. In his published columnar section, Mitchell distinguished between the Juana Díaz and Ponce formations, but in his description he included the basal clastics and shaly beds of the Juana Díaz area in the lower portion of the Ponce Formation.

Hubbard (1920) first subdivided the Ponce Limestone while attempting to correlate formations on the north and south coasts of Puerto Rico. He correlated the Juana Díaz shale with the San Sebastian Formation, his lower Ponce limestone with the Lares and Cibao, and his upper Ponce limestone with the uppermost limestones of the north coast. He did not define the limits of the two divisions of the Ponce.

In this report the Ponce Limestone is considered to include the entire sequence of limestones overlying the clastics and shales of the Juana Díaz Formation, and it is divided into a lower buff chalky limestone member and an upper hard white limestone member.

Outcrops of the Ponce Limestone in the Coamo area include only the lower part of the lower member. It is thin- to thick-bedded light-gray to buff soft limestone. Some of the beds contain abundant foraminiferal biomicrite rich in planktonic species. The matrix is locally slightly recrystallized and dolomitic.

Assuming an average dip of 15° SW., about 380 meters of Ponce Limestone crops out in the southwestern part of the Coamo area.

According to Zapp, Bergquist, and Thomas (1948), the lower Ponce is of late Oligocene or early Miocene age. The Ponce Limestone is a transgressive shallow-water limestone that overlaps the basal epiclastic Juana Díaz Formation in the area west of Ponce.

TERTIARY AND QUATERNARY ROCKS AND SEDIMENTS IN THE SUBSURFACE OF THE SOUTH COAST

Unconsolidated and semiconsolidated gravelly deposits of sand and silty clay with minor interbeds of limestone were found at depths of 500 to about 3,000 feet in drill holes along the south coast. The holes, designated CPR–1, CPR–2, and CPR–3, were drilled during 1959–1960 by Kewanee Interamerican Oil Company. The wells are between Ponce and Santa Isabel along the coast and are shown on the geologic map of southeastern Puerto Rico (pl. 1). Brief logs are given as columnar sections in figure 30. Ages given in figure 31 are based upon fossil identifications by W. A. Gordon, and the generalized lithology is taken from summary logs in the well-completion reports furnished to the Puerto Rican Economic Development Administration by Kewanee.

The subsurface sequences, as interpreted from the cuttings, do not correspond well with the rock units mapped at the surface. The Juana Díaz Formation in CPR–1 is similar to the type section in thickness and lithology, but in CPR–2 the log does not indicate a distinctive upper contact for the Juana Díaz. In CPR–3 there is a distinctive break at the top of the Juana Díaz, but a thick sequence of green silty shale supplants the abundant coarse conglomerate and sandstone found updip at the type locality.

The Ponce Limestone appears as a very thin and unusually sandy limestone in CPR–1. In CPR–2, the sequence described from the cuttings seems to contain more epiclastic material than limestone, and the Ponce could not be identified with certainty. The presence of the Ponce Limestone seems well established in CPR–3. A sequence of middle(?) and upper Tertiary to Quaternary gravelly sand with limestone lenses in the CPR wells overlies the middle Tertiary sequence correlated with rocks cropping out to the north. In CPR–1, there is an unconformable contact between hard Ponce Limestone and the unconsolidated gravelly Tertiary to Quaternary sequence above. This contact is indefinite in CPR–2 and may be lower than shown. At CPR–3, a definite lithological break occurs at about 550 feet, which may correspond to the unconformity at nearly 3,000 feet in CPR–1. Fossils and interrelated limestone beds indicate that the poorly consolidated middle(?) and upper Tertiary to Quaternary sequence is principally a marine deposit.

The geologic map of southeastern Puerto Rico (pl. 1) shows that north of the CPR wells the resistant south-dipping Ponce Limestone and Juana Díaz Formation are unconformably overlapped by Holocene alluvial-plain deposits. Moreover, a projection of the middle Tertiary rocks into the area of drilling suggests that a thick sequence of Ponce Limestone would be found under a rather shallow cover of Quaternary alluvium. Offshore, middle Tertiary limestone caps the older volcanic core of Isla Caja de Muertos. In short, the CPR wells reveal a previously unknown sequence, because there are no outcrops of great thicknesses of conglomeratic and sandy epiclastic rock of middle(?) and late Tertiary to Quaternary age anywhere in the area, or to the writer's knowledge anywhere in Puerto Rico.

The surface and subsurface data suggest that during the middle(?) or late Tertiary (probably Miocene) the Ponce and Juana Díaz were uplifted, eroded, tilted southward, and probably faulted along the Isla Caja de Muertos fault. Thereafter, subsidence created the Ponce basin and submerged the Muertos shelf; these have filled with a Tertiary to Holocene coarse epiclastic sequence. The tectonic development of the Ponce basin and Muertos shelf is discussed on p. 88 and 89.

SURFICIAL DEPOSITS OF QUATERNARY AGE

The distribution of the surficial deposits was determined principally by study of aerial photographs and the composition and structure of the deposits were studied by widely scattered observations on the ground. The following deals with the distribution and interrelationship of these deposits. Brief descriptions of composition and internal structure are included in the explanation of the geologic map.

CORAL REEFS, BEACH, AND MANGROVE-SWAMP DEPOSITS

A discontinuous line of coral reefs lies offshore from Bahía de Jobos on the east to Punta Petrona, and smaller reef patches are near shore at Punta Petrona and Punta Pastillo. Beach sands and swamp deposits make up small islands leeward of the offshore reefs, and large areas of beach and mangrove-swamp deposits occur along the shore.

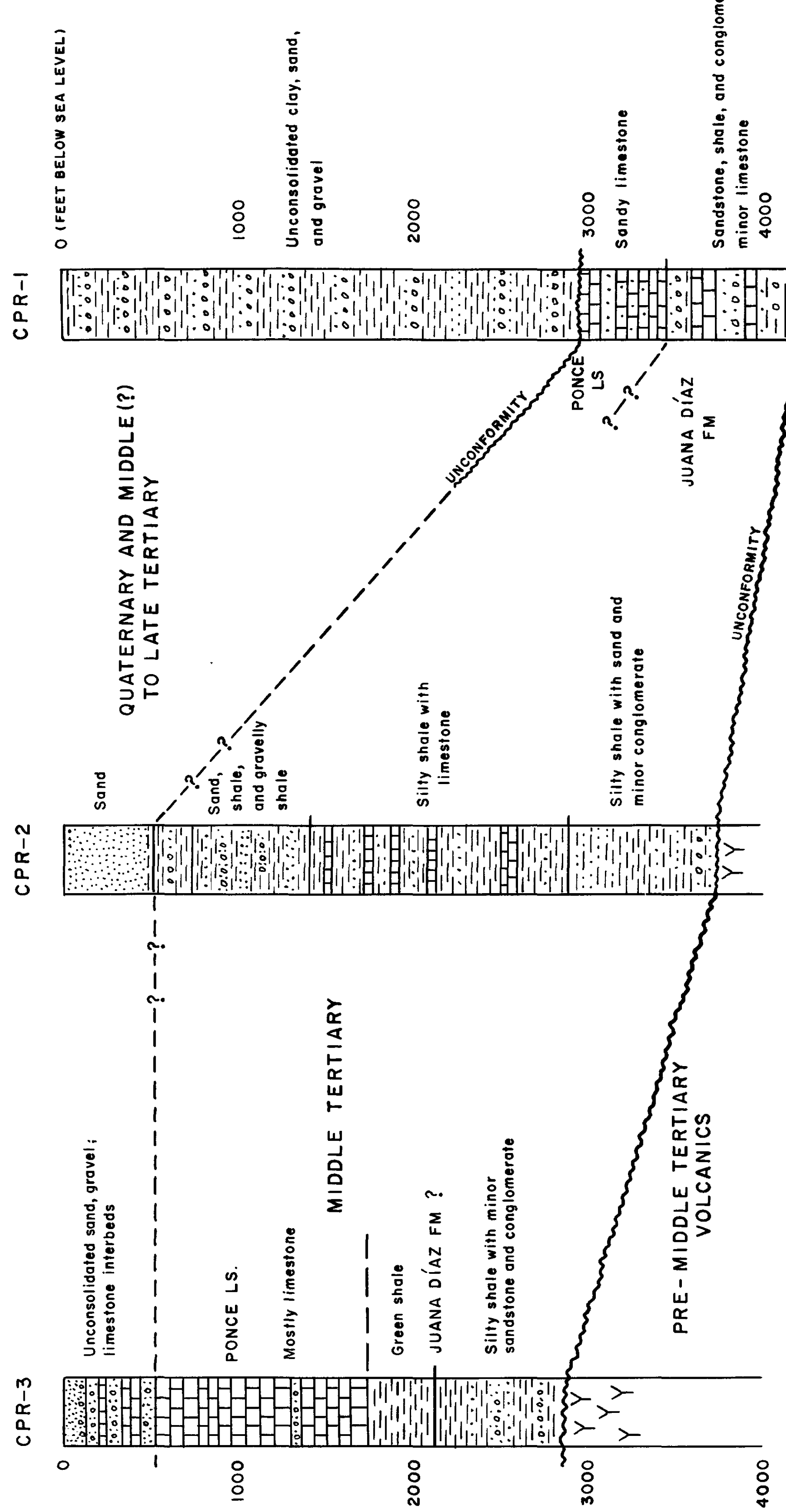


FIGURE 30.—Columnar sections of Kewanee Interamerican Oil test wells CPR-1, CPR-2, and CPR-3, south Puerto Rico. Generalized from well-completion reports prepared by Thomas N. Ambrose with paleontology by W. A. Gordon.

ALLUVIAL AND COLLUVIAL DEPOSITS

Colluvium, moved principally by sheet wash, blankets the lower slopes of the large stream valleys in the central Coamo area. The colluvium blankets and probably interfingers with the outer edges of the terrace alluvium and stream-bottom alluvium.

Terraced alluvium at elevations above recent flood levels is common along the Río Coamo and Descalabrado and their tributaries. The braided stream channel of the Río Nigua-Salinas is floored with coarse bouldery alluvium.

Alluvial cones and small alluvial fans occur in the central-western Coamo area near Proyecto Vázquez, west of the water gap of the Río Jueyes through the Cerro de las Cuevas, near the mouth of the Río Jueyes, and a couple of kilometers east of Juana Díaz.

A piedmont alluvial plain along the south coast has been formed by coalesced alluvial fans.

INTRUSIVE IGNEOUS ROCKS

Intrusive igneous rocks crop out over about 5 percent of the surface of the Coamo area. Most occur in the northeastern half of the area, but this distribution may be more apparent than real because of the extensive cover of younger rocks and surficial deposits in the southwest. Dikes are the most abundant form of intrusive, small stocks are common, and sills seem rare. One large intrusive in the center of the Coamo quadrangle appears to be a disruptive laccolith or chonolith. The control exerted by structure on magma emplacement is shown where several of the larger intrusives (Los Panes, Cuyón, and stock in Salinas Training area) were injected along older fault zones.

The igneous rocks are chiefly andesite and its coarser equivalent microdiorite, along with dacite and quartz microdiorite. Granodiorite and basaltic andesite or gabbro, respectively, constitute less than about 5 percent of the intrusive igneous rocks. The igneous rocks described below have been dated by observing their superposition, structure, and metamorphic effects within the stratigraphic and structural framework of the area and by petrographic comparison of intrusive rocks with lavas or pyroclastic rocks of known age.

PYROXENE ANDESITE AND MICRODIORITE OF PROBABLE LATE ROBLES AGE

Intrusives contemporaneous with the Robles Formation seem to be rare in the Coamo area as only five were discovered during this investigation. One of these is a small dike about 1 km east-northeast of Cacao in a tributary of the Quebrada Montería, northwestern Coamo quadrangle. It is a basic pyroxene andesite or basalt containing phenocrysts of augite in a pilotaxitic groundmass richer in pyroxene than in feldspar. Amygdules of prehnite and quartz and chloritization of the matrix reflect contact metamorphism which is attributed to the nearby Quebrada Montería stock in the Barranquitas quadrangle (Briggs and Gelabert, 1962) of Maravillas to Coamo age (p. 78). Amygdules suggest shallow emplacement. The dike was observed to be cutting tuffs of the Robles Formation, and it was probably injected during Cenomanian to Santonian time. A similar dike occurs in the Robles tuffs just east of Proyecto Vázquez, western Cayey quadrangle, and a small feeder(?) dike of augite microdiorite was seen in the type area of the Lapa Lava Member in central-western Cayey quadrangle.

In northeastern Coamo quadrangle near Escuela Degetau is an elliptical outcrop of coarse-grained augite andesite or microdiorite similar to some of the upper Robles lavas. This outcrop is shown as intrusive on the geologic map (Glover, 1961a), but contacts are not exposed and it could also be interpreted as an inlier of lava. A similar rock is shown on the northeasternmost outcrop of Las Tetas(?) Lava along the Lapa fault in southeastern Coamo quadrangle.

HORNBLENDE MICRODIORITE OF MARAVILLAS AGE

LOS PANES INTRUSIVE

A disruptive laccolith(?) or chonolith(?) just east of the town of Coamo, central Coamo quadrangle, was named the Los Panes intrusive by Glover (1961a). The intrusive crops out over an irregular subequant area of about 5 or 6 sq. mi. Contact with the country rock is broadly concordant but in detail very discordant. Rocks as old as the lower Robles Formation are commonly found around the margin of the Los Panes, but the pre-Robles rocks do not appear at the surface. The instrusive probably had feeder dikes along a preexisting west-northwest fault zone (p. 88) that passes near its center, and the loccolith was injected laterally along the disconformity at the base of the Robles. Its position with respect to major structures is discussed on (p. 88).

The principal rock type in the Los Panes is a medium-light-gray hornblende microdiorite. Many outcrops reveal a breccia structure of angular to subrounded fragments of porphyritic andesite or microdiorite in an igneous matrix of similar rock. Breccia structure occurs near the center of the laccolith as well as marginally; however, it seems to be more common near the margins. Xenoliths or mafic autoliths of coarse-grained hornblende diorite are common.

The core of the Los Panes contains abundant subequant calcic plagioclase crystals that are twinned and strongly zoned from labradorite to andesine or oligoclase. Hornblende is less than half as abundant as plagioclase. Pyroxene is rare or absent. Magnetite and apatite are each present in amounts of as much as about 3 percent.

Near the margins of the Los Panes, the texture seems to be more strongly porphyritic, and in some specimens the rock was described as porphyritic andesite rather than microdiorite. Plagioclase is similar in composition and habit to that in the core. Augite appears as a second mafic mineral in association with hornblende, but the total of mafic minerals is about equal to that of hornblende in the core rocks. Magnetite is more abundant (maximum about 10 percent) in the rocks richest in augite. Apatite is ubiquitous in amounts to about 3 percent.

Moderate deuteric alteration has affected most of the rocks to such an extent that much of the primary mineralogy and texture are obscured. Common alteration effects are complete replacement of the calcic plagioclase core by a variety of minerals that are generally too small to identify. Those that could be determined include albite, quartz, calcite, laumontite, prehnite, epidote, sericite, and chlorite. In porphyritic andesites, the matrix is patchily replaced by the same minerals. Hornblende is marginally altered to magnetite, chlorite, and calcite. Near the margin of the Los Panes, hornblende is completely altered to chlorite, calcite, and magnetite, and subhedral to anhedral grains of fresh augite appear. Lastly, numerous small veinlets of calcite and quartz-epidote-calcite occur throughout the laccolith.

It seems likely that loss of volatile pressure near the margin of the intrusive caused the breakdown of previously crystallized hornblende and allowed the late crystallization of pyroxene. Contact metamorphic effects are slight for an intrusive of this size.

HORNBLENDE ANDESITE DIKES AND EXPLOSION BRECCIAS

Hornblende andesite similar to that of the Los Panes occurs as dikes and pipelike intrusives in an area of about 0.5 sq km (square kilometers) along Highway 14, 1 km south of the northern border of the Coamo quadrangle. In the outcrops along the highway is an excellent exposure of what is doubtless a cross section of a late Cretaceous volcanic vent herein named the Asomante pipe. Hornblende andesite and explosion breccia are intimately mixed in such a way that mutual crosscutting relations are abundantly observable.

The breccia comprises angular and subrounded ill-sorted blocks of country rock which may be more than 2 meters in greatest dimension. Some of the breccia blocks seem to belong to the Robles Formation, some possibly belong to the pre-Robles, and others are from the Cariblanco Formation which forms the walls of the conduit at the level of the highway cuts. Many blocks have been metamorphosed to varying degrees. One sample from which a thin section was cut proved to be a tuff completely altered to an albite-epidote-quartz-chlorite-calcite rock.

An interesting component of the breccia is the hornblende andesite itself. It occurs as irregular clots of congealed magma showing marginal chilling effects reflected in grain size, color, and crystal orientation. Other pieces are irregular and broken into angular fragments. Locally the hornblende andesite predominates, and a rock similar in texture and lithology to tuff breccia or lapilli tuff results. Field relations show that the breccia occurs as dikes and sills, however, so that its origin seems clear.

Other moderately large intrusives of similar hornblende andesite and microdiorite include the Coamo Arriba and Quebrada Montería stocks in southwestern Barranquitas quadrangle (Briggs and Gelabert, 1962). In addition, numerous dikes and small intrusives of hornblende andesite occur in southeastern Coamo quadrangle and as small somewhat radially disposed dikes around the Los Panes laccolith.

CORRELATION WITH THE MARAVILLAS FORMATION

Hornblende andesite and microdiorite intrusives were found only in strata of Maravillas age or older. The petrographic similarity of the intrusives with the pyroclastic blocks in the Maravillas is striking and unique in the area.

Evidence is abundant for very shallow emplacement in the Los Panes laccolith, which is exposed at stratigraphic levels to within about 400 meters below the base of the Maravillas Formation. Pertinent is the autobrecciation of the intrusive, porphyritic texture for a mass of this size, and evidence of rapid loss of volatiles shown by the breakdown of hornblende and general paucity of contact metamorphism.

Finally, the explosion breccia-hornblende andesite complex along Highway 14 seems reasonably interpreted as a volcanic vent and strongly supports the contention that some of these hornblende andesite and microdiorite intrusive centers were sites of volcanoes that contributed pyroclastic material to the Campanian and Maestrichtian(?) Maravillas Formation.

PYROXENE ANDESITE AND DIORITE OF PROBABLE COAMO AGE

Dikes of porphyritic augite andesite having a pilotaxitic to intergranular matrix are common in the north-central Coamo area. Most of these are identical in lithology to the fragments in the coarse tuff breccias of the Coamo Formation.

Actual vent sites of Coamo age were not identified with certainty during the course of this investigation. However, the exceptionally massive nature of the Coamo Formation in northeastern Río Descalabrado quadrangle and the presence of an intrusive center (Zanja Blanca stock) along the Río Descalabrado suggest the former existence of source vents in this general area. The intrusive has not yielded many fresh samples, but it seems to be a complex of altered and sheared pyroxene andesite country rock and dikes and plugs(?) of pyroxene andesite(?) and coarse-grained diorite. The diorite is somewhat altered, so that identification of the original mafic mineral is in doubt. Plagioclase is strongly zoned with labradorite cores, and there is a minor amount of primary(?) quartz and potassium feldspar. Tourmaline occurs with calcite and chlorite as a replacement of pyroxene in one sample of metamorphosed andesite from the western edge of the intrusive, and a conspicuous zone of pyritized albite-epidote hornfels surrounds the center.

CUYÓN STOCK (LATEST CRETACEOUS OR EARLY TERTIARY)

The Cuyón stock, in northwestern Cayey quadrangle (Berryhill and Glover, 1960), comprises coarse-grained hypidiomorphic granular hornblende quartz diorite and basic granodiorite. Basic xenoliths of hornblende diorite are common. Study of two thin sections of the stock revealed the following approximate mode:

- 50 percent plagioclase, strongly twinned and zoned from cores of about An_{50} to rims more sodic than An_{28}; average composition is andesine;
- 15 to 20 percent quartz, interstitial;
- 12 percent hornblende, subhedral to anhedral;
- 5 to 10 percent orthoclase, interstitial;
- 2 to 5 percent biotite;
- 4 percent magnetite; and
- 1 percent each, sphene and apatite.

The stock has a broad contact aureole of bleached, pyritized, and metasomatically altered andesite tuff and conglomerate in which quartz, sericite, and clay minerals are conspicuous. Chalcopyrite occurs with the disseminated pyrite in the country rock and in the margins of the intrusive body, and secondary copper carbonates are found locally. A nearby limestone has been converted to a skarn rock near the east side of the intrusive, and some boulders of magnetite-rich rock on the west side probably were formed by replacement of the same limestone unit.

DIKES AND SILLS NEAR THE CUYÓN STOCK

Numerous small dikes and sills of hornblende- and pyroxene-bearing porphyritic rocks surround the Cuyón stock. Many were metamorphosed by it and therefore predate at least some of the intrusive activity in the area.

The Cuyón seems to have been intruded along an old fault zone, the Collao fault, which may also have guided the hydrothermal solutions that produced the Monte El Gato hydrothermally altered zone in east-central Cayey quadrangle (Berryhill and Glover, 1960).

Geologic relations shown on the map indicate that the Cuyón stock is younger than the Maestrichtian Cuyón Formation which is metamorphosed by it. Because of this and its similarity in composition to the Maestrichtian to middle Eocene Jacaguas Group and to the Utuado and San Lorenzo batholiths, the Cuyón is herein considered to be of Maestrichtian to middle Eocene age.

DACITE AND QUARTZ MICRODIORITE DIKES OF LATEST CRETACEOUS OR EARLY TERTIARY AGE

Dikes of dacite and quartz microdiorite are rare to common throughout the Coamo area. One dike about 6 km long trends west-northwest from a point about 2 km southeast of Coamo. It crops out discontinuously along strike and cuts the Los Panes intrusive and the Coamo Formation. A thin section of an altered sample of this dike was reported as quartz keratophyre in the Coamo quadrangle (Glover, 1961a). Additional study shows that the rock is a fine-grained biotite-bearing microdiorite or dacite. Most of the rock is composed of fine-grained sodic plagioclase. Quartz (20 percent) occurs as fine euhedral crystal and anhedral patches in the groundmass. Anhedral biotite makes up 5 to 7 percent; magnetite and sphene (?), about 2 percent.

In northeast-central Río Descalabrado quadrangle, several similar dikes trend north. Biotite was absent, although hornblende occurred in two of them.

A hornblende dacite dike occurs in the hills near Salinas just northwest of Parcela Ochenta. A discontinuous dike of augite-bearing quartz microdiorite with late (deuteric?) hydrobiotite strikes north from a point near the southeastern corner of the Coamo area. A similar dike containing hornblende and hydrobiotite crops out in the Río Coamo in the central-northern part of the area.

All these dikes are of similar composition, and some cut the Campanian or Maestrichtian Coamo Formation. Principally on the basis of compositional similarity with the Jacaguas Group, they are herein considered to be of Maestrichtian to middle Eocene age.

METAMORPHISM

Most of the rocks in the Coamo area contain secondary mineral assemblages characteristic of diagenetic alteration or low-grade regional metamorphism. Volcaniclastic rocks are commonly spotted or mottled by zeolitization (fig. 14*B*, *C*); where zeolitization is more complete, many are dull gray. Extensive zeolitization tends to produce a soft, somewhat friable rock likely to be identified in routine sampling as "excessively weathered." Zeolitized pyroclastic rocks tend to have a variety of colors which are probably relict from original differences in oxidation state of the fragments. Relict textures are well preserved in these rocks. The common patchy development of bright-blue-green celadonite also is especially common in, though not restricted to, the zeolitized rocks.

In contrast to the low-grade zeolitized rocks, the higher grade prehnite- and epidote-bearing rocks are drab and more uniformly medium yellowish to grayish green. These rocks are also more highly indurated and commonly are cut by veinlets containing some or all of the minerals quartz, prehnite, and epidote.

The rocks of the Coamo area are only foliated near large faults. The original textures of most rocks are well preserved.

The zeolite facies predominates in the Coamo area, but locally the higher grade prehnite-pumpellyite metagraywacke and greenschist grade rocks are found. The classification of low-grade mineral facies and zones used here is that proposed by Coombs, Ellis, Fyfe, and Taylor (1959) and Coombs (1961) and outlined by Brown and Thayer (1963).

The low zeolite facies (heulandite [clinoptilolite]-analcime zone) occurs principally in the Jacaguas Group of the Coamo area. Some rocks possibly belonging to this facies also occur in the Coamo and Maravillas Formations near the Río Jueyes fault. In addition to the diagnostic heulandite-quartz mineral assemblage, associated secondary minerals are montmorillonite, celadonite, chlorite, calcite, mordenite, and clinoptilolite Phenocrysts are commonly unaltered in this zone, most of the secondary minerals having formed from alteration of abundant glass of andesite to dacite composition (figs. 23*C*, *D*; 24 *B*, *C*).

The high zeolite facies (laumontite zone) comprises most of the volcaniclastic rocks of the Coamo area. It includes all the Coamo, Maravillas, and Cariblanco rocks north of the great southern Puerto Rico fault zone, as well as most areas of Robles rocks north of the fault zone. The characteristic mineral assemblage of this zeolite zone is laumontite and quartz, and the associated minerals are albite, analcime, clay minerals, chlorite, minor celadonite, and calcite. In this zone, plagioclase phenocrysts are extensively altered (figs. 14*B*, *C*; 21*B*), generally to laumontite and albite. Phenocrysts of augite, hornblende, sanidine, and quartz are unaffected. The laumontite zone overlaps the heulandite zone to some extent, particularly in the Miramar Formation. It also overlaps the quartz-prehnite zone in the Robles and pre-Robles rocks of the eastern Coamo area.

The prehnite-pumpellyite metagraywacke facies occurs in the Robles Formation of the northeastern Coamo area and in the upper pre-Robles rocks. It also occurs south of the Río Jueyes fault in rocks of the Coamo, Maravillas, Cariblanco, and Robles Formations. Pumpellyite is rare; most of the rocks of this facies contain prehnite and less commonly they contain epidote. Quartz-prehnite and quartz-prehnite-epidote are the characteristic mineral assemblages, and these are associated with albite, chlorite, calcite, sphene, and rarely pumpellyite. Laumontite in some of these assemblages north of the Río Jueyes fault indicates overlap with the zeolite facies.

The greenschist facies is attained only locally in the Coamo area. Quartz-albite-epidote-chlorite assemblages have been discovered south of the Río Jueyes fault as well as in the upper pre-Robles rocks in the eastern Coamo area. The boundary between the greenschist and metagraywacke facies is also broadly overlapping. None of these rocks are schistose.

Contact metamorphism around dikes and stocks in the Coamo area has led to development of albite-epidote hornfels and lower grade albite-prehnite-quartz-bearing rocks. Retrogressive zeolitization affected both the hornfels marginal to the Campanian Los Panes intrusive and the intrusive itself. Chlorite-sericite-heulandite-quartz veins were found in the Cuyón stock of probable Maestrichtian to early Tertiary age, but no zeolitization of the stock or its contact rocks has been observed.

A hydrothermally altered zone of pre-Robles rocks occurs east of the Coamo area (Berryhill and Glover, 1960). This alteration zone is probably of early Tertiary age.

The tectonic and igneous history of the Coamo area and the distribution of metamorphic facies described above suggest a complex diagenetic and metamorphic history. North of the Río Jueyes fault, the older and more deeply buried formations are more highly metamorphosed. They also crop out nearer the major pluton. South of the Río Jueyes fault, all autochthonous Cretaceous formations are uniformly metamorphosed to high metagraywacke or low greenschist facies. Thus the laumontite subfacies occurs in the Coamo Formation north of the Río Jueyes fault, and metagraywacke or greenschist facies occurs in the Coamo Formation south of the fault.

The zeolite facies isograds must cross stratigraphic boundaries, contrary to Otálora's (1964) belief.

Reconnaissance data suggest a generally systematic increase in metamorphic grade toward the major centers of batholithic intrusion (pl. 1), and the stratigraphic distribution of the higher grade facies suggests a major thermal event that is post-Coamo, possibly Maestrichtian-Paleocene in age.

Although the sequence is broken by faults, both low zeolite facies (allochthonous Jacaguas Group) and high metagraywacke facies (autochthonous Cretaceous rocks) occur south of the Esmeralda fault, and the low-grade rocks are exclusively from the Jacaguas Group. Hence, there is a suggestion of a metamorphic discontinuity coinciding with the major unconformity at the base of the Jacaguas. Major folding and emplacement of plutonic rock also occurred about this time (fig. 17).

Contrary to the idea of a regional metamorphic episode at the end of the Cretaceous, the apparent systematic decrease in grade of metamorphism across the basal Jacaguas unconformity north of the Esmeralda fault zone suggests a middle Eocene metamorphism. A satisfactory solution may be obtained by the studies now in progress of the distribution of metamorphic facies over a large area.

STRUCTURAL GEOLOGY

The largest fold structure of the region is the Puerto Rico geanticline (fig. 4), a young feature defined by the gentle dips of the rocks of middle Tertiary age. The Coamo area includes only a very small part of the southern flank of this broad structural element. Smaller, more intensely deformed structural elements include the southern flank of the Barranquitas anticlinorium and the great southern Puerto Rico fault zone. Structures of the next smaller order of magnitude are the domes and associated folds and small faults related to emplacement of shallow igneous bodies, and structures such as the gravity-slide sequence and megabreccia.

Left-lateral strike-slip faulting seems to have been an important mode of deformation during the Cenomanian to middle Eocene interval (fig. 34). Folding preceded and accompanied batholithic intrusion during the Late Cretaceous and early Tertiary. Finally, broad geanticlinal upwarp followed cessation of igneous activity and diminution of faulting during the middle Eocene to early Oligocene interval.

Six unconformities occur in the rock sequence of the Coamo area. They are indicated in the stratigraphic summary and discussed with the appropriate stratigraphic units.

The Puerto Rico geanticline is the broad asymmetrical upwarp defined by the gentle dips of the middle Tertiary sequences of northern and southern Puerto Rico (fig. 4). On the northern flank of the geanticline the middle Tertiary rocks dip northward at angles of only a few degrees, but the southern flank is steeper, and near Ponce it dips as much as 30° S. The crest of the structure nearly coincides with the present drainage divide of Puerto Rico, which also lies nearer the south coast of the island. Geanticlinal upwarp along an east-trending axis began during the middle Eocene to early Oligocene interval and has continued sporadically until the present. Monroe (1962) has documented the arching and uplift as recorded in unconformities within the middle Tertiary rocks of the north coast.

The trend of the geanticlinal crest is east-west, at an angle of about 30° to the dominantly west-northwest structural trends in the older volcanic rocks.

SOUTHERN FLANK OF THE BARRANQUITAS ANTICLINORIUM

The Barranquitas anticlinorium is shown in figure 4 and on the geologic map of southeastern Puerto Rico (pl. 1). The anticlinorium is herein defined to include on its southern flank the Lapa anticline and Coamo syncline. The axial trace of the anticlinorium passes near the town of Barranquitas, from which the structure takes its name. The Amoldadero and Arenas anticlines of the Comerío quadrangle (Pease and Briggs, 1960) and the extension of the Amoldadero anticline in the Barranquitas quadrangle (Briggs and Gelabert, 1962) lie along the crest of the Barranquitas anticlinorium. The axis of the crestal anticline swings more northwest as it approaches the Utuado batholith. A complementary curve in the axis of the Coamo syncline occurs on the south flank of the anticlinorium. Folds on the north flank of the anticlinorium can be recognized in the great northern Puerto Rico fault zone north of the Coamo area (M. H. Pease, Jr., unpub. data) and are shown on the geologic map of southeastern Puerto Rico (pl. 1).

COAMO SYNCLINE

The Coamo syncline in the northern part of the Coamo area is a broad open fold with a near vertical axial plane and flanks that dip about 20°. The general trend of the structure is east, but the axial trace seems to be sinistrally offset along northwest-trending faults near the east end, and the trace curves west-northwestward near the west end. The Coamo syncline is more than 30 km long. The west end of the structure was refolded by doming around the Utuado batholith. At the eastern plunging end of the Coamo syncline, smaller folds with east-trending axial planes are common and cause some uncertainty in locating the axis of the principal fold. These folds are probably large drag folds coeval with the major syncline. Only a few of these folds have been shown on the geologic map (pl. 2). Additional bedding attitudes, if available, would undoubtedly define many others.

LAPA ANTICLINE

The Lapa anticline in south-central Coamo area is a broad open structure complementary to the Coamo syncline. The Lapa anticline is somewhat obscured because of refolding of an earlier dome coincident with the Los Panes intrusive. The effect of refolding the Los Panes dome was to shift the axial trace of the resultant composite structure northward. The Lapa anticline plunges westward beneath the onlapping Jacaguas Group which does not seem to be folded with the structure.

The Lapa anticline may have been localized by late pre-Robles topography. In the Cayey quadrangle (Berryhill and Glover, 1960) pre-Robles formations B, C, and D form an antiformal structure of probable depositional origin that seems to be part of the Lapa anticline. These formations rest with probable unconformity upon westward-dipping strata of pre-Robles formation A, which is warped into a gentle syncline plunging west. Most of the pre-Robles rocks are near-vent coarse marine pyroclastic rocks and lavas. The structure and rock types suggest an ancient submarine volcanic cone comprising formations B, C, and D, which were deposited upon the subsiding volcanic strata of formation A. Some of the effects of Paleocene-Maestrichtian folding of the Lapa anticline must have been to tighten the primary anticlinal structure of the late pre-Robles sequence and to partly unfold the synclinal structure of formation A.

STRUCTURES ASSOCIATED WITH THE LOS PANES INTRUSIVE

The Los Panes intrusive crops out over a subcircular area nearly 5 km in diameter near the center of the Coamo quadrangle. The intrusive was emplaced during the Late Cretaceous (Campanian) (p. 78). Therefore the structures associated with it antedate the main Maestrichtian-Paleocene folding that formed the Lapa anticline.

The contact of the Los Panes mass is broadly concordant with the domal structure of the host rocks, but in detail the intrusive is quite discordant. The country rocks dip away from the intrusive on all sides, and there is little doubt that they were domed at the time of intrusion. The oldest rocks at the surface along the margin of the intrusive are the lower Robles Formation; no pre-Robles rocks were found. The porphyritic texture and autobrecciation (p. 77) of the Los Panes reflect rapid cooling and multiple injection at a depth of about 400 meters (p. 78). Restriction of the Las Tetas Lava to the northern half of the Los Panes has been related to the presence of a possible ancient fault (p. 77) along which the magma may have been injected. The Los Panes may be a discordant laccolith or chonolith emplaced along the contact between the Robles and pre-Robles.

Along the western edge of the intrusive, overturned bedding was noted along a ridge crest. A curved fault convex westward was mapped at the east foot of the ridge. Easily weathered mafic lava composes most of the eastern upthrown block. This fault is interpreted to be a low-angle thrust fault dipping eastward, and the overturned bedding on the ridge crest is believed to reflect footwall drag-folding. Differential weathering resulted in the footwall block becoming a topographic high. The thrusting probably occurred during the intrusive doming.

Doming due to emplacement of the Los Panes intrusive in Campanian time formed an ill-defined northeast-trending synclinal structure to the southeast, which was later deformed by the plunging nose of the Maestrichtian-Paleocene Lapa anticline.

ASOMANTE PIPE

Reasons for considering the Asomante pipe a volcanic vent site are discussed on p. 78. Structurally the feature may be described as a vertical pipe of explosion breccia and hornblende andesite dikes centered on a small dome in the Cariblanco Formation.

CONGLOMERATE DIKES

Dikes of intrusive volcanic conglomerate were found in two localities. In the bed of the Río Descalabrado about 2.5 km north of the water gap through Cerro de Las Cuevas are several small dikes. One about half a meter thick strikes N. 50° E. and dips vertically. Among the well-rounded boulders and cobbles are coarse-grained diorite, banded chert, porphyry, and calcareous volcanic siltstone or calcereous tuff. The matrix seems to be a fine- to medium-grained tuff, and the country rock is massive tuff breccia of the Coamo Formation. The source for the dike rocks may have been in the Maravillas or Cariblanco conglomerates, but this is considered unlikely because of the presence of coarse-grained diorite. Such diorite cobbles are rare or absent in formation older than the Coamo. Alternatively, the conglomerate may have moved downward into a tension crack from the surface of unconformity below the Miramar Formation.

Intrusive conglomerate also occurs along Highway 555 about 0.6 km south of Escuela Quebrada Grande in northeastern Río Descalabrado quadrangle (fig. 31).

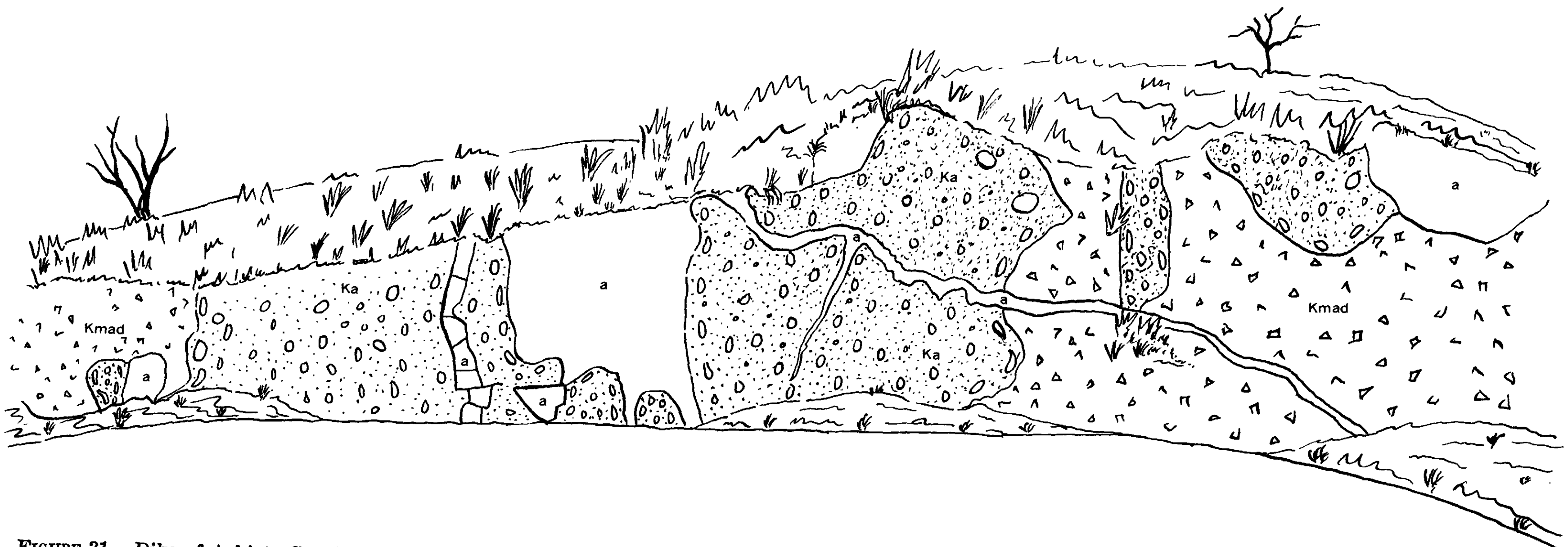


FIGURE 31.—Dike of Achiote Conglomerate, Ka, intrusive into massive San Diego Member, Kmad, of the Maravillas Formation. Younger andesite dike, a cuts both formations, but preferentially intrudes the softer Achiote Conglomerate. Exposure is about 50 meters wide. Looking north in sharp west bend of Highway 555 about 0.5 km south of Escuela Quebrada Grande, northeast corner of the Río Descalabrado quadrangle. Sketch by Jeremy Reiskind, July 21, 1961.

Red boulder conglomerate from the Achiote Conglomerate has moved upward about 150 meters into the overlying San Diego Member of the Maravillas Formation. Near vertical alinement of the ellipsoidal boulders, "streaking out" of softer gravel, and abundant evidence in the fabric of vertical flowage nearly parallel to the irregular sides of the dike testify to the diapiric mode of emplacement. A fault strikes toward the diapir from the southeast, but it was not detected at the site of intrusion. Perhaps this fault localized the diapir.

Rapidly deposited clay-rich sediments such as the Achiote Conglomerate probably remain viscous and water saturated for geologically long periods of time. The host San Diego Member was eroded by the scouring action of the viscous conglomerate during injection. The competence of the San Diego, therefore, suggests that it was well indurated, and the time of intrusion may have been as late as the early Tertiary.

GREAT SOUTHERN PUERTO RICO FAULT ZONE

GENERAL

The great southern Puerto Rico fault zone (fig. 4, pl. 1) which trends west-northwest through the island is the major fault system in the Coamo area. The fault zone has undergone major vertical and left-lateral wrench movements during a history of intermittent activity that may have begun in the Early Cretaceous. Major changes in the Albian to Santonian stratigraphic sequences occur across this fault zone; the pre-Robles, Robles-Río Orocovis, and possibly the Cariblanco-Achiote sequences of the central block have not been recognized in the southwestern block, and they are perhaps represented by only a very thin unit of lava (Río Loco Lava of Mattson, 1960), which is unconformable upon the Lower Cretaceous (Albian or older) serpentine-rich Bermeja complex (Mattson, 1960). Although the lithofacies are quite different on either side of the fault zone, the sequence of Upper Cretaceous Maravillas and Coamo rocks of the central block correlates with the Mayagüez Group (Mattson, 1960). The Mayagüez Group conformably overlies the Río Loco in the southwestern block. The Maestrichtian Miramar Formation of the central block correlates in part with the San Germán Formation (Mattson, 1960) of the southwestern block and the lithofacies are similar. Lower Tertiary rocks are similar in both blocks.

Amphibolite from the serpentine of the Bermeja complex has been dated radiometrically as about 100 m.y. (million years) (P. H. Mattson, written commun., 1964); hence, this unit is probably of Albian age or older. Most likely the Bermeja complex is oceanic crust (Mattson, 1960; Hess, 1964) upon which the Albian pre-Robles sequence of the central block was deposited. The Río Loco Lava has not been dated, but it is conformably overlain by the Mayagüez Group, which is probably no older than Campanian, possibly Santonian (Pessagno, 1960b).

Although critical data are sparse, they suggest the following conclusion: (1) The volcanic rocks of Puerto Rico were deposited upon the Bermeja complex, which probably is oceanic crust, (2) any Albian to Santonian cover (exception Río Loco? in the southwestern block) is either very thin or was eroded prior to deposition of the Mayagüez Group, and (3) the rocks presently juxtaposed along the fault zone may not have shared a similar environment of deposition until the Maestrichtian. All this indicates that the great southern Puerto Rico fault zone is an ancient one that has undergone intermittent movement during most if not all of the geologic history of Puerto Rico.

Southeast of Puerto Rico, a continuation of the zone along strike is suggested by discontinuities shown on the total magnetic intensity map (Geddes and Dennis, 1964), and by a submarine scarp forming the south wall of the Virgin Islands Trough. These relations are shown in figure 32.

DETAILS OF THE FAULT ZONE IN THE COAMO AREA

The great southern Puerto Rico fault zone in the Coamo area (pl. 2) forms a west-northwest-trending belt of horsts and grabens. The Maestrichtian to middle Eocene Jacaguas Group and large gravity glide structures in the Coamo area are confined to the fault zone. The principal high-angle faults are remarkably straight and apparently dip steeply. Gravity studies (Andrew Griscom and W. L. Rambo, unpub. data) have shown that similar faults of the system occur beneath the alluvial plain along the coast.

The Río Jueyes fault forms the northern boundary of the fault zone. This fault is well exposed in the south-central part of the area. To the southeast it is covered by the alluvial plain, but its presence is indicated by the ragged fault-line scarp of pre-Robles rocks and by the proximity of the Miramar Formation west of Coquí village to the Lapa Lava just northeast of the village.

West of the Río Coamo the fault enters the belt of glide structures on Cerro de Las Cuevas and could not be detected just west of the crest of the mountain. About 3 km west of the crest and on strike the fault appears again as a high-angle fault cutting the glide structures.

The thermal springs at Baños de Coamo (Hodge, 1920) are along the Río Jueyes fault and related nearby fractures. Similar hydrothermal activity in the geologic past probably accounts for the numerous

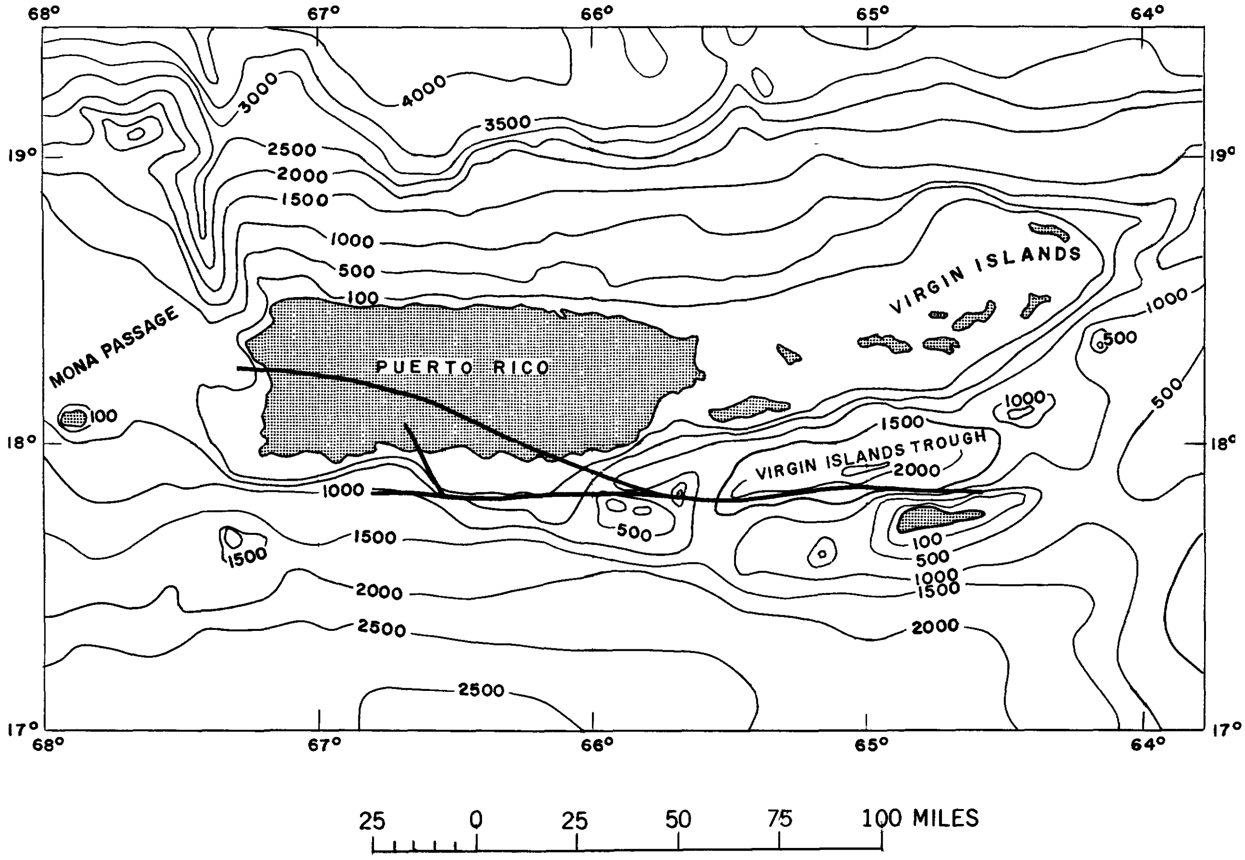


FIGURE 32.—Great southern Puerto Rico fault zone and its junction with the southern boundary fault of the Virgin Islands Trough. Bathymetry from Geddes and Dennis (1964). Isobaths, in fathoms.

pockets of dolomitized Cuevas Limestone in the belt of outcrops between the "ends" of the Río Jueyes fault and suggests the presence of the fault at depth.

The Río Jueyes fault is believed to have been active during the Maestrichtian or earlier because of the evidence for a fault-line scarp along its course during the deposition of the Jacaguas Group. The Cuevas Limestone was deposited disconformably upon the Coamo Formation north of the fault, whereas south of the fault, several pre-Cuevas and post-Coamo formations occur (Miramar, Raspaldo, Los Puertos). These stratigraphic relationships are illustrated in a diagrammatic restored section shown on plate 4.

The Esmeralda fault is the second major fault of the zone in the Coamo area. It is south of the Río Jueyes fault and is separated from it by only 1½ to 2 km for at least 30 km along strike. West of the Río Coamo, the fault branches; the southern branch is herein named the Cañas Abajo fault. The Cañas Abajo and Esmeralda approach and possibly join beneath the mid-Tertiary sequence near Juana Díaz.

Great thicknesses of fault gouge occur along the Esmeralda fault. These are shown somewhat diagrammatically on the structure sections (pl. 4) and on the geologic map north of Cuatro Calles. North of Cuatro Calles, the gouge (B) is intensely sheared volcanic rock and limestone, the gouge foliation dipping at very high angles. The limestones are similar to pre-Coamo limestones, and the volcanic rocks include types typical of pre-Coamo rocks also. From the geologic map and cross sections it can be seen that the Coamo Formation probably forms the walls of the fault on both sides of the Esmeralda. The gouge is, therefore, stratigraphically out of place.

Although the gouge could have originated in several ways, additional observations on the great southern Puerto Rico fault zone suggest that intermittent high-angle reverse faulting, left-lateral wrenching, and diapiric movement of gouge all have combined to create the present structure.

Left-lateral movement is indicated on the south side of the Cañas Abajo fault west of the Río Descalabrado by a large synclinal drag fold in the Maravillas Formation. The south limb of the syncline probably reflects the prefault structure of these rocks. The northeast strike and northwest dip of this limb, therefore, indicate that it is part of the nose of the Lapa anticline. This reconstruction suggests a left-lateral displacement of at least 10 km of post-Campanian-Maestrichtian movement.

This solution is not unique, but other possibilities are considered less likely. Among these possibilities one might consider simple uplift of the block south of the Cañas Abajo fault, but such uplift would not be likely to produce a synclinal drag fold. The stratigraphic relations shown on the map demonstrate the relative uplift of the block south of the Cañas Abajo fault, but the large-scale drag folding and development of very thick and intensely sheared gouge along these remarkably straight and steeply dipping faults suggests that large-scale left-lateral wrench movement was an important factor.

According to Andrew Griscom and W. L. Rambo (unpub. data), a fault trending N.80°W. is buried beneath the alluvial-plain sediments and mid-Tertiary sequence in the southern part of the Coamo area. This fault, postulated from a very steep gravity gradient, is subparallel to the principal fault trend of the area and is undoubtedly a part of the great southern Puerto Rico fault zone. The fault is shown on plate 1.

GRAVITY GLIDE STRUCTURES

The rocks of the Jacaguas Group in the Coamo area are highly deformed by folding and faulting. In addition to the high-angle faults of the great southern Puerto Rico fault zone, a great many faults dip 45° or less, and some faults with very sinuous traces are nearly horizontal. Tight, locally almost isoclinal folding preceded and accompanied the low-angle faulting. Such structures are rare in the older Cretaceous rocks of Puerto Rico. In the Coamo area they developed in the younger volcanic rocks as gravity glide structures formed principally during the middle or late Eocene. Tilting of the major blocks in the great southern Puerto Rico fault zone simply dumped the shallower and less consolidated parts of the sequence toward the north-northeast.

The geologic map of the Coamo area (pl. 2) and the cross sections of the great southern Puerto Rico fault zone (pl. 4) show the details of these structures that occur most abundantly in the area west of the Río Coamo. The imbricate allochthonous plates of folded rocks west of the river are bounded on the southern side of the zone by nearly horizontal faults which become steeper and approach 45° on the northern side. Faults that are not horizontal generally dip south, and the most steeply dipping faults of the glide system are those near the Río Jueyes wrench fault and its postulated fault-line scarp.

West of the Río Coamo, individual plates in the imbricate structure have outcrop widths of as much as 1 km and may exceed 8 km in unbroken outcrop length. East of the river, the Jacaguas Group probably consists of a single allochthonous plate 2 km wide and more than 10 km long. The plates are also segmented by later movements of the high-angle faults belonging to the great southern Puerto Rico fault zone. This post-gliding segmentation of the plates and the imbricate nature of the glide structures preclude direct measurement of the maximum size of any one plate. Probably the maximum size approaches that of the larger structural blocks bounded by the high-angle faults of the great southern Puerto Rico fault zone (about 15×3 km).

Two to four allochthonous plates are commonly found in a traverse across the Jacaguas Group (pl. 4). Some allochthonous plates are separated by only a thin tectonic breccia, but other plates are separated by thick zones of the megabreccia (mB_1, mB_2) (p. 71).

Many of the large blocks in the megabreccia were derived from the older Cretaceous sequence (p. 72), and the nearest present-day outcrops of similar rocks are in the steeply dipping gouge zone (B) of the Esmeralda fault. Many of these blocks are intensely sheared like the rocks in the Esmeralda gouge, and they show a higher grade of metamorphism than rocks of the Jacaguas Group. These large blocks of sheared and metamorphosed Cretaceous rocks are very different from the tectonic breccia that occurs elsewhere between allochthonous plates. The tectonic breccia in contrast is thin and comprises principally Jacaguas Group rocks generally cognate with subjacent and superjacent rocks. In the few localities where the tectonic breccia is well exposed, it is made up of angular fragments and does not seem to be sheared with the intensity observed along faults of the high-angle system.

The most likely source of the large older Cretaceous rocks found in the megabreccia is the Esmeralda fault zone. The great volume of the megabreccia suggests that it did not originate entirely as accidental blocks torn from the autochthonous Cretaceous rocks by the superjacent glide plate, but that landsliding of breccia from an ancient Esmeralda fault scarp may have been an important factor. Diapiric extrusion of Esmeralda fault gouge is another possible mechanism of origin suggested by the fact that rocks in the Esmeralda gouge originated from formations at depth and not entirely from the present stratigraphic level of the wallrock. The north dip of the Cuatro Calles fault where it is in contact with the Esmeralda gouge (B) at Cuatro Calles suggests doming by more recent diapiric movement of the gouge (B). This is the only fault in the glide sequence that dips northward.

Moderate to strong folding characterizes many of the allochthonous plates (pl. 4). The folds are cut by the low-angle faults, and as a result, steeply dipping beds of similar attitude in different formations occur above and below a nearby horizontal fault. Such relations may be seen south of Poblado Guayabal at the western edge of the Coamo area where the steeply dipping Guayo Formation (Tgb) is thrust over a large block of megabreccia (mB_2) as well as over the underlying plate of Miramar Formation (Kmi), all of which dip and strike in general conformity with the Guayo.

The larger folds truncated by the low-angle faults undoubtedly formed prior to most of the faulting. Probably the tilting first caused folding of the thin-bedded sequence which then failed by faulting along gently northward-dipping planes at high angles to the bedding.

Very tight to moderately tight folding of smaller amplitude is found at the edge of some allochthonous plates. An excellent example of this is found in the Río Descalabrado just south of the water gap through Cerro de las Cuevas. At this locality, thin to medium-bedded tuffs of the Río Descalabrado Formation are tightly folded where the edge of the allochthonous plate abuts the competent Cuevas Limestone.

Nine determinations of paleoslope directions were made on sedimentary features in the Jacaguas Group. Measurements were made in all formations of the group except the Guayo. Indicators used were principally slump folds or crossbedding associated with graded bedding of turbidity-current origin. Seven determinations suggest a paleoslope toward the north-northeast and two, a paleoslope toward the south-southwest. The slopes, whether north-northeast or south-southwest, probably reflect tilting of blocks within the great southern Puerto Rico fault zone.

Four principal faults west of the Río Coamo (Los Llanos, Guayabal, Cañas Arriba, and Cuatro Calles faults) apparently persist laterally and divide the Jacaguas rocks into a basal autochthonous unit overlain by four principal allochthonous plates (pl. 4, sections *A–A′* through *E–E′*). East of Río Coamo, a single large allochthonous plate occupies the graben between the Río Jueyes and Esmeralda faults (pl. 4, sections *F–F′ G–G′*). The four plates west of the Río Coamo are partly segmented by vertical faults of the great southern Puerto Rico zone and by subsidiary faults of the low-angle glide system. Each of these segmented plates probably represents a distinct if nearly coeval episode of gravity gliding.

Several lines of evidence suggest that the block east of the Río Coamo is allochthonous. First, the thin-bedded Raspaldo Formation has moderately tight folds similar to those in the allochthonous plates west of the Río Coamo. Secondly, near the eastern edge of the block, the contact between the Miramar and Raspaldo Formations is a low-angle fault in partially consolidated sediments. A tightly folded small anticline of relatively competent calcareous(?) tuff near this contact is embedded in slumped and plastically disrupted fine-grained tuffaceous mudstone of the Raspaldo Formation. Thirdly, the Miramar Formation occurs in the bed of the Río Jueyes just south of the water gap. Because this outcrop is surrounded at higher elevations on three sides by steeply dipping Cuevas Limestone, a concealed low-angle fault probably truncates the Miramar. Fourthly, offset of the Cuevas Limestone at the Río Coamo water gap indicates a north-northeast-trending fault of considerable magnitude. Because the fault does not cleave rocks north of the Río Jueyes fault, it must be a tear fault in a glide sheet. The tear fault, called the Río Coamo fault, is shown on the geologic map as concealed beneath the alluvium of the Río Coamo. This evidence indicates that an early glide plate, moving along the Los Puertos(?) detachment surface, tore with a sinistral motion along the Río Coamo fault. Subsequent movement along the great southern Puerto Rico fault zone resulted in preservation of the detached Jacaguas rocks in a graben between the Esmeralda and Río Jueyes faults.

The available evidence suggests that the rocks of the Jacaguas Group slid downslope toward the north-northeast. In summary, this evidence is as follows: (1) The imbricate structure has a dominant southerly dip, (2) the only known source of the more highly metamorphosed blocks in the megabreccia lies south of their present position and, (3) the northeastern edges of the glide sheets are crumpled where they abut more competent rocks. Moreover, sedimentary features within the Jacaguas Group suggest paleoslopes down toward the north-northeast during part of the deposition of the group.

The sliding occurred principally in the time interval between the middle Eocene and early Oligocene, because middle Eocene rocks deformed by gliding are unconformably overlain by undeformed Juana Díaz Formation, the base of which has been dated as early Oligocene.

Miocene or younger stata are tilted 15° to 30° S. as shown by bedding attitudes in the middle Tertiary rocks. Therefore, the north-northeast paleoslope has been diminished by about this amount since the gliding took place.

OTHER PRE-OLIGOCENE FAULTS

The Coamo area has undergone relatively shallow deformation accompanied over a long period of time by igneous activity, deposition, and metamorphism. It is not surprising, therefore, that many faults seem to have random relations to the better defined fold structures and fault systems in the area. Localization of heat, intrusive rocks, deposition, and erosion all tend to produce changes in the thickness and physical strength of the developing crust and thereby tend to warp and deform old structures and to deflect younger ones. The following discussion, therefore, regards much of the minor faulting as a nearly random shattering and attempts to relate only a few of the larger or more easily explained faults to some of the structural features previously described.

Faults parallel and subparallel to the great southern Puerto Rico fault zone are common and probably are parts of the same system. They are particularly abundant between the Los Panes intrusive and the Río Jueyes fault and in this area are most obviously related to that system.

A conspicuous zone of faulting just north of the Los Panes extends parallel to the great southern Puerto Rico fault zone. Early movement on the zone north of Los Panes during the Cenomanian or Santonian (p. 20) could well account for the different thicknesses and facies of the Robles Formation on either side of the fault zone in the vicinity of Proyecto Vázquez. This possible early movement also suggests the antiquity of the great southern Puerto Rico fault system of which it is a part.

The Collao and Río Matón faults, west of Cayey, are similar in trend and are also possibly part of the same system as the great southern Puerto Rico fault zone.

Another group of faults, the Orocovis-Llanos, Cotorra, and Matrullas, that trend from north-northwest to north-northeast enter the Coamo area from the north but seem to end abruptly. They are major faults, however, and extend many kilometers northward as shown on plate 1. According to Briggs (oral commun.) some strike-slip movement occurred on these faults, especially in the Orocovis quadrangle, where they offset older faults that are part of the great southern Puerto Rico fault system. Similar offsets occur in the Coamo area 2 km west of the Cuyón intrusive where the Orocovis-Llanos fault truncates two west-northwest-trending faults.

The Orocovis-Llanos-Cotorra-Matrullas fault system is part of a group of perianticlinal cross faults and normal cross faults (de Sitter, 1964, p. 193) related to the folding of the Barranquitas anticlinorium. According to de Sitter, during the growth of a fold by tangential compression, the culmination (highest point on the axis) moves forward more than the pericline (plunging end of the fold). Thus, tension along the axis causes high-angle cross faults to develop, and where the axis curves, a wrench component of movement also results. Cross faults die out abruptly on the flanks of the fold.

The relation of the cross faults to the anticlinorium implies that their principal movement took place in the Maestrichtian because development of the anticlinorium was completed at that time. This is additional evidence that some movement on the great southern Puerto Rico fault system occurred during the Cretaceous, because faults belonging to this system are cut by the Maestrichtian cross faults.

OLIGOCENE TO HOLOCENE DEFORMATION

The unconformity at the base of the middle Tertiary sequence is made conspicuous by the contrast between the greatly dipping nonvolcanic carbonate-rich rocks above, and the highly deformed, often steeply dipping volcanic rocks below. Volcanism and intense deformation seem to have waned simultaneously.

Middle Tertiary arching along an east-trending axis approximately coincident with the present island drainage divide resulted in the asymmetrical Puerto Rico geanticline previously described. Bedding attitudes as steep as 30° S. were measured by Zapp, Bergquist, and Thomas (1948) in the Ponce Limestone just west of Ponce, and attitudes of 15° SSW. were measured during this investigation in the type area of the Juana Díaz Formation.

PONCE BASIN

The Ponce basin is herein defined as the basin containing the thick sequence of Miocene(?) to Holocene rocks and sediments bounded on the southeast by the Caja de Muertos fault, on the northeast by the limits of middle Tertiary outcrop, and on the northwest by a concealed fault(?) or hinge line parallel to the Caja de Muertos fault (pl. 1).

The evidence for the Caja de Muertos fault comes chiefly from a seismic reflection survey by United Geophysical Company, Inc., made in 1948 (Denning, 1955). The survey disclosed a well-defined line of "no reflection" and sharp dip reversal that suggests drag due to downward movement of the block west of the fault. Offset was also suggested by the dip information and consequent impossibility of closing the seismic traverses across the trend of the no-reflection zone. A scissors movement is suggested by the observation that about 3,600 feet of vertical displacement near Isla Caja de Muertos dwindles to nothing just west of Santa Isabel. Don Mabey (written commun., 1963) restudied the seismic-reflection data and concluded in part that

> . . . The northeast trending fault inferred by United near SP–32 is certainly a major seismic feature. In addition to the no reflection area described in United's report, there is an indication that the sedimentary section is much thinner southeast of the feature. The 3,600-foot displacement indicated by United on their structure horizon is a reasonable displacement on the surface of the basement complex. . . .

Additional evidence favoring the fault hypothesis is found in the linear topographic scarp coincident with the no-reflection zone, and the occurrence of outcropping volcanic rocks of probable early Tertiary age on Isla Caja de Muertos.

Along the northern margin of the basin, Zapp, Bergquist, and Thomas (1948) mapped a syncline and an anticline. During the present investigation, a normal fault was found at the contact between the Juana Díaz Formation and the older volcanic rocks (pl. 1). This fault apparently is evidence of reactivation of the old high-angle reverse and sinistral wrench system of the great southern Puerto Rico fault zone. The parallelism of the axial trace of the adjacent syncline with the fault suggests a simultaneous origin for these structures.

The northwestern boundary of the Ponce basin seems to be a hinge line, though part of it could be a fault. The trace of the hinge is suggested by the northeasterly lineation of topographic and geologic elements and by the swing of strike of middle Tertiary rocks toward the northeast on the basin side of the hinge line.

The sequence of rocks and sediments in the oil test wells (CPR–1, –2, –3; p. 75) suggests that the Ponce basin originated during an episode of Miocene faulting. The basin has been rapidly filled, principally with coarse terrigenous debris reworked from river alluvium, and in part with fine sediments and lenses of reef limestone.

ISLA CAJA DE MUERTOS SHELF

A broad shallow shelf, 10 by 50 km in overall dimensions and covered by water generally less than 15 fathoms deep, lies offshore south of the Coamo area (pl. 1). The shelf is herein named for Isla Caja de Muertos, a monadnock of lower and middle Tertiary rocks rising from a submerged and partly buried fault-line scarp. The southern edge of the shelf is bounded by a very straight, steep slope with an inclination of about 400 fathoms per mile, or about 22°.

The shelf is bounded on the north and perhaps on the west by faults of the great southern Puerto Rico fault zone. The steep and straight southern slope suggests that this part of the shelf is also bounded by a fault.

Seismic refraction work (Officer and others, 1959) on the shelf suggests the presence of volcanic rocks (v_P about 4.0 km/sec) at depths of about 1 km near the southeastern and southwestern edges of the shelf. South of the shelf, the volcanic sequence thins abruptly (fig. 33). The volcanic rocks are overlain by materials of low seismic velocity, probably middle Tertiary to Holocene sediments.

The scanty data suggest that the slope on the top of the volcanic sequence is about as steep as that on the middle Tertiary to Holocene cover. If this is so, then the steep southern slope beyond the shelf probably persisted from Late Cretaceous and early Tertiary time. Although the slope might be depositional, its striking uniformity suggests faulting as the more probable origin.

The tectonic history of the Coamo area suggests that the shelf was blocked out as a tectonic feature during the Late Cretaceous and early Tertiary, principally by movements along faults of the great southern Puerto Rico fault zone. Erosion during the Maestrichtian and middle to late Eocene then beveled the surface of the volcanic rocks. The middle Tertiary and Holocene sediments merely blanketed the earlier volcanic shelf and aggraded the surface where later structures such as the Ponce basin were formed. Pliocene(?) and Pleistocene lowering of sea level undoubtedly led to further beveling and perfected the shelflike form.

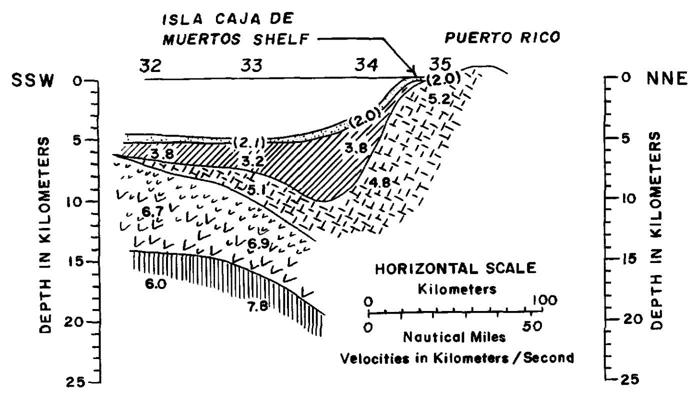


FIGURE 33.—Seismic refraction profile across Isla Caja de Muertos shelf. (From Officer and others, 1959.) Diagonals and stipples probably correspond to middle Tertiary to Holocene sediments; hachures probably correspond to Cretaceous and lower Tertiary volcanic rocks; checks correspond to crust, chiefly serpentinized periodotite(?); vertical bars correspond to mantle rocks, periodotite(?). Vertical exaggeration about 7:1.

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COMMENTS ON GREATER ANTILLEAN VOLCANIC ISLAND ARC-TRENCH PHENOMENA

The concepts of island arcs and orogeny provide a framework of general interest within which some aspects of the geology of the Coamo area can be summarized briefly. Most branches of geology are concerned to some extent with the questions posed by these broad concepts; a few of these questions are recounted here. What is the nature of the arc-trench phenomenon? To what extent are tensional, compressional, or wrench structures important in its development? What is the nature of the prearc crust? What is the origin of the magma, and to what extent is it derived from the crust and from the mantle? How closely are the plutonic and volcanic phenomena related? What were the sources and conditions of deposition of the sediments in the arc setting? Did the intermediate Caribbean crust originate by erosion of a continental crust; or did it evolve by some other means, perhaps as a modification of oceanic crust? Are island arcs and trenches similar to geosynclines? What is the nature of the orogeny?

These questions also bear upon the problems of mantle convection and continental drift. They are not completely answered by studies of one or even a few small districts such as the Coamo area. In view of this, and mindful of the limitations of conclusions based upon such a small sample of the Antillean island arc, the following summary comments parallel the questions raised above.

STRUCTURAL FEATURES

The principal system of west and west-northwest faults in Puerto Rico has been intermittently active at least since Cenomanian time. Movement along this system probably reached a climax during the middle or late Eocene, and this climax coincided with the cessation of volcanicity in Puerto Rico. Most of this faulting took place along high-angle fractures. Both normal and reverse movements occurred, but it has not always been possible to evaluate the relative magnitude of each. On some faults, however, the amount of strike-slip movement greatly exceeds that of the dip-slip displacement. The largest displacement suggested for a fault in southern Puerto Rico is left-lateral strike-slip movement of about 10 km for the Esmeralda fault of the great southern Puerto Rico fault zone. Movement of a similar sense and magnitude also occurred on many faults of the great northern Puerto Rico fault zone (M. H. Pease and R. P. Briggs, oral commun., 1965).

An interpretation of the relation of the west-northwest faults in Puerto Rico to the Greater Antillean fracture system is shown in figure 34. The faults on land, generalized from detailed geologic maps, have been projected offshore along prominent bathymetric lineaments and along discontinuities shown on the total magnetic intensity map of Geddes and Dennis (1964). The major west-trending boundary faults of the Puerto Rico Trench are near 19° and 20° N. latitude. These faults have been located from the seismic refraction data of Bunce and Fahlquist (1962) and have been projected along strike on the basis of bathymetric lineaments. Other east-trending faults north of 19°30′ N. are taken from seismic reflection profiles by Ewing and Ewing (1962), as is the major east-trending fault along the Muertos Trough south of Puerto Rico.

The west-northwest-trending faults are not expressed in the bathymetry as conspicuously as the major west-trending set, but northwest-trending faults seem to be present in Mona Canyon and southwest of Puerto Rico among other places. A northwesterly topographic grain in the Puerto Rico Trench was commented on by Ewing and Heezen (1955) and is probably fault controlled.

Aeromagnetic mapping (Geddes and Dennis, 1964) shows a strong west-northwest grain on the Outer Ridge similar to the magnetic pattern produced by faulting in Puerto Rico.

In northeastern and southwestern Puerto Rico east-trending segments of the major left-lateral wrench faults are joined at acute angles by west-northwest-trending second-order shears. The geometry and origin of such a shear pattern have been discussed by Moody and Hill (1956). A similar fault junction apparently occurs offshore near southeastern Puerto Rico. It is inferred that the west-northwest-trending faults of Puerto Rico and the offshore areas also bear a second-order shear relation to the major west-trending offshore faults. The principal west-trending faults probably have much greater left-lateral transcurrent movement than do the second order west-northwest-trending faults.

Low-angle overthrusting or gravity gliding toward the north is inferred from bathymetry just north of 19° N. This may arise as a surficial phenomenon associated with upthrust and wrench movements of the steeply dipping southern trench-boundary fault. Modern earthquake activity is concentrated along this boundary fault (Sykes and Ewing, 1965).

Deformation by folding in the Coamo area is not as intense as deformation by faulting, an observation that seems to be generally true for all of Puerto Rico. Moderate to tight folding occurs locally in the Coamo area, but it is associated only with superficial gravity glide structures. Most folds in Puerto Rico are broad open structures having wavelengths of the order of 10 km and nearly vertical axial planes. Cretaceous folding culminated in the formation of the west-northwest-trending Barranquitas anticlinorium of central Puerto Rico.

Trends of fold axes are generally northeast in the northeastern structural block of Puerto Rico, west to west-northwest in the central structural block, and northwest in the southwestern structural block (fig. 34 and Briggs, 1964). Fold trends are strongly discordant across the boundary between the central and northeastern blocks, and the trends are moderately discordant across the boundary between the central and southwestern blocks. Left-lateral movement along the great southern and northern Puerto Rico fault zones appears to have segmented a broadly convex-southward salient of folds producing this discordancy. Differential movement across both fault zones may be as much as 100 km.

The Puerto Rico geanticline is principally a middle and late Tertiary structure. Its crest trends west along the island drainage divide and it gently refolds all the earlier structures described above. The growth of this geanticline may well parallel the development of the present Puerto Rico Trench (W. H. Monroe, oral commun., 1966).

The succession of structural events outlined above cannot easily be reconciled with any single stress-field orientation. Left-lateral wrenching along the Greater Antillean fracture system seems to have recurred frequently during Cretaceous and early Tertiary time, but at times northerly oriented compression may have contributed to development of the major fold structures.

PRIMITIVE CRUST

The prearc crust does not crop out in the Coamo area, and only one accidental fragment possibly derived from the crust was found. This is a cobble of foliated amphibolite from the Cariblanco Formation. It is similar to the basic amphibolite from the serpentine-rich Bermeja complex of southwestern Puerto Rico, which is believed to represent part of the oceanic crust (Mattson, 1960; Hess, 1964).

MAGMAS

The rocks of the Coamo area have shed little light on the origin of the magmas, chiefly because of the difficulties inherrent in sampling a sequence consisting mostly of altered pyroclastic rocks for studies of chemical variation. The petrology of the Robles lavas reported herein is at variance with some conclusions of Lidiak (1965) who studied a lava sequence in north-central Puerto Rico that includes rocks correlative with part of the sequence in the Coamo area. According to Lidiak (p. 84)

> The andesitic magmas were possibly formed by partial fusion under hydrous conditions. Magmas of plagioclase-rich rocks were generated at depths where basaltic phases were present; magmas of clinopyroxene-rich rocks, at depths of eclogitic phases. The andesitic rocks range from andesitic-basalt to dacite and show a calc-alkalic chemical trend.

The lavas of the Robles in the Coamo area in contrast show alkalic affinities and probably originated under anhydrous conditions (see Osborn, 1959). Mattson (unpub. data) has shown that many, if not most, of the Robles-Río Orocovis rocks are similarly subalkalic. The rest of the Puerto Rican volcanic sequence seems to be calc-alkalic and may have originated under hydrous conditions.

The plutonic and volcanic phenomena probably are intimately related. Radiometric and geologic dating (P. H. Mattson, unpub. data) suggest that the bulk of the Utuado batholith was emplaced during the Maestrichtian-Paleocene interval and that later phases of the pluton probably intruded middle Eocene rocks. The bulk of the batholith is quartz diorite which is equivalent in composition to the dacitic volcanics of the Jacaguas Group that were being erupted from the vicinity of the batholith at about the same time.

VOLCANISM AND SEDIMENTOLOGY

The geology of the Coamo area is of much interest because of its contribution to knowledge of the sources and conditions of deposition of the sediments in this part of the arc. The pre-Oligocene sequence is chiefly a pile of locally erupted primary and reworked pyroclastic rocks. Pyroxene andesite and dacite in subequal amounts constitute more than 80 percent of the rocks in the area. Basalt makes up less than 1 percent of the sequence in the Coamo area, although it probably makes up 5 to 10 percent of the whole island. Limestone and epiclastic rocks constitute less than 10 percent each. The volcanogenic rocks are dominantly fragmental and dominantly deep-water marine. Undoubtedly the submarine environment of eruption promoted explosive rather than the effusive activity.

Typical volcanic activity consisted of submarine eruptions from centers of volcanism that shifted with time in an apparently random fashion within central Puerto Rico. There is little evidence of a systematic shift of volcanic centers that might be related to crustal flow into the jaws of a tectogene, as Christman (1953) postulated for the Lesser Antilles. Some volcanic centers have an obvious relation to ancient faults; in other cases this relation is not so obvious. Nevertheless the long-

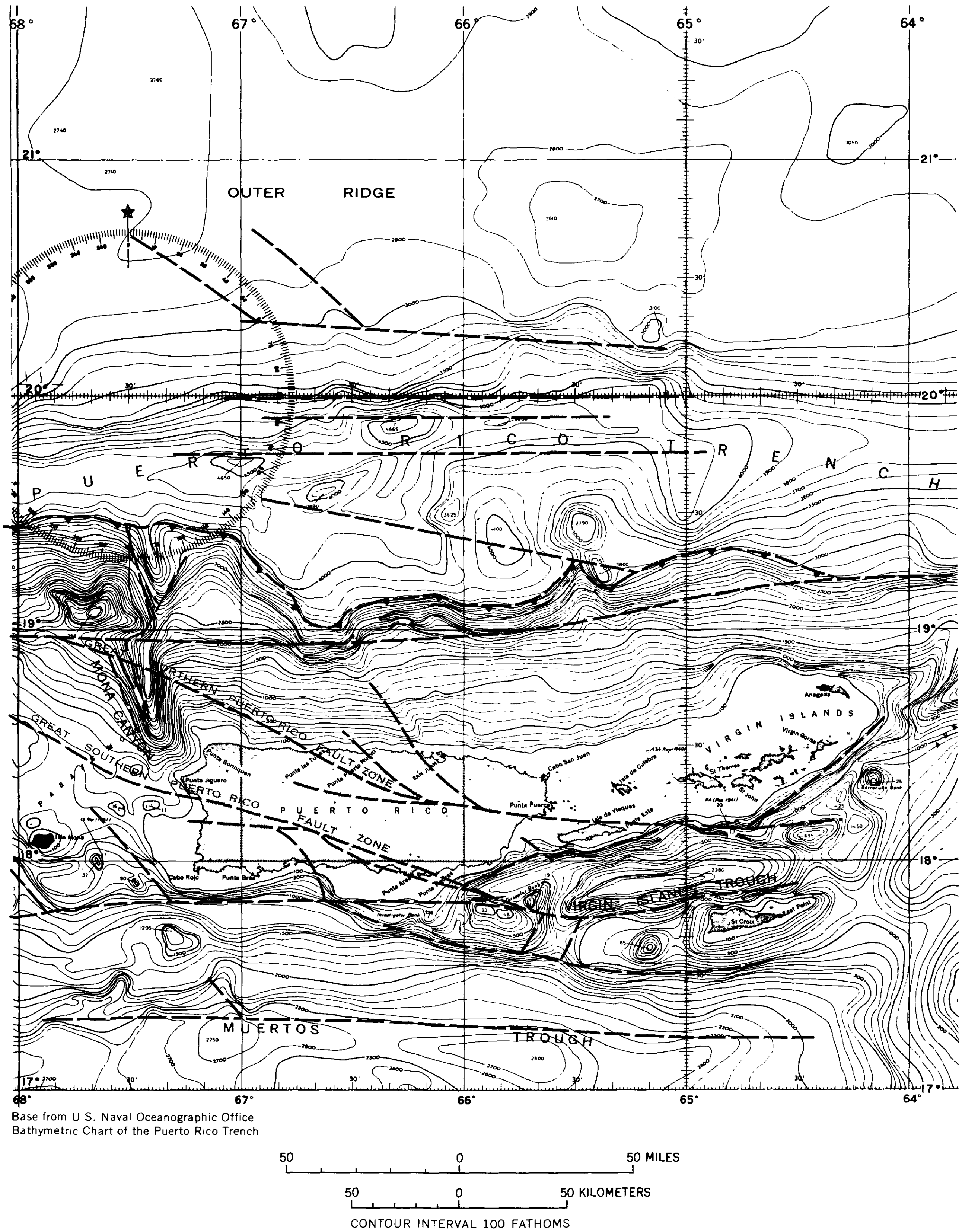

FIGURE 34.—Greater Antilles fracture system near Puerto Rico.

term picture was one of volcanic centers related in some way to a deep-seated fracture pattern similar to the present Greater Antillean fracture pattern shown in figure 34.

Most of the pyroclastic debris in the Cretaceous and lower Tertiary rocks was deposited by turbidity currents, submarine pyroclastic flows, and submarine slides and by fallout from the remnants of submarine eruption clouds that drifted laterally over the ocean floor. The high efficiency of these dispersal mechanisms is indicated by the lateral persistence of many of the map units. Undoubtedly the frequent earth tremors, moderate to steep slopes near volcanic sources, the low density of vesicular pyroclasts, and buoyancy of submerged particles contributed to instability and an almost continual downslope movement of material.

Shoal areas and islands were created both by tectonic uplift and by depositional embankments around volcanic centers. The earliest tectonic shoaling discernable in the Coamo area is Santonian, although the unconformity at the base of the Robles may be partly due to tectonic uplift. Marked tectonic uplift is recorded by the Maestrichtian, middle Eocene, and middle to late Tertiary unconformities. Although very large volumes of rock were eroded to produce the unconformities within the volcanic sequence, the succeeding sequence above each unconformity except the middle Eocene one is primarily a pyroclastic deposit. This relationship, as well as the fact that epiclastic rocks are uncommon in the Coamo area and rare in Puerto Rico in general, suggests that the products of erosion were generally transported into deeper water to the north and south of Puerto Rico throughout most of its history. Accordingly, this part of the arc has been a generally positive area since Early Cretaceous time, and since early Oligocene time it has been very shallow or subaerial.

Carbonate sediments accumulated principally during times of diminished volcanicity when shallow water was transgressing upon surfaces of unconformity. Thus, most of the limestone in Puerto Rico is found in the middle Tertiary sequences, but in the Coamo area such transgressive limestones also occur at the base of the middle Eocene (Cuevas Limestone) and in the Albian (Río Matón Limestone).

Another source of limestone was in the coral reef patches that grew around volcanic cones built above sea level. Although the cones and reefs were removed by erosion, they are recorded in the deep-water rudistid-bearing wacke conglomerates, reef fragments, and graded dark impure limestones of the Maravillas Formation. There the permanent accumulation of the limy debris depended upon its early transport from the shallow fringing reefs to deep water at the base of the cones. Earthquakes and eruption shocks undoubtedly initiated transport by submarine slide and turbidity-current mechanisms.

A third and least common mechanism of carbonate sediment accumulation was pelagic rain of plankton and fine lime silt onto the deep ocean bottom. Locally, as in the lower Tertiary sequence, this process produced a minor amount of thin-bedded foraminiferal biomicrite.

Red beds make many of the shallow marine to nonmarine deposits conspicuous among the generally drab sequence of rocks in Puerto Rico. This facies is not abundant, however, and it is doubtful whether it constitutes more than 5 percent of the total sequence. Such rocks are more common in the younger parts of the sequence and provide much of the evidence for progressive oscillatory shoaling of the Puerto Rico volcanic pile with time.

The tectonic framework of sedimentation in the Coamo area was characterized by the intermittent appearance of submarine fault-bounded basins, some of which probably were stagnant.

CARIBBEAN CRUST

The Coamo area provides little direct evidence bearing upon the origin and nature of the Caribbean crust. The interpretation that Puerto Rico was a generally positive area of submarine deposition rising above the surrounding ocean floor suggests that, since at least the Albian, the Caribbean south of the island has been deeply submerged. The crust beneath the Caribbean Sea did not contribute in any way as a source of sediment in the Coamo area.

PUERTO RICO TRENCH

The concept of a shoaling embryonic Puerto Rico composed principally of andesitic pyroclastic rocks may also shed some light on the origin of the Puerto Rico Trench. Dispersal from submarine eruption clouds during the volcanic pre-Oligocene interval would surely have transported large quantities of volcaniclastic rocks into the trench if a slope similar to the present one between the island and trench existed at that time. Some of the geophysical data can be interpreted to indicate either that a comparable slope did not exist during the volcanic interval or that left-lateral displacement along the southern boundary fault of the trench has been large enough to juxtapose a thinner and more nearly oceanic crust against the thick andesitic pyroclastic sequence of Puerto Rico.

The crustal-layer model (fig. 35) of Bunce and Fahlquist (1962) implies a correlation of layers, on the

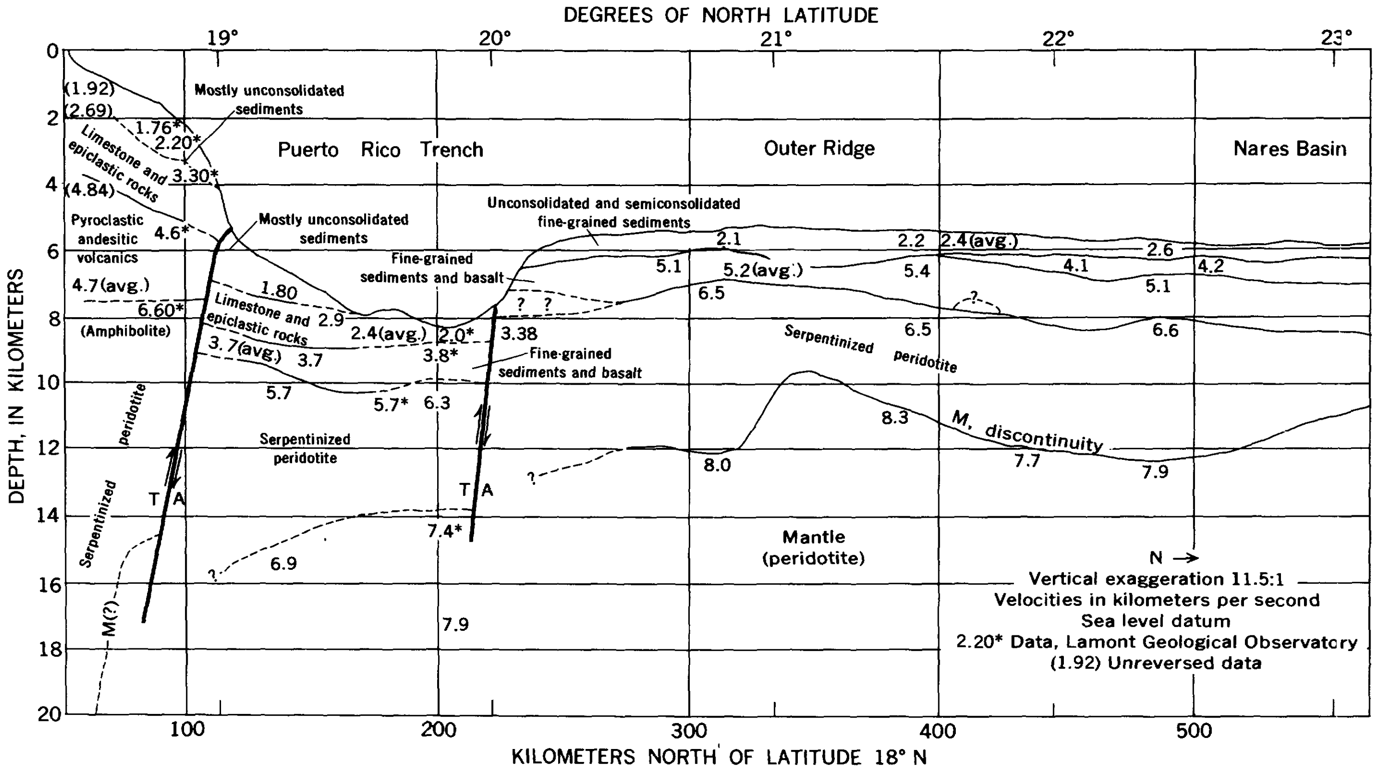

Figure 35.—Structure section through the Puerto Rico Trench to the Nares Basin along longitude 66°30′ W. From Bunce and Fahlquist (1962) with modifications by Glover based in large part upon observations and interpretations by Hersey (1963), Hess (1964), and Bowin, Nalwalk, and Hersey (1966).

basis of seismic velocity, superposition, and thickness trends, from Puerto Rico to the Outer Ridge. If the correlations are correct, the average seismic velocities of the layers in the trench sequence have been reduced by as much as 1 km/sec. Bunce and others have suggested that shearing may be the cause of the apparently reduced velocities. Variation in layer velocity and thickness across the trench boundary faults may also be due to juxtaposition of different parts of the layers during large-scale transcurrent faulting.

The interpretive structure section shown in figure 35 strongly suggests that the trench sequence is a modified oceanic crust similar to that on the Outer Ridge. It differs from the Puerto Rico sequence which seems to contain (1) more serpentine than the oceanic sequence, (2) a thick pile of pyroclastic andesitic volcanic rocks in place of the thin sequence of basalt lavas intercalate with mudstone, chert, and limestone, and (3) coarse-grained limestone and coarse epiclastic rocks and sediments in place of the upper low-velocity layer of unconsolidated and semiconsolidated mudstones and claystones.

THE GREATER ANTILLEAN FRACTURE ARC

The concept of a linear pile of submarine volcanic rocks developing over a major zone of wrench faulting and flanked by deeply submerged crust of oceanic and intermediate types bears little resemblance to the classical geosyncline described by Hall (1859, p. 66) and Dana (1873, p. 430). The familiar elements of a flanking continental crust and abundant shallow-water epiclastic sediments are lacking in the Puerto Rican example. Neither does the Greater Antillean arc resemble the smoothly curved single or double arcs to which the tectogene theory has been convincingly applied (Fisher and Hess, 1963). Rather, the Greater Antilles bear closer resemblance in tectonic framework to the nearly straight "fracture arcs" (Jacobs and others, 1959) of the Pacific such as the Solomon Islands, New Hebrides, and New Zealand-Kermadec-Tonga Islands. Perhaps a more appropriate name would be "the Greater Antillean fracture arc."

NATURE OF THE OROGENY

The nature of the orogeny in the Puerto Rican segment of the Greater Antillean fracture arc is portrayed by figure 36. Orogenic movements accompanied the development of the entire Puerto Rican sequence. There was, however, a broad climax extending from Maestrichtian to middle Eocene. The sum of folding, faulting, volcanicity, plutonism, and metamorphism suggests two maxima on this broad climax of intensity, one in the Maestrichtian and one in the middle Eocene.

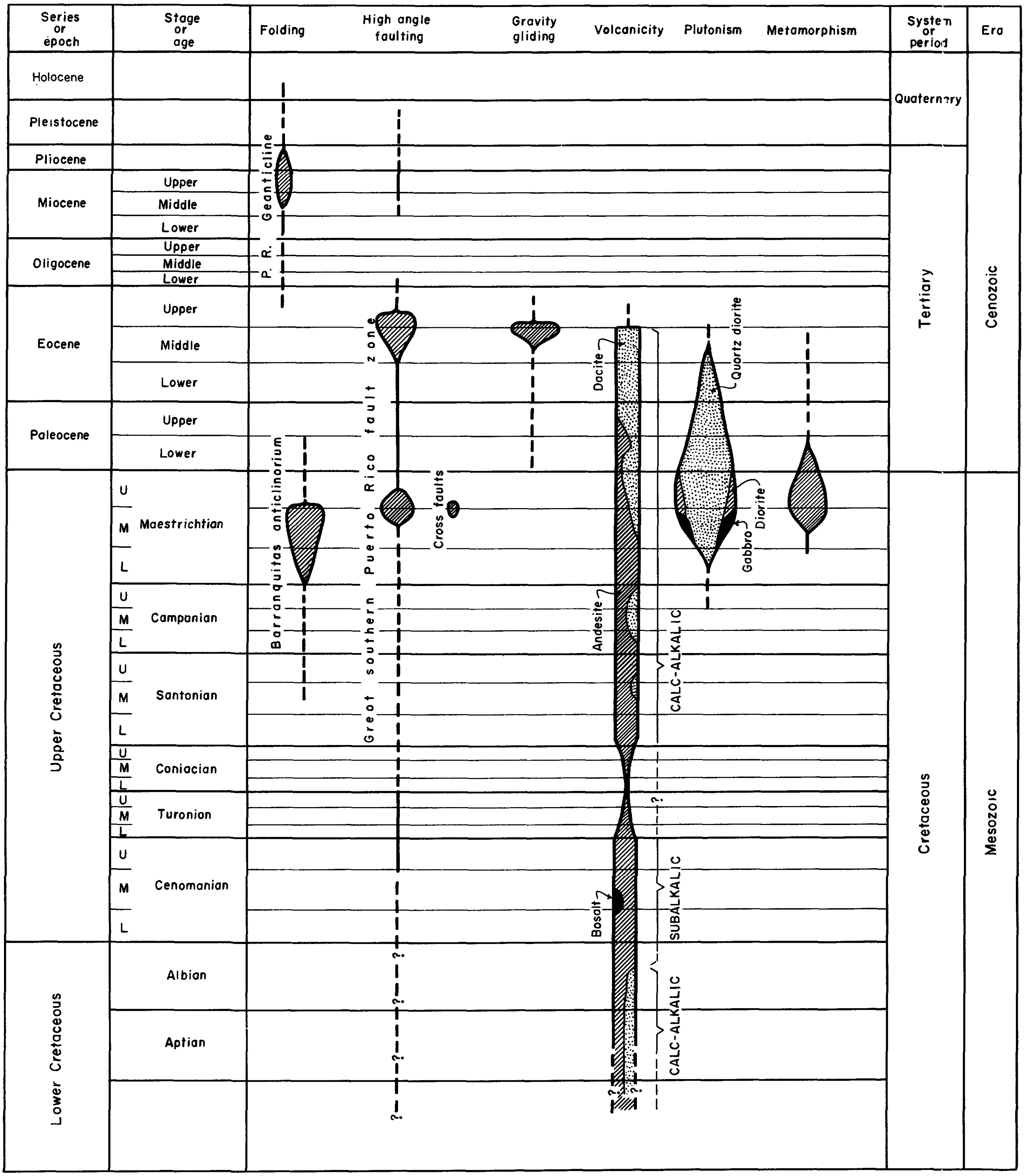

FIGURE 36.—Intensity and duration of orogenic events in south-central Puerto Rico.

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