# Geology of the Ciales Quadrangle Puerto Rico

GEOLOGICAL SURVEY BULLETIN 1184

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*By* HENRY L. BERRYHILL, Jr.

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By HENRY L. BERRYHILL, Jr.

## ABSTRACT

The 7½-minute Ciales quadrangle covers about 184 sq km in north-central Puerto Rico. It was mapped by the U.S. Geological Survey in cooperation with the Department of Industrial Research, Puerto Rico Economic Development Administration, as a part of a project to prepare detailed geologic maps of the Commonwealth.

The quadrangle includes two major physiographic divisions. The northern half lies within the Northern Foothills; the southern half is a part of the Mountainous Interior. The Northern Foothills includes two subdivisions: a karst area to the north and an adjacent narrow northward-sloping dissected pediment to the south. The southern boundary of the karst area is marked in most places by a cuesta inface. The maximum relief in the quadrangle is about 706 meters, and the highest altitude is about 731 meters above sea level.

The rocks of the quadrangle may be divided into two parts: (1) those of Late Cretaceous age and Late Cretaceous or early Tertiary age and (2) those of middle Tertiary (middle Oligocene to early Miocene) and Quaternary age. The Upper Cretaceous or lower Tertiary rocks consist of highly faulted, structurally complex volcanic and sedimentary rocks, intruded by plutonic igneous bodies and hypabyssal dikes. The volcanic and sedimentary rocks, which possibly were deposited in a eugeosyncline, comprise four formations, of which three are Late Cretaceous (Campanian(?) to Maestrichtian) and the fourth is either Late Cretaceous or early Tertiary in age. The formations of Late Cretaceous age are, in ascending order: The Río Orocovis, about 4,500 meters of predominantly basaltic and andesitic pillow lava and some tuff and breccia; the Manicaboa, about 2,140 meters of cyclically interbedded reworked andesitic tuff and reworked and epiclastic andesitic volcanic breccia; and the Pozas, about 1,400 meters of andesitic volcanic breccia, red tuff (including welded tuff), and andesitic lava. The dacitic welded tuff of the Pozas Formation is probably genetically related to granodiorite that intruded the Upper Cretaceous rocks. The chemical variability of Upper Cretaceous volcanic rocks from basalt through andesite to dacite implies a progressive change in magma chemistry during the Late Cretaceous volcanism. The Carreras Siltstone of either Late Cretaceous or early Tertiary age is represented by several hundred meters of laminated calcareous siltstone.

Intrusive bodies, including scattered dikes and slightly larger masses of basalt, gabbro, hornblende andesite, diorite, augite syenite, alkali syenite, and granodiorite cut the Upper Cretaceous rocks. The two largest intrusive masses, the Morovis and Ciales stocks, are plutonic granodiorite. Many of the intrusive bodies are associated with faults.

The middle Tertiary rocks, ranging in age from middle Oligocene to early Miocene, are predominantly limestone, but they include chalk, marl, clay, sand, and gravel. Formations recognized are the lenticular San Sebastián, about 125 meters of gravel, sand, clay, and sandy limestone; the Lares, about 175–275 meters of massive pure limestone; the Cibao, about 185 meters of chalk, marl,

limestone, and sand; and the Aguada, a limestone whose outcrops are restricted to the extreme northern part of the quadrangle.

The middle Tertiary rocks form a homocline with a gentle northward dip. They are separated from the older folded and faulted rocks by a pronounced unconformity whose surface has local topographic relief of as much as 60 meters.

The Quaternary sediments include terrace gravels of probable Pleistocene age and alluvial deposits and colluvium (talus and landslide debris) of Recent age. Deep residuum is restricted mainly to upland surfaces in the southern part of the quadrangle and seems to be remnant material that probably formed in Pliocene and early Pleistocene time when relief was more gentle.

Structural features of the quadrangle were formed during two tectonic periods. The principal early Tertiary(?) structures are, from southwest to northeast, a graben, a wrenched horst, and a faulted syncline, which are separated by high-angle west-northwest-trending faults. Development of the graben probably began in very Late Cretaceous time by crustal sag above a magma chamber. Subsequent shaping of the synclinal graben, as well as the associated wrenched horst and the faulted syncline, was accomplished somewhat later by strike-slip and vertical movements along the principal faults. Stratigraphic displacement along these faults may locally exceed 3,000 meters. The middle Teritary rocks dip gently northward and show little evidence of disturbance other than gentle uplift.

Since early Miocene time the mapped area has undergone uplift and erosion. With progressive uplift since early Miocene time, consequent streams have gradually readjusted themselves to their pre-middle Oligocene channels. A pause in the degradation of the region is marked by strath terraces along the Rio Grande de Manatí of probable Pleistocene age.

The mineral resources of the quadrangle include copper, galena, barite, limestone, and sandstone. The metalliferous deposits are small and have not been worked commercially.

## INTRODUCTION

The study of the Ciales quadrangle was made as a part of a continuing project for the geologic mapping of Puerto Rico. This project is being carried out by the U.S. Geological Survey in cooperation with the Department of Industrial Research, Puerto Rico Economic Development Administration, as a part of a broad program of industrial development for the Commonwealth. The purpose of this joint undertaking is to provide geologic data that can be utilized in promoting economic growth. In keeping with the overall purpose of the project, this report endeavors to (1) provide a detailed geologic map suitable for use in minerals exploration and in engineering and industrial planning, (2) outline and describe the mineral resources of the area studied, and (3) record and interpret the geologic history.

For preciseness and utility, the report deals largely with features in the Ciales quadrangle, but certain stratigraphic and structural features have been related to regional patterns.

The field investigations upon which this report is based were made periodically from October 1957 to May 1959. The total time devoted to the fieldwork was approximately 17 man-months, with 3 men participating at one time or another.

The writer, assisted by F. A. Hildebrand, mapped the Cretaceous volcanic rocks and Oligocene sedimentary rocks underlying the southern two-thirds of the area; W. H. Monroe mapped the middle Tertiary Cibao and Aguada Formations in the northern third of the area as a part of his regional study of the middle Tertiary rocks of northern Puerto Rico.

## PREVIOUS WORK

This report is the first detailed presentation of the geology of the Ciales quadrangle, but a general knowledge of the area was used by members of the New York Academy of Science, beginning with Berkey (1915), in preparing a series of reconnaissance geologic reports and maps. Subsequent reports by this group that include the general geology of the Ciales quadrangle are those of Semmes (1919), Lobeck (1922), and Meyerhoff (1933). These early reconnaissance studies were done without benefit of the modern net of topographic maps or of the many outcrops now afforded by an extensive system of highways; consequently, both stratigraphic and structural concepts have been much modified by later work.

Relatively recent regional reports, incorporating the geology of the Ciales quadrangle in varying degrees of detail, are those of Roberts (1942), Zapp, Bergquist, and Thomas (1948), McGuinness (1948), Mitchell (1954), Kaye (1956), and Berryhill and others (1960).

## ACKNOWLEDGMENTS

The observations and advice of Ray E. Wilcox during a visit to the field and his aid during the petrographic studies in the laboratory have been especially helpful. His knowledge of petrogenesis, drawn from experience with volcanic rocks of several provinces, has contributed to a clearer understanding of the volcanic processes that played a large role in the geologic history of the Ciales area. Other colleagues, both on the Puerto Rico project and elsewhere, have contributed ideas that influenced the report. However, I assume full responsibility for all stated facts and opinions that are not specifically referred to other persons.

## GEOGRAPHY

### LOCATION, SETTLEMENT, AND ACCESSIBILITY

Puerto Rico is about 1,000 miles east-southeast of Florida and about 500 miles north of Venezuela (fig. 1). It is the smallest and easternmost of the group of islands within the West Indies chain known as the Greater Antilles (Jamaica, Cuba, Hispaniola, Puerto Rico). The maximum dimensions of the island are 177 km from east to west and 59 km from north to south.


FIGURE 1.—Index map showing location of Puerto Rico.

The Ciales 7½-minute quadrangle, an area of about 184 sq km in north-central Puerto Rico, is bounded by the meridians of long 66°22′30″ and 66°30′ W. and the parallels of lat 18°15′ and 18°22′30″ N. (fig. 2).

The only two towns in the quadrangle are Ciales and Morovis. Ciales, with a population of about 5,000, is near the center of the northwestern quarter of the quadrangle about 0.6 km south of the confluence of the Río Grande de Manatí and its tributary, the Río Cialitos; Morovis, with a population of about 2,500, is in the northeastern quarter of the quadrangle near the headwaters of the Río Morovis. Until recent years these towns served solely as centers of commerce supported by the agricultural economy of the surrounding area. Since 1952 both towns have been selected as sites for small manufacturing plants under the Commonwealth industrial development program, thus diversifying their economic structure and that of the general area.

The Ciales quadrangle is a populous area; excluding local concentrations in Ciales and Morovis, the inhabitants are uniformly distributed over the quadrangle except for a few areas of relatively rugged topography, such as the karst areas of the northwest and the steep river valleys in the southern half where conditions are not favorable for farming. Population statistics are not available for the Ciales quadrangle as a unit, but the concentration for the area probably is somewhat less than the island average of 650 persons per square mile.

Surfaced roads afford adequate access by automobile to much of the Ciales quadrangle. Two paved secondary north-south highways that traverse the quadrangle and connect with Highway 2 link the Ciales area with San Juan, the capital city and principal harbor of Puerto Rico (fig. 2). Highway 149, which is a direct north-south route across the island, passes through Ciales and the western part of the quadrangle; Highway 155, which joins to the south with a network of paved roads that connect several towns in central and southeastern Puerto Rico, passes through Morovis and the eastern part of the Ciales quadrangle. Areas between principal paved roads in the northern part of the quadrangle are crossed by connected surfaced roads, but the south-central and southwestern parts have only one-lane dirt roads that are impassable by motor vehicle during wet weather.

## PHYSIOGRAPHIC SETTING

The principal physiographic feature of Puerto Rico is the Cordillera Central and its southeastern extension, the Sierra De Cayey, the highest parts of a mountain range that trends roughly east-west across the island. Because the crest of the Cordillera lies in the southern third of the island, the north-south topographic profile

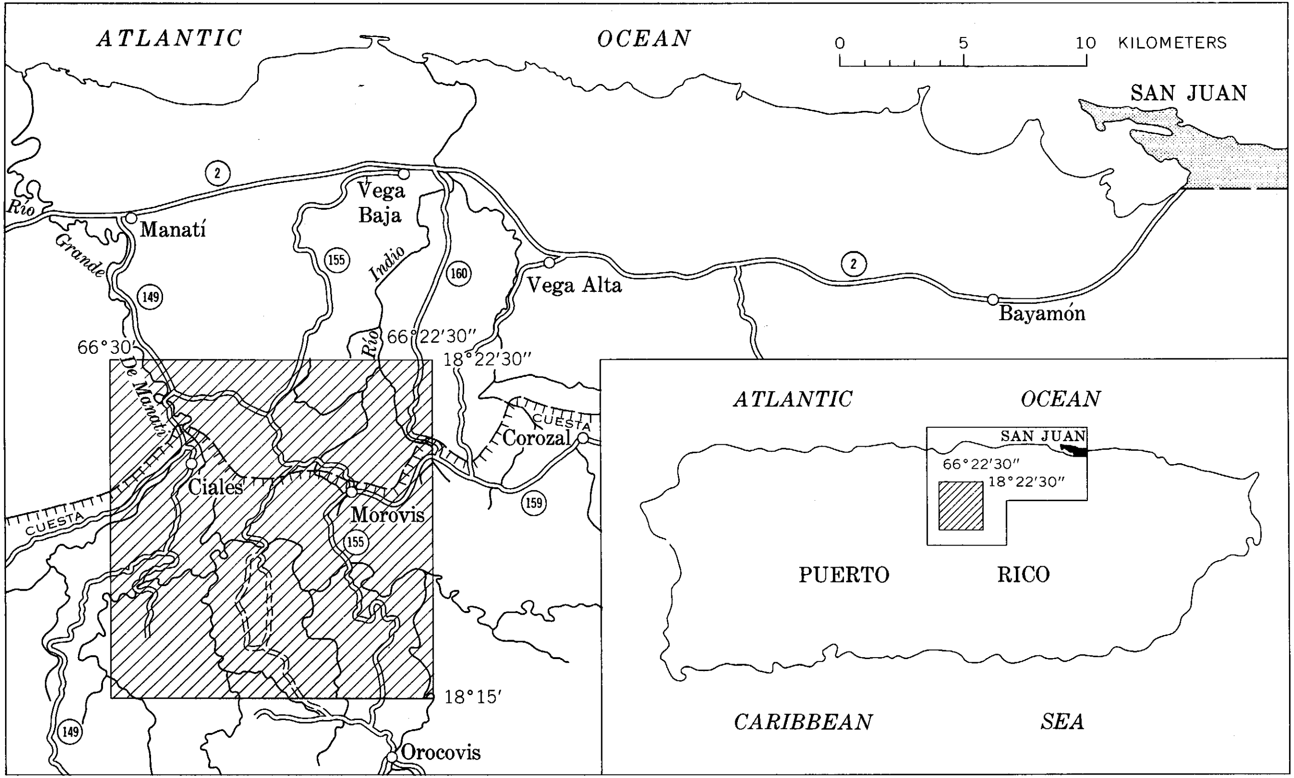


FIGURE 2.—Map showing location of Ciales quadrangle.

across Puerto Rico is asymmetrical; the northern flank of the Cordillera is relatively broad with a gradual northward slope, and the southern flank is steep with an abrupt southward slope.

The Ciales quadrangle lies on the northern flank about halfway between the crest of the Cordillera and the Atlantic Ocean (fig. 3). It straddles two physiographic subdivisions as established in a classification by Picó (1937, fig. 9). Approximately the northern half lies within the Northern Foothills; the southern half is a part of the Mountainous Interior. Maximum relief in the quadrangle is about 706 meters from the lowest elevation of 25 meters at the north edge in the bed of the Río Grande de Manatí to the highest elevation of 731 meters at the top of a peak near the southeastern corner. The Northern Foothills physiographic subdivision, defined as an intermediate region between the Northern Coastal Lowlands and the Mountainous Interior by Picó (1937, p. 66), is an east-west-trending belt roughly outlined by the 77-meter contour on the north and the 308-meter level on the south. With increased relief, the Northern Foothills passes gradually into the higher elevations and more rugged relief of the Mountainous Interior. Within the Ciales quadrangle these two physiographic subdivisions are characterized not only by elevation differences but also by diverse topographic forms.

### TOPOGRAPHY OF THE NORTHERN FOOTHILLS

The part of the Ciales quadrangle within the Northern Foothills can be further subdivided into two parts: the karst area to the north and an adjacent narrow northward-sloping dissected pediment to the south from which most of the karst-forming limestones and associated basal gravels have been stripped by erosion.

A southward-facing dissected escarpment, or ceja, sharply defines the southern boundary of the karst area in most places. This prominent topographic feature is a cuesta inface whose expression is pronounced across much of northern Puerto Rico. The cuesta inface is a cliff with relief of about 50–70 meters around the reentrants formed by the Río Grande de Manatí and the Río Cialitos in the northwestern quarter of the quadrangle; it is similar but less sheer around the reentrant cut by the Río Unibón and the Río Las Carreras at the edge of the northeast quarter. Between the reentrants, the cuesta is much more subdued; it is absent locally from near the center of barrio Torrecillas eastward to the Río Morovis for a distance of about 2½ km.

From the upper edge of the cuesta inface, the cuesta surface dips gently northward until interrupted by a rise across a second, but less prominent, cuesta inface of local extent that lies along the north edge of the quadrangle. Over much of its extent, the surface between the

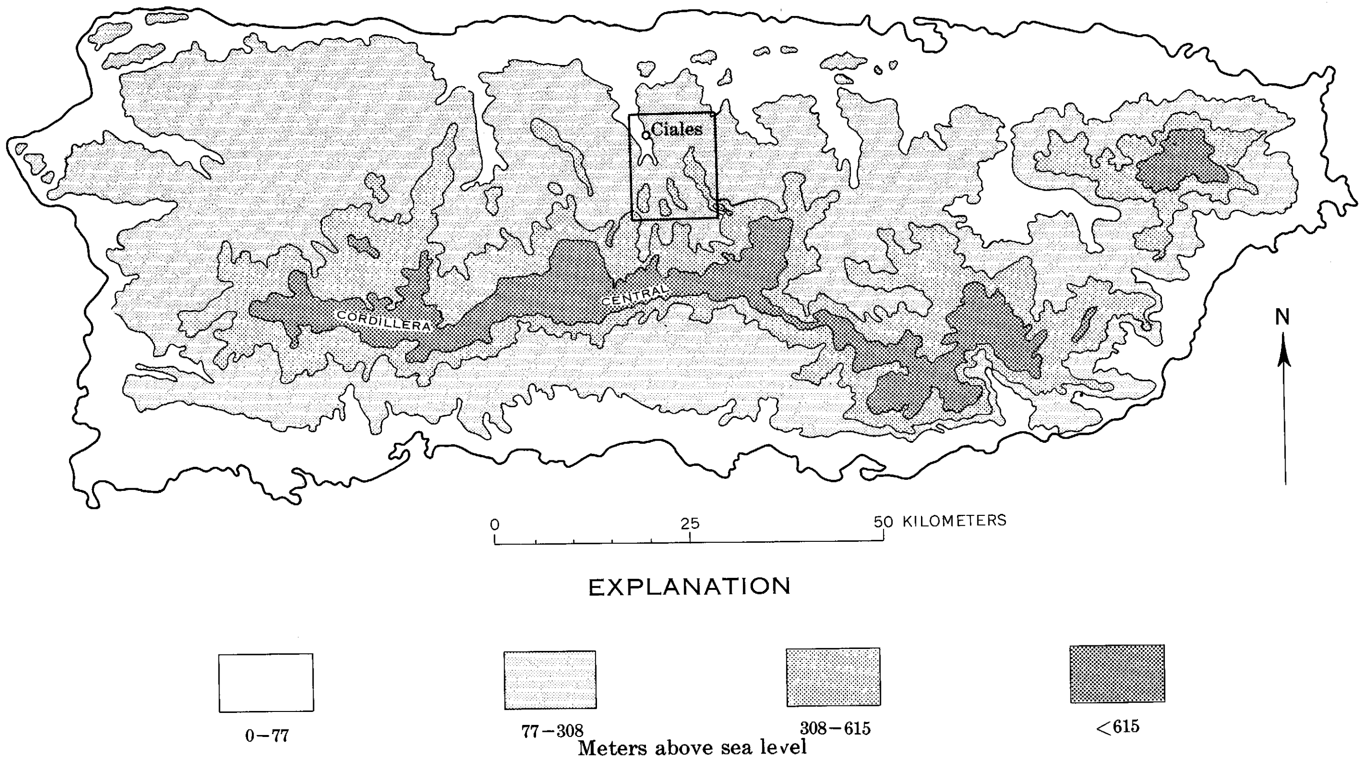


FIGURE 3.—Generalized topographic map of Puerto Rico Modified from Picó (1937, fig. 2). Outline of Ciales quadrangle is shown.

cuesta infaces is an area of marked karst topography, distinguished by a maze of haystack hills, or pepinos, and intervening sinks with short steep slopes. Three types of karst topography are recognized in the Ciales quadrangle: very rugged topography in the northwest, where pepinos are typically separated by narrow ravines rather than by sinks; moderately rugged topography in the northeast typified by rounded and conical pepinos and broad bowllike depressions; and subdued topography between the other two areas having very shallow relief and a general surface lying about 100 meters below the summits of the pepinos in the adjacent areas. In all three types of karst topography the pepinos and sinks show a preferred orientation, suggesting alinement along joints. This feature is most pronounced in the area of subdued topography where most of the shallow valleys trend northeastward.

The pediment south of the karst area extends from the base of the cuesta inface at the edge of the karst area southward for about 2½ km to the general latitude of the valley of the Río Grande de Manatí and its tributary, the Río Toro Negro. The pediment surface has been extensively dissected and largely obliterated by erosion except for two remnants—one south of Ciales and the other south of Morovis. Ciales is on the pediment surface at an elevation of about 100 meters; Morovis is farther south at an elevation of slightly more than 200 meters. From both localities the pediment surface rises uniformly southward to high points of just over 350 meters.

The topography of the Northern Foothills topographic province is shown on figure 4.

### TOPOGRAPHY OF THE MOUNTAINOUS INTERIOR

The part of the Ciales quadrangle south of the Río Grande de Manatí and the Río Toro Negro is in the Mountainous Interior. The topographic grain of this part of the quadrangle is that of a dendritic drainage pattern of coarse texture. Principal topographic units are four broad digitate northward-trending ridges separated by deep narrow valleys that have been cut by the northward-flowing tributaries of the Río Grande de Manatí. The rugged topography of this area is characterized by stream valleys having steep to precipitous slopes. Maximum relief is about 650 meters. The highest elevations are on summits near the southern edge of the quadrangle, and from there the general topographic slope rises southward to the crest of the Cordillera Central, some 7 km distant.

The topography of the Mountainous Interior is shown on figure 5.

## CLIMATE

The climate of Puerto Rico is tropical to subtropical with a strong marine influence. The Northern Foothills of the Ciales quadrangle

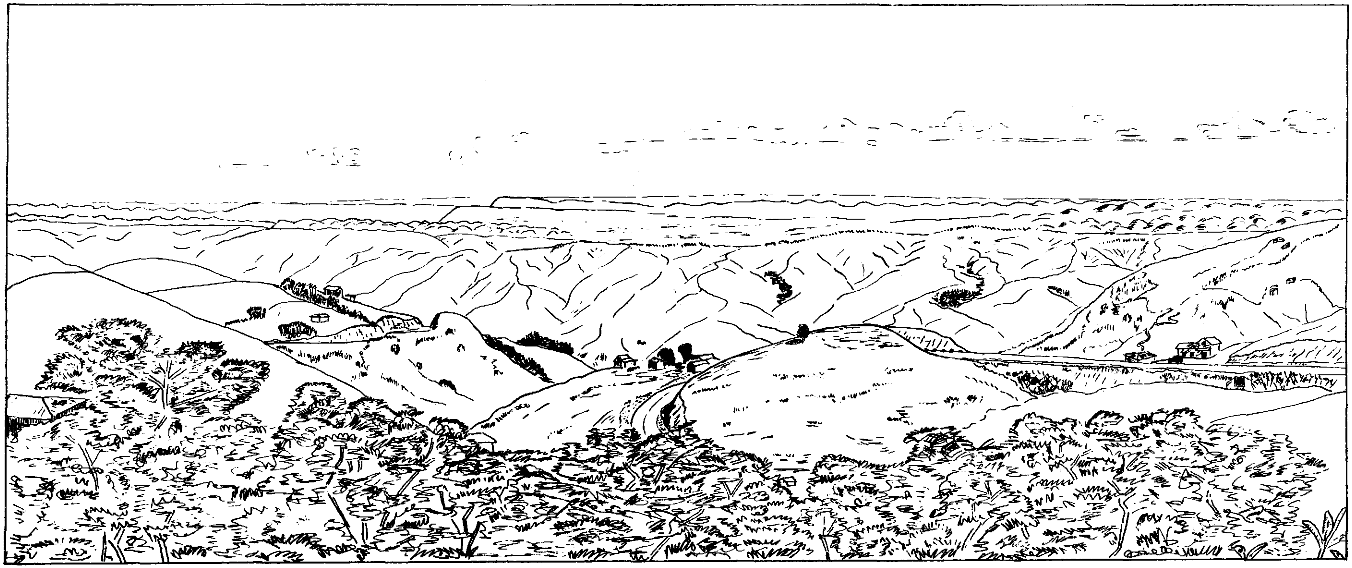

FIGURE 4.—Sketch of view from Highway 155 near Cerro Quiros showing topography of the northern part of the Ciales quadrangle and the adjacent area to the north. Atlantic Ocean forms horizon.

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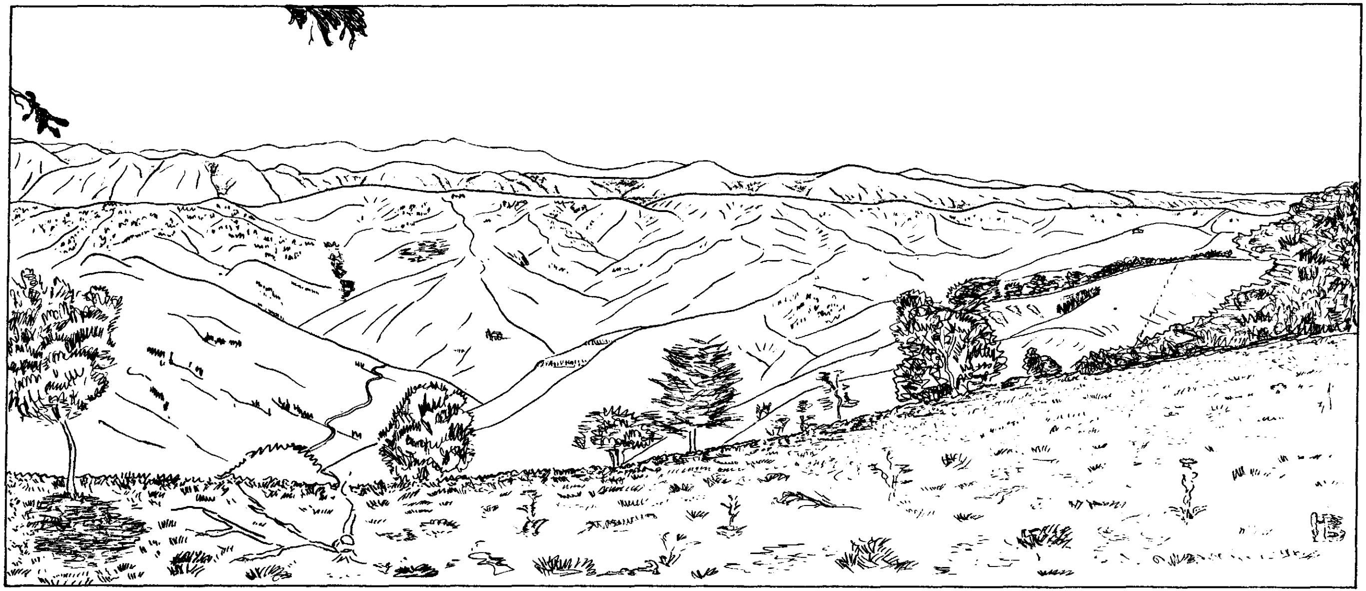

FIGURE 5.—Sketch of view to southwest from road along south boundary of barrio Pasto showing topography of the southern part of the Ciales quadrangle and the adjacent area to the south and southwest. The highest peaks mark the crest of the Cordillera Central; scarp in middle distance is along the Damián Arriba fault; and dissected area in foreground is the Cerro Cedro graben.

lies within the peripheral tropical belt of Puerto Rico that also includes the coastal lowlands. In the Northern Foothills the average annual temperature is about 78°F.; the maximums seldom exceed the low 90's. During the summer months this part of the quadrangle has high relative humidity that is moderated much of the time by sea breezes. The subtropical mountainous southern half of the quadrangle has an average annual temperature of about 72°F. Occasionally during the winter months nocturnal minimums of 54°–58°F. are recorded in the extreme southern part.

The Ciales quadrangle, in its position on the north side of the Puerto Rico Cordillera, is under the almost constant sweep of the east to northeast trade winds which play a prominent role in molding the rainfall patterns of the island. Cooling of the warm sea air as it moves southwestward across the island causes precipitation that increases progressively in amount as the higher elevations of the Cordillera are reached. Rainfall in the Northern Foothills of the Ciales quadrangle averages 60-80 inches a year; the mountainous southern part receives 80–90 inches (Picó, 1937, p. 32). There is seasonal variability of rainfall, with the rainy period extending from May to December; February and March are dry months in most years.

## DRAINAGE

Most of the Ciales quadrangle is drained by the Río Grande de Manatí and its tributaries—the Río Orocovis, the Río Sana Muerto, the Río Bauta, the Río Toro Negro, and the Río Cialitos—all of which flow northward in deeply entrenched courses. The Río Grande de Manatí and its tributaries form one of the three major drainage basins of northern Puerto Rico. The pattern of this system consists of the long main trunk of the Río Grande de Manatí, which follows a relatively straight narrow notch from the southern edge of the karst belt to the Atlantic Ocean, and the coarsely dendritic net formed by its tributaries in the Mountainous Interior south of the karst area.

The central and northeastern parts of the quadrangle drain to the Río Indio through its tributaries, the Río Unibón and the Río Morovis. Throughout the karst area, some of the runoff percolates through an underground drainage system before reaching the main surficial streams.

The drainage pattern of the Ciales quadrangle is shown on figure 2.

## LAND UTILIZATION

Land usage in the Ciales quadrangle is determined in large part by the topography and climate. Topography is a governing factor in the selection of areas for both settlement and farming; climate determines the type of agricultural products that can be grown. Thus, differences in land utilization within the quadrangle largely follow physiographic boundaries.

Except for the more rugged and densely bush-covered parts of the karst area, the low relief and fertile soils of the Northern Foothills are ideally suited to the raising of sugar cane. This is the principal crop of much of the subdued karst area in the north-central part of the quadrangle, the pediment areas south of Morovis and just south of Ciales, and the flood plain of the Río Grande de Manatí.

Principal cash crops of the mountainous southern part of the quadrangle, with its thinner soils and steeper slopes, are coffee and tobacco. Subsistence crops of the mountains are chiefly beans and yams, sweet potatoes, and related rhizomes. Large tracts of cleared mountain slopes are used for the grazing of cattle and goats.

Bananas and plátanos, both staples in the native diet, and oranges are grown throughout the quadrangle. These fruits are used for both subsistence and marketable commodities.

## GEOLOGIC FORMATIONS

### GENERAL FEATURES

The rocks of the Ciales quadrangle fall by age, geographical position, and structural complexity into two categories—those of Late Cretaceous and Late Cretaceous or early Tertiary age in the southern two-thirds of the quadrangle and those of middle Tertiary age (middle and late Oligocene and early Miocene) in the northern third of the quadrangle. The structurally complex sedimentary and volcanic rocks of Late Cretaceous and Late Cretaceous or early Tertiary age were intruded by plutonic igneous bodies. The undeformed and gently northward dipping middle Tertiary rocks are largely stratified limestone and marly limestone containing lenses of calcareous sand and gravel. Both categories of rocks are overlain by unconsolidated alluvium, stream-terrace deposits, and colluvium of Quaternary age. (See pl. 1.) The distribution of these rocks in the Ciales quadrangle relative to the general stratigraphic and structural framework of eastern Puerto Rico is shown on figure 6.

The ages of the relatively unfossiliferous Upper Cretaceous and the Upper Cretaceous or lower Tertiary rocks have been derived largely by correlations with fossil-bearing equivalents in other areas. These correlations must be classified in part as tentative until detailed mapping in Puerto Rico is completed. Almost all the Upper Cretaceous rocks are of volcanic origin (lava, tuff, and breccia), and they possibly accumulated in a eugeosyncline. These rocks range in age from Turonian(?) to Maestrichtian and have an aggregate thickness of roughly 8,700 meters. The Upper Cretaceous or lower Tertiary rocks are calcareous siltstone whose limited area of outcrop

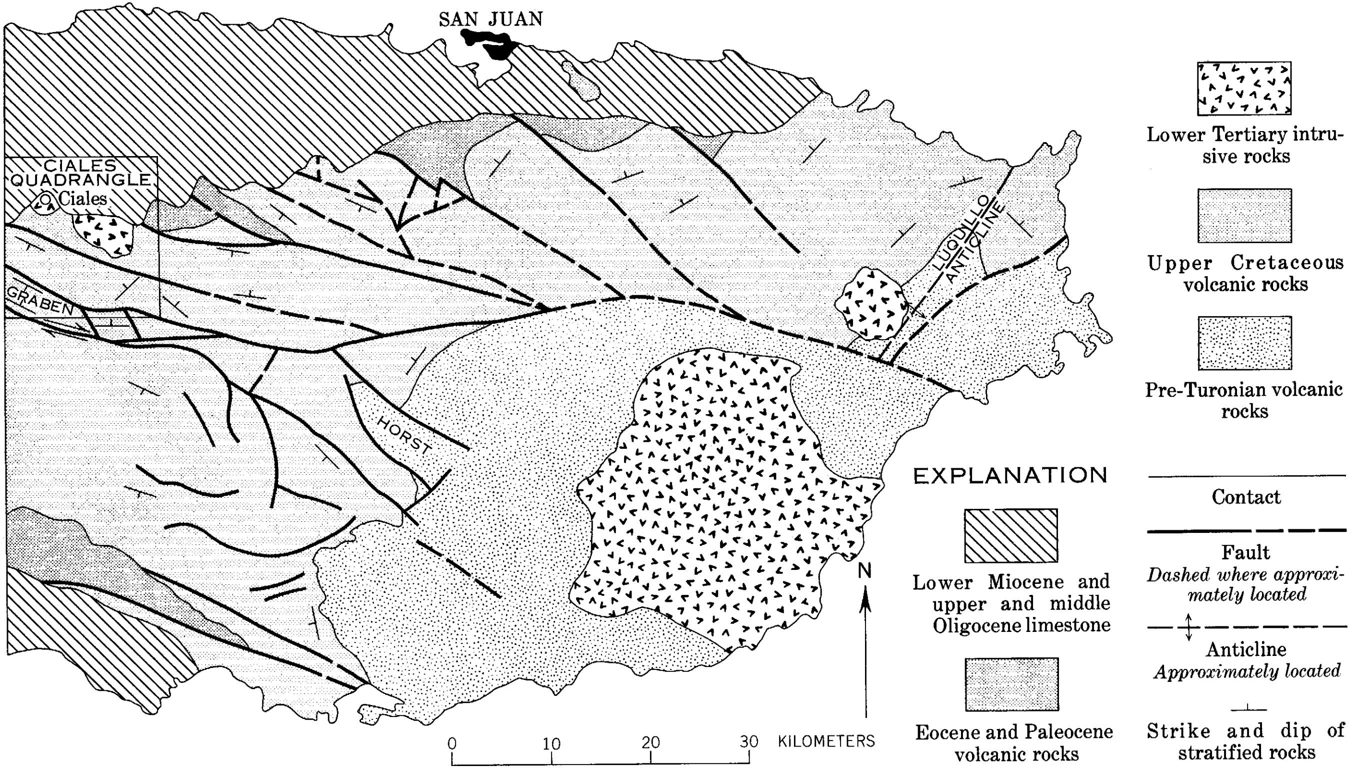


FIGURE 6.—Generalized geologic map of eastern Puerto Rico. Adapted from Berryhill and others (1960).

lies at the east-central edge of the quadrangle. These rocks are also probably eugeosynclinal, but they accumulated either at a late stage when volcanic activity was dying out or at a considerable distance from volcanic sources. This siltstone is in fault contact with Upper Cretaceous rocks, and its base lies in the adjacent Corozal quadrangle. The thickness given for the Upper Cretaceous rocks is only an approximation, for faulting, massiveness, lenticularity of units, and scarcity of outcrops in many areas preclude establishment of a true overall thickness.

The plutonic bodies cutting the Upper Cretaceous rocks are stocks and smaller masses of granodiorite, augite syenite, alkali syenite, diorite(?), and gabbro. The gabbro is metamorphosed and faulted and possibly is of early or middle Late Cretaceous age. The other plutonic bodies seem to have intruded during either very Late Cretaceous or early Tertiary time. The plutonic bodies of very Late Cretaceous or early Tertiary age are unmetamorphosed, and contacts with surrounding rocks are abrupt and well defined. Metamorphic effects of the plutonic bodies upon adjacent rocks were low grade and included some secondary silicification and pyritization.

The Upper Cretaceous or lower Tertiary dikes and sills include basalt, andesite, hornblende andesite, and diorite. Although these minor intrusives are widely dispersed, they are not numerous. Many of the hypabyssal rocks are associated with faults.

An unconformity separates the Upper Cretaceous and the Upper Cretaceous or lower Tertiary rocks from the middle Tertiary rocks. From approximately Paleocene or early Eocene to middle Oligocene time uplift and erosion took place.

The middle Tertiary rocks are predominantly limestone and subordinate amounts of chalk, marl, clay, sand, and gravel. Abundant invertebrate fossils indicate an age range of middle Oligocene to early Miocene.

The Quaternary deposits are terrace gravel, colluvium, including talus and landslide material, and alluvium.

The sequence and thickness of the Cretaceous, Tertiary, and Quaternary rocks are shown in the following stratigraphic summary (table 1).

The complex structure of the Upper Cretaceous and the Upper Cretaceous or lower Tertiary rocks is a manifestation of profound crustal disturbances that seem to have reached culmination in early Tertiary (Paleocene or Eocene) time. The gross structural pattern is that of linear but warped crustal blocks circumscribed by regional faults that strike west-northwest. Flexures within individual blocks are second-order structural features that cannot be traced into adjacent blocks. Apparently the crust was initially segmented by faulting and then warped and fractured in patterns that reflect the response of individual blocks to regional stress. However, the manner in which each block responded was in large measure influenced by the movement of adjacent blocks.

TABLE 1.—*Stratigraphic summary of the Ciales quadrangle, Puerto Rico*

| Period | Epoch | Stratigraphic unit | Brief description | Approximate thickness (meters) |
|---|---|---|---|---|
| Quaternary | Recent | Alluvial deposits | Unconsolidated gravel along beds of streams and similar stratified flood-plain deposits adjacent to streams; deposits in limestone sinks. | 0–10± |
| | Recent and Pleistocene | Stream-terrace deposits and colluvium | Unconsolidated gravel on remnant stream-planed surfaces. Talus and landslide material. | 0–15± |
| | | —Unconformity— | | |
| Tertiary | Miocene | Aguada Limestone | Light-colored thick-bedded limestone. Alternating layers of hard pure limestone and soft chalky limestone and marl. | 90± |
| | Miocene or Oligocene | Cibao Formation | Chiefly chalk and marl containing lenticular beds of limestone and tongues of sand. Quebrada Arenas Limestone Member in upper part; Río Indio Limestone and Almirante Sur Sand Members in lower part. | 185± |
| | Oligocene | Lares Limestone | Light-colored thin-bedded to massive locally coralline limestone. | 140–260 |
| | | San Sebastián Formation | Chiefly stratified but poorly consolidated sand, silt, and clay containing much gravel. Tongue of sandy limestone at top and lenses of cobble conglomerate at base. | 0–145 |
| | | —Major unconformity— | | |
| Tertiary or Cretaceous | | Intrusive igneous rocks | Plutonic masses of granodiorite and diorite. | |
| | | Carreras Siltstone | Dark-gray thin- to medium-bedded calcareous siltstone. Weathers very light brown with grayish-red streaks. | 300± |
| Cretaceous | Late Cretaceous | Pozas Formation | Chiefly subaerially deposited pyroclastic rocks. Upper (andesitic) breccia member at top; Blacho (dacitic, red) Tuff Member and andesitic Minguillo Lava Member at base. | 1,400± |
| | | Manicaboa Formation | Cyclically interbedded sequence of massive volcanic breccia alternating with thin- to medium-bedded laminated reworked tuff. | 2,100± |
| | | Río Orocovis Formation | Typically amygdaloidal basaltic pillow lavas characterized by pyroxene phenocrysts and high potash content. Avispa Lava Member makes up the upper part; the Perchas Lava Member makes up the middle part; and the Magüeyes Member and its probable lateral equivalent, the basalt tuff member, the lower part. | 4,500± |

The middle Tertiary rocks dip gently northward as part of a regional homocline and show little evidence of disturbance other than gentle uplift. Their east-west trend is oblique to the general west-northwest trend of the underlying rocks. The present topography has been controlled in large part by the structure of underlying rocks. Several streams in the southern half of the quadrangle have cut narrow valleys along faults of early Tertiary age.

Specific outcrops described in the various sections of this report are referred to by a locality number. The locality index is given in table 2. Color descriptions and their symbols follow Goddard and others (1948).

TABLE 2.—*Index for localities described in this report*

| Locality (pl. 1) | Location [1] | Remarks |
|---|---|---|
| 1–2 | SE | Type locality for Río Orocovis Formation. |
| 3, 3a | SE | Magüeyes Member, Río Orocovis Formation. |
| 4–5 | SE | Andesitic lava in Magüeyes Member, Río Orocovis Formation. |
| 6–12 | SE | Perchas Lava Member, Río Orocovis Formation. |
| 9a, 9b, 9c | SE | Localities for chemical analyses, Magüeyes and Perchas Lava Members, Río Orocovis Formation. |
| 13–14 | SE | Type locality for Avispa Lava Member, Río Orocovis Formation. |
| 15–16 | SW | Manicaboa Formation. |
| 17–18 | SW | Minguillo Lava Member, Pozas Formation. |
| 19–20 | SW | Type locality for Blacho Tuff Member of Pozas Formation. |
| 21–22 | SW | Type locality for upper breccia member of Pozas Formation. |
| 19a, 19b, 20a, 22a, 22b. | SW | Localities for chemical analyses, Minguillo Lava and Blacho Tuff Members, Pozas Formation. |
| 23 | NW | Sandy limestone member, San Sebastián Formation. |
| 24 | NW | Lares Limestone. |
| 25 | NW | Do. |
| 26 | NE | Type locality for Almirante Sur Sand Member, Cibao Formation. |
| 27 | SE | Cerro Cedro graben. |
| 28–42 | SE, NE, SW, NW | Points of copper and galena and barite mineralization. |
| 35 | NW | Locality for chemical analysis, Ciales stock. |
| 42a | SW | Nodular limestone at base of Pozas Formation. |
| 43 | SE | Alkali syenite intrusive. |

[1] By quarter subdivision of quadrangle.

## UPPER CRETACEOUS ROCKS

### STRATIFIED VOLCANIC AND SEDIMENTARY ROCKS

The stratified Upper Cretaceous rocks of the Ciales quadrangle include four general types of volcanic rocks: pillow lava; water-laid tuff, volcanic breccia, and conglomerate; subaerial ash-flow deposits; and reef limestone. The thick sequence of pillow lavas and associated thin stratified tuffaceous rocks that crops out in the southeastern and central parts of the quadrangle makes up the Río Orocovis Formation, which has been subdivided into three members, listed in ascending order: the Magüeyes Member which contains, in addition to basaltic lavas, a substantial amount of volcanic breccia and reworked tuff; the Perchas Lava Member, characterized by basaltic lavas of high potash content; and the Avispa Lava Member, characterized by lavas of andesitic habit. Locally at the base of the Avispa Lava Member is a lenticular reef limestone. The large quantity of well-bedded water-laid tuffaceous material and volcanic breccia stratigraphically above the lavas comprise the Manicaboa Formation. The subaerial dacitic ash-flow deposits and associated fluvial gravel and volcanic breccia in the southern and southwestern parts of the quadrangle are included in the Pozas Formation. All three of these formations have been further subdivided into both formally and informally designated units that have been mapped both to show stratigraphic succession within thick formations and to demonstrate structure. Predominance of albite over other types of plagioclase and abnormally high potassium oxide content are characteristics of the Upper Cretaceous basaltic lavas.

The Upper Cretaceous rocks of the Ciales quadrangle are a part of what most previous workers have called the older or basement complex of Puerto Rico. The indicated Turonian(?) to Maestrichtian (latest Cretaceous) age for these rocks is based on correlations with fossil-bearing representatives in adjacent areas.

### NOMENCLATURE OF CLASTIC AND PYROCLASTIC ROCKS

Fragmental material of volcanic origin is an important constituent of the Río Orocovis Formation, and it comprises virtually all the Manicaboa and Pozas Formations. Classification of much of this material is difficult because the rocks consist of a water-laid intermixture of pyroclastic and epiclastic fragments and do not lend themselves to the widely used classification of Wentworth and Williams (1932) for subaerial pyroclastics. Most of the fine-grained clastic rocks closely resemble ordinary siltstone and sandstone megascopically. Although the particles have a volcanic origin, some were blown directly into the water by explosive eruptions; some fell upon land but before induration were transported by wind, water, mudflow, or landslide into the depositional site; others became indurated rocks that were eventually broken down by weathering and carried away by streams. The rock formed from these intermixed first- and second-generation volcanic particles is a sedimentary rock whose features differ from those of primary volcanic rocks. A classification such as that of Wentworth and Williams does not accurately convey either the lithology of this type of rock or the history of its components.

The nomenclature suited for the clastic volcanic rocks of the Ciales quadrangle is that proposed by Fisher (1960a, b; 1961, p. 1409–1414) in a classification scheme based primarily on type of fragmentation. Autoclastic fragments are those that formed and stayed within a volcanic vent or formed by movement of lava; pyroclastic fragments formed by volcanic eruption and expulsion from vents; and epiclastic fragments formed by weathering and erosion of lithified volcanic rocks. In Fisher's classification, the grain size limits are the same as in nonvolcanic rocks, and the several clastic types may be mixed in any proportion.

The nomenclature proposed by Fisher has been adopted for this report, and the following classification chart (table 3) taken from Fisher (1960b, p. 1865; 1961, p. 1409–1414) illustrates the sense in which these terms are applied and also the interrelations of the terms. Although the classification of Wentworth and Williams (1932) would serve for the subaerially deposited Pozas Formation, the classification of Fisher will be used here also for the sake of uniformity.

In this report epiclastic is used only for rocks containing appreciable quantities of fragments from lithified volcanic rocks, including lava broken down by epigenic processes. "Reworked pyroclastic" is used for rocks made up largely of pyroclastic fragments that fell on land and remained there in an unconsolidated state before being transported to a site of subaqueous deposition.

TABLE 3.—*Nomenclature for clastic volcanic rocks, as used in this report*

[Reprinted from Fisher, 1961]

| Predominant grain size (mm) | Autoclastic [1] | Pyroclastic,[1] primary or reworked | Epiclastic [1,2] | Equivalent [1,2] nongenetic terms |
| --- | --- | --- | --- | --- |
| | | Pyroclastic breccia | Epiclastic volcanic breccia | Volcanic breccia |
| — 256 — | Flow breccia | | | |
| | Autobreccia | Agglomerate | Epiclastic volcanic conglomerate | |
| — 64 — | Intrusion breccia | Lapillistone | | Volcanic conglomerate |
| — 2 — | | Coarse tuff | Epiclastic volcanic sandstone | Volcanic sandstone |
| — 1/16 — | Tuffisite | Fine tuff | Epiclastic volcanic siltstone | Volcanic siltstone |
| — 1/256 — | | | Epiclastic volcanic claystone | Volcanic claystone |

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

## RÍO OROCOVIS FORMATION

*Distribution.*—The Río Orocovis Formation is here named for its exposures in the southeastern part of the Ciales quadrangle along and adjacent to the valley of the Río Orocovis between localities 1 and 2, plate 1. It crops out principally in the southeastern and central parts of the Ciales quadrangle. Individual areas of outcrop are bounded in large part by faults. The large rectangular area making up much of the southeastern quarter of the quadrangle is bounded on the south by the northwestward-trending Quebrada El Gato fault and on the north by the northwestward-trending Río Grande de Manatí fault. Other areas of outcrop are south of Ciales, between the Ciales and Morovis stocks, at the town of Morovis, and east of the Morovis stock. (See pl. 1 for areas of outcrop.) The part of the Río Orocovis Formation in the southeastern and central parts of the Ciales quadrangle is in a warped structural block. Beveling by erosion of a truncated northward-plunging anticline within this block has exposed the oldest rocks of the formation at the southeast corner of the quadrangle. The part of the Río Orocovis Formation north of the Río Grande de Manatí fault is in a complexly faulted synclinal block. Rocks stratigraphically lower but similar to those of the Río Orocovis Formation crop out to the southeast across the northern part of the Barranquitas quadrangle where they have been designated informally as formation "L" (Briggs and Gelabert, 1962).

*Thickness and stratigraphic relations.*—Strata of the Río Orocovis Formation have been extensively warped and faulted; all dips are steep and almost every outcrop reveals evidence of fracture and displacement by faulting. Furthermore, the base of the formation is not exposed in the area. Under such conditions, measurement of a true thickness for these rocks was impossible. The estimated thickness in the southeast and central areas of outcrop is 4,500 meters, the base of the formation being concealed by faulting. The estimated thickness in the belt west and east of the Morovis stock is 2,250 meters, but in this structurally complex area, which is bounded on two sides by faults and on a third by plutonic intrusive rocks, much of the upper part of the formation has been eroded. Because of probable repetition of strata by faulting, the indicated maximum thickness of 4,500 meters for the Río Orocovis Formation in the Ciales quadrangle may exceed the true thickness.

If similar rocks to the southeast in the adjacent Barranquitas quadrangle are considered a continuation of the Río Orocovis Formation, it can be assumed that approximately the upper two-thirds of the formation is represented in the southeastern part of the Ciales quadrangle. Rocks presumably near the middle(?) of the formation are exposed in areas of outcrop adjacent to the Morovis and Ciales stocks.

*Lithology.*—The Río Orocovis Formation includes a great accumulation of massive dense andesitic pillow lava, basaltic pillow lava, subordinate clastic rocks, and a lens of reef limestone. The compact clastic rocks, which are interstratified with the pillow lavas, are, in order of abundance: intermixed primary basaltic tuff and primary basaltic pyroclastic breccia; intermixed reworked pyroclastic and epiclastic breccia; reworked coarse and fine tuff; and intermixed epiclastic calcareous volcanic conglomerate and calcareous epiclastic volcanic sandstone. The conglomerate, sandstone, and limestone are minor constituents restricted to a local occurrence in the upper part of the formation.

Based on the composition of the pillow lava and on the relative abundance of detrital rock, the Río Orocovis Formation has been divided into four members. The lowest of these members, the Magüeyes, is a sequence of basaltic lavas that includes many layers of detrital rocks. Its probable lateral equivalent, an unnamed basaltic tuff and pyroclastic breccia, seems to intertongue with the Magüeyes. Above these members the Perchas Member is principally basaltic lava in which detrital rocks occur sporadically as thin lenses, and the Avispa Member is a sequence of andesitic lavas which includes layers of detrital rocks and a lens of reef limestone. In addition, some of the thicker detrital units within the members have been mapped and informally designated (pl. 1). Composite sections of the Río Orocovis Formation, one for the southeastern and central parts of the quadrangle and another for the east-central part, are shown on plate 2.

#### MAGÜEYES MEMBER

Outcrops of the Magüeyes Member are restricted mainly to the southeast corner of the quadrangle where the member forms the central part of a northward-plunging faulted anticline (pl. 1). Rocks that resemble parts of the Magüeyes Member crop out in faulted blocks in the east-central part of the quadrangle. These rocks are assigned to the Magüeyes Member because of the abundance of lava; however, it is possible that they are either a part of the basalt tuff member or a stratigraphic unit between the two. The Magüeyes is named for outcrops along, and adjacent to, the Río Orocovis from locality 3 just west of Cerro Magüeyes south to the Quebrada El Gato fault, locality 1. (See pl. 1.) The member crops out in almost continuous sequence along the Río Orocovis, and outcrops are numerous in the lower part of the valley wall; but deep weathering and cover obscure details of the sequence on the higher terrain. The exposed thickness in this quadrangle is about 1,560 meters; but the base of the member is concealed by faulting, and parts of the member are probably repeated by faulting. Equivalent rocks are probably thicker east of the Ciales quadrangle.

The volcanic rocks composing the Magüeyes Member in the southeastern part of the Ciales quadrangle are predominantly amygdaloidal basaltic pillow lava and subordinate reworked pyroclastic volcanic breccia, lapillistone, and reworked fine and coarse tuff. Included in the lower half of the Magüeyes Member is a unit of basaltic pyroclastic breccia and basaltic tuff that seems to be part of the basalt tuff member. The thicker detrital units in the Magüeyes Member have been mapped and informally designated on the geologic map by an appropriate lithologic symbol for breccia and for tuff.

For the purpose of description, the Magüeyes Member is divided stratigraphically into two parts: a lower part and an upper part that are separated by tuff of the basalt tuff(?) member. The general stratigraphy of the member is shown on plate 2.

### Lower Sequence

The sequence in the lower part of the Magüeyes Member is amygdaloidal basaltic pillow lava, pyroclastic volcanic breccia, and relatively thin amygdaloidal basaltic pillow lava flows separated by thin layers of greenish-gray reworked tuff.

The pillow lava flows in this lower sequence, ranging in thickness from 5 to 50 meters or more, are dark greenish gray (5*GY* 4/1), porphyritic, and highly amygdaloidal. The size of pillows ranges from about 0.5 to 1 meter. Red (jasperiod) chert occurs sporadically in irregular masses between pillows. Phenocrysts are primarily pyroxene (1–4 mm) with subordinate small and stubby plagioclase. The groundmass is aphanitic but finely crystalline. Amygdules concentrated in outer parts of pillows are calcite with thin outer rims of either zeolite or chlorite.

The greenish-gray tuff, probably a mixture of primary and reworked particles, occurs in dense, even-bedded, and distinctly laminated units that range in thickness from 1 to about 5 meters. Lamination is caused both by grain size differences and by mineral segregation within the unit. Laminae rich in plagioclase are whitish; those rich in pyroxene are dark green. Many of the crystal-rich laminae may represent individual ash falls, but considering the evident gradation in grain size within these tuff units, lamination resulting from differences in grain size can probably be attributed largely to differential settling of particles from turbid currents. Characteristically, the tuff units break down upon weathering to distinctly angular pieces.

Volcanic breccia in the lower sequence is mainly of two types: primary pyroclastic and reworked pyroclastic. Small amounts of epiclastic debris are intermixed with the other two types. The primary pyroclastic volcanic breccia, not shown on the geologic map, consists of masses of dark-greenish-gray (5*GY* 4/1) and dark-reddish-brown (10*R* 3/4) oxidized amygdaloidal lava masses in a matrix of basaltic tuff. The reworked pyroclastic breccia, including beds of reworked coarse tuff and epiclastic volcanic breccia-conglomerate, forms a thick unit that underlies the basalt tuff(?) member (pl. 1). Epiclastic angular fragments and cobbles in this unit are detritus from lava, volcanic breccia, and laminated tuff.

### Upper Sequence

The sequence in the thick upper part of the Magüeyes Member above the basalt tuff (?) member is massive, generally basaltic, amygdaloidal pillowed lava flows, containing many thin lenticular layers of reworked(?) fine tuff, andesitic(?) lava, massive reworked pyroclastic volcanic breccia, and massive basaltic amygdaloidal pillow lava containing many lenticular layers of reworked(?) tuff, some of which are as much as 10–15 meters thick.

The pillowed lavas of the upper sequence are porphyritic with pyroxene phenocrysts and are otherwise similar in megascopic appearance to the lavas below the basalt tuff(?) member. Most seem to be basaltic, all are massive with thicknesses probably exceeding 75 meters, and all are amygdaloidal. One variant within this part of the member is a thick lava (±150 meters) of seemingly more salic (andesitic(?)) composition, with stubby plagioclase instead of pyroxene phenocrysts and an almost porcelaneous groundmass. Also, in contrast to the other lavas with medium-sized pillows (±1 meter) and crystal-rich, finely crystalline rinds, this lava is made up of very large pillows (4–5 meters in diameter) that are encased in reddish siliceous cryptocrystalline rinds rich in lime. Lumps of reddish limetsone fill some interstices between pillows. This unit is well exposed on the Río Orocovis between localities 4 and 5, and continues eastward into the Corozal quadrangle.

Lenses of laminated dense tuff, probably including both primary and reworked fractions, are numerous throughout the upper part of the Magüeyes Member. Only the thicker and seemingly more persistent units are shown on the geologic map (pl. 1) and in the columnar sections (pl. 2).

Volcanic breccia within the upper part of the Magüeyes Member is confined largely to a single thick unit that is characterized by large pillowlike masses of amygdaloidal lava, ranging from a few centimeters to as much as a meter or more in diameter. Some parts of the unit are compact with little fine-grained matrix and seem to consist of primary pyroclastic breccia; other parts have a considerable fine-grained matrix. This intermixture of very coarse fragments and a fine-grained matrix suggests a submarine slump or slide phenomenon by which fragments of pyroclastic breccia and fragments of epiclastic lava, including pillows, were transported to the site of deposition. Within the volcanic breccia unit are several thin layers of laminated tuff.

The lava and breccia that are restricted to the narrow faulted syncline near the east edge of the quadrangle have been correlated with the Magüeyes Member because of their stratigraphic position above the basalt tuff member (pl. 2); however, as already pointed out, these rocks may be a part of the basalt tuff member. The sequence within this faulted outlier is lava overlain by reworked pyroclastic and epiclastic(?) volcanic breccia, but the lava, instead of being pillowed, is a flow breccia of reddish hue. Presumably, the part of the Magüeyes Member above the basalt tuff member thins sharply toward the north, as shown on plate 2, but complicated structure between the two areas of outcrop and extensive erosion of that part of the member in the north-central part of the quadrangle prevent confirmation of this assumption.

### BASALT TUFF MEMBER

The basalt tuff member is a massive and dense basaltic tuff containing disoriented masses and stringers of basaltic amygdaloidal lava of varying sizes and shapes and sporadic thin lenses of laminated tuff. Many of these basaltic masses resemble pillows. The petrography of the member suggests a close petrogenic relationship to the basaltic lavas of the Río Orocovis Formation. The basalt tuff member crops out in the northern part of the quadrangle adjacent to the Ciales and Morovis stocks; the member also crops out as a linear belt across the central part of the Corozal quadrangle which adjoins the Ciales quadrangle to the east.

The basalt tuff member in the Ciales quadrangle is in a narrow faulted syncline that has been divided into two parts by the Morovis and Ciales stocks (pl. 1). Faulting has obscured the stratigraphic relation of the basalt tuff member to other members of the Río Orocovis Formation, and, for this reason, a formal name is not applied to the tuff. Along the southern boundary of the syncline the basalt tuff member is in fault contact with the overlying(?) Avispa Lava Member. Along the north side of the western part of the syncline the basalt tuff member is also in fault contact with the Avispa Member, but along the north side of the eastern part the basaltic tuff has been faulted against rocks of Late Cretaceous or early Tertiary age, except at the west end where it is overlain unconformably by rocks of middle Oligocene age.

Rocks that are correlated with the basalt tuff member of the northeastern part of the quadrangle separate two parts of the Magüeyes Member near the southeast corner of the Ciales quadrangle. The exposed part of the basalt tuff member in the northern part of the quadrangle is estimated to be about 500 meters thick. Because of possible repetition by faulting, this estimate may be excessive. The thickness to the southeast is only about 100 meters.

The basaltic tuff is distinguished from all other pyroclastic rocks in the area by its massiveness, homogeneous composition, greenish color, and profusion of pyroxene crystals. When fresh, the tuff is dense, dark greenish gray (5*G* 4/1), and indistinguishable megascopically from basaltic lava. Reddish to brownish oxidized particles typical of most tuffs are conspicuously absent. Weathering reveals numerous pillow-shaped masses and contorted stringers of basaltic lava scattered randomly through the tuff. Where this material is deeply weathered, saprolite and soil residuum are marked by a distinctive green color and numerous loose pyroxene crystals. Good outcrops of the member are in the banks of the highway that crosses the southern part of barrio Monte Llano and the northern part of barrio Cuchillas, east-central Ciales quadrangle.

The basaltic tuff seems to be a facies equivalent of a part of the basaltic pillow sequence in the Magüeyes Member; however, this relationship can only be inferred because of structural complications. The implied stratigraphic relations of the two rock types are shown on plate 2. The Río Orocovis Formation is probably an intertonguing complex with each member locally intertonguing with or overlying part of another member.

### PERCHAS LAVA MEMBER

Much of the Río Orocovis Formation in the southeastern part of the Ciales quadrangle consists of a sequence of massive amygdaloidal pillow lavas and thin lenticular layers of tuff, epiclastic volcanic sandstone, and epiclastic volcanic breccia having a thickness of about 1,500 meters. This sequence is here named the Perchas Lava Member for excellent outcrops along the banks of the highway that crosses Quebrada Perchas in barrio Pesas, Municipio de Morovis. The type area extends along the Morovis-Orocovis highway from locality 6 in barrio Gato northward to locality 7 which is just south of the Río Grande de Manatí. (See pl. 1.) The uppermost part of the member lies north of the river and northwest of locality 7. The area of outcrops is largely defined by faults (pl. 1); locally near the center of the quadrangle the Perchas Member is truncated by the Morovis stock. Structurally, the Perchas occupies the west limb of a faulted anticline. Dips are steep and overall structure was determined from the attitude of thin beds of tuff that are scattered through the member. The lava forms a bold topography with scattered massive cliff-forming outcrops. A small outlying area of lava southeast of Morovis is probably Perchas. There the lava is in juxtaposition to the south with the Morovis stock; it is overlapped from the north by middle Tertiary gravel of the San Sebastián Formation.

The lavas of the Perchas Member are virtually indistinguishable from most lavas of the Magüeyes Member. The contact between the two members is placed at the stratigraphic position where the relatively thick tuff layers characteristic of the Magüeyes Member become much less numerous.

The dark-gray (*N* 3) to greenish-black (5*G* 2/1) lava is porphyritic with aphanitic but very finely crystalline groundmass. Phenocrysts are characteristically pyroxene (3–6 mm) with subordinate small phenocrysts of plagioclase (0.5–1 mm). The only marked lithologic variant in the entire sequence of lava flows of the Perchas is a feldspathic pillowed lava flow near the middle of the member, which is mapped separately (pl. 1). This flow is characterized by abundant and very large zoned plagioclase phenocrysts (1–2 cm). Adding to the distinctiveness of this unit is the cruciform arrangement of some of the phenocrysts.

Most of the lava flows seem to have an average thickness of between 15 and 50 meters. Individual flows could not be identified or traced over sufficient distance to determine their lateral extent. The sole exception is the feldspathic lava noted above, which averages 10–20 meters thick and can be traced for almost 4 km.

Pillow structure and abundance of amygdules are features of all lavas in the Perchas Member. The pillowed structures typical of the member are shown in figures 7–9. The pillows average 0.5–1 meter in diameter, except in the feldspathic lava flow of the Perchas where pillows locally are as much as 2 meters in diameter. Casements or

FIGURE 7.—Pillow structures in the Perchas Lava Member. Lava flow showing pillows, bank of Highway 155 at curve near northwest boundary of barrio Gato.

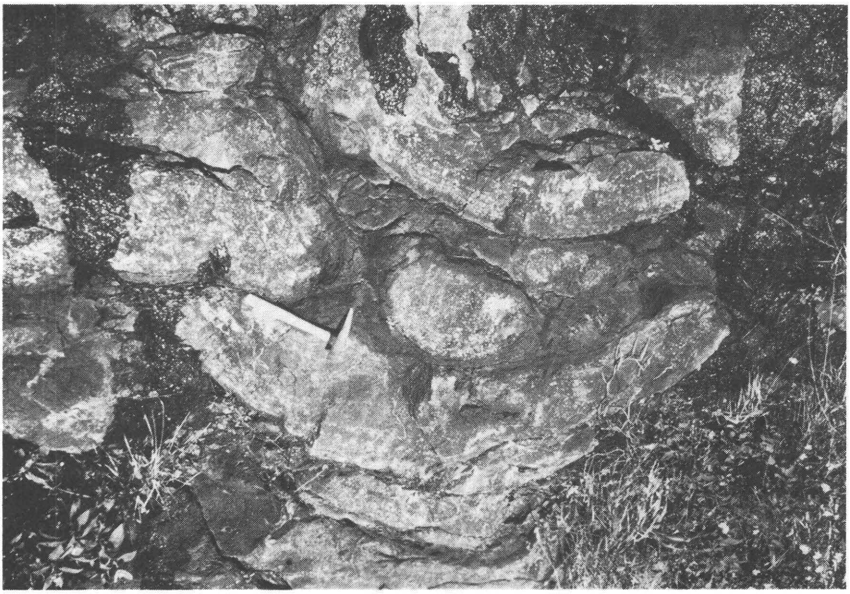

FIGURE 8.—Pillow structures in the Perchas Lava Member. Concentration of amygdules as concentric bands in outer parts of pillows, 150 meters north of area shown in figure 7.

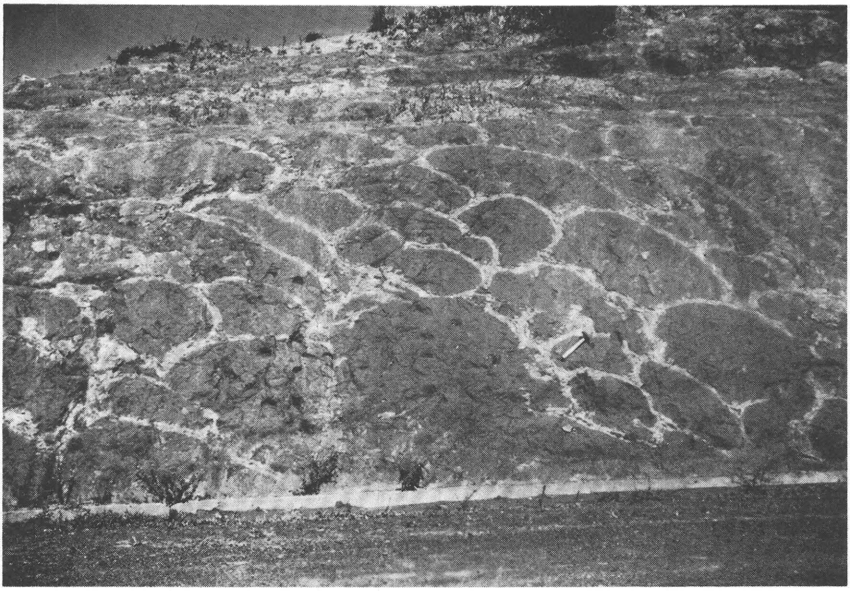

FIGURE 9.—Pillow structures in the Perchas Lava Member. General shape and size of pillows, 300 meters southwest of area shown in figure 7.

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rinds around pillows are aphanitic to porcelaneous lava; lumps of jasper and reddish limestone occur sporadically as interstitial fillings between pillows.

Included in the Perchas Lava Member are bedded lenses of laminated fine-grained dense tuff, coarse friable tuff, epiclastic volcanic sandstone, and epiclastic volcanic breccia. Thickness of individual layers of tuff seldom exceeds a few meters and consequently most of the thinner laminated fine tuff layers were contorted during extrusion of the immediately overlying lava flows. The approximate stratigraphic distribution of clastic rocks is indicated by the spacing of the dip-strike symbols along the Morovis-Orocovis highway. Volcanic breccia is rare, and most occurrences seem to have a general form that could be attributed to a deposit of pillow-lava rubble transported by a submarine avalanche. A bedded unit of local extent near the top of the Perchas Member (loc. 11) contains, in addition to epiclastic volcanic sandstone with limy matrix, thick beds of epiclastic volcanic breccia. The detritus in this unit is basalt; it obviously was derived by local reworking of lava in the Perchas Member. This material is associated with a local oxidized zone at the top of the lava sequence of the Perchas (loc. 12) and probably accumulated around a small lava island.

### AVISPA LAVA MEMBER

The Avispa Lava Member is here named for its exposures on and in the vicinity of Cerro Avispa, central Ciales quadrangle, between localities 13 and 14, plate 1. It crops out in three general areas within the Ciales quadrangle: in the central part where outcrops form a northwestward-trending belt that is outlined in part by faults and in part by boundaries of the Morovis and Ciales stocks; in the south-central part in a narrow belt whose regional northeastward strike is perpendicular to the trend of the adjacent belt to the north; and at the southwest corner of the quadrangle where the northwestward trend is parallel to the trend in the largest area of outcrop in the central part of the quadrangle. All areas of outcrop are extensively faulted. The central belt seems to be part of a syncline that is characterized by high-angle strike-trending faults and steep dips; the south-central belt of outcrop is on the west limb of a faulted anticline; and the outcrops in the southwest are in and adjacent to the highly deformed zone associated with the Damián Arriba fault. Lavas similar to those in the Avispa Member are known to extend eastward across the adjacent Corozal quadrangle, southward into the Orocovis quadrangle, and westward into the Florida quadrangle.

The thickness of the Avispa Member is highly variable, ranging from about 100 meters in the south-central part of the Ciales quadrangle to an estimated thickness of 1,500 meters in the northwestward-trending belt of outcrop across the central part of the quadrangle where repetition of parts of the formation by faulting is probable. No estimate of thickness was made for the highly deformed part of the formation in southwestern Ciales quadrangle.

The Avispa Member overlies the Perchas Member in south-central Ciales quadrangle along a north-northeastward-trending line of contact. No hiatus is evident between the two members, but attitudes in the basal part of the Avispa are divergent from those in the upper part of the Perchas, indicating onlap of the Avispa across an irregular upper surface of the Perchas in this area. The base of the Avispa Member is not exposed elsewhere in the Ciales quadrangle because of faulting.

Lava similar to the Avispa is reported to tongue into and lens with Magüeyes and Perchas-like lava to the east of the Ciales quadrangle in both the Corozal and Naranjito quadrangles (M. H. Pease and Arthur Nelson, written commun., 1961). This fact indicates that over the general region of north-central and northeastern Puerto Rico both types of lava were extruded contemporaneously. Possibly some of the thick Avispa Lava Member in the faulted synclinal central belt of the Ciales quadrangle is equivalent in age to the Perchas Member elsewhere, but the Avispa Lava Member in the south-central belt of outcrop consistently overlies the Perchas Member.

In the south-central part of the quadrangle the Avispa Member contains in its upper part volcanic breccia that seems to intertongue with the overlying Manicaboa Formation, suggesting that locally the upper part of the Avispa and the basal part of the Manicaboa Formations are time equivalents. Because of faulting, however, the relation between the Avispa and the Manicaboa is not clear cut. The Manicaboa Formation seems to overlie the Avispa Member conformably in south-central and east-central Ciales quadrangle; the San Sebastián Formation and locally the Lares Limestone, both of Oligocene age, unconformably overlie the Avispa in the west-central part of the quadrangle.

The Avispa Member is characteristically andesitic pillow lava with reworked tuff as a minor but widespread constituent. Conglomerate, volcanic breccia, tuff, and reef limestone are local components. In order to demonstrate the structure of the Avispa Member, the more prominent clastic units within the formation have been mapped and given informal designation on plate 1. Composite sections of the Avispa Member are shown on plate 2.

The massive lava of the Avispa, which includes a multitude of individual flows, is characterized by uniform composition and by plagioclase phenocrysts; the latter distinguish lava of the Avispa from those of the underlying Perchas and Magüeyes with pyroxene phenocrysts. Pillow structure is well developed except in the area between the Morovis and Ciales stocks, and pillows in many parts of the member are enclosed by rinds of chert. Good outcrops showing the siliceous rinds are along the unimproved road south of Cerro Avispa.

The lavas are dark-greenish-gray (5*G* 4/1) rocks of porphyritic texture with abundant phenocrysts of lath-shaped plagioclase set in an aphanitic groundmass. Phenocrysts of pyroxene occur sporadically through the sequence but are always less abundant than plagioclase. The phenocrysts of plagioclase range in size from about 0.5 to about 7 mm and probably average about 3 mm. The groundmass in most specimens is very finely crystalline; in a few specimens it is dense and almost glassy.

Units of reworked tuff as much as 30 meters thick occur as lenses throughout the member; these are dense well-bedded banded rocks that break into angular pieces upon weathering. Lenticular units of volcanic breccia, including both reworked pyroclastic(?) and epiclastic lava fragments, are present locally in the south-central, east-central, and west-central parts of the quadrangle. Conglomerate, which includes beds of epiclastic sandstone and siltstone, is confined to the area of Avispa outcrops in the central part of the quadrangle as a discontinuous intramember unit that consists largely of pebbles, cobbles, and boulders of lava reworked from the Avispa. Beds of fine-grained clastic rocks within this unit are locally contorted and faulted in a manner that suggests penecontemporaneous deformation, perhaps by earthquakes associated with the volcanic activity.

A single lenticular unit of limestone occurs in the basal part of the member in central Ciales quadrangle. East of the Río Grande de Manatí, the limestone lies at the base of the Avispa Member and rests on oxidized lava of the Perchas Member; west of the river the limestone lies within the Avispa Member and above a tongue of clastic rock. Maximum thickness is about 5 meters. The limestone is a mixture of algae and small rudistid fragments and contains scattered fragments of reworked oxidized lava in its basal part. Fossil remains are so fragmented that generic identification is not possible. The oxidized condition of underlying rocks suggests that reef growth followed shallow submergence of a small island of lava.

## PETROGRAPHY

### Lavas of the Magüeyes and Perchas Members

Under the microscope, the porphyritic basaltic lavas of the Magüeyes and Perchas Members reveal a microlitic (hyalopilitic to pilotaxitic) groundmass. Megaphenocrysts of clinopyroxene (mainly augite) and microphenocrysts of glomerophyrically intergrown orthopyroxene(?), plagioclase, and magnetite are set in a groundmass consisting of plagioclase and clinopyroxene microlites and interstitial devitrified glass, which contains much opaque dust and many fine microlites of ilmenite(?). Pseudomorphs of quartz, chlorite, and calcite after olivine and orthopyroxene(?) are present in some lavas. Anhedra of quartz and orthoclase(?) are scattered sporadically through the groundmass of some lava units. The amount of glassy material and ratio of plagioclase microlites to clinopyroxene varies between lava units, but in general plagioclase is considerably more abundant than clinopyroxene.

Partial alteration of both phenocrysts and groundmass is a feature common to the entire Magüeyes and Perchas sequence, but the process of alteration was noticeably selective in that some minerals were attacked more extensively than others. For example, the large calcic clinopyroxene (augite) phenocrysts typical of most lavas in the sequence are unaltered, but most of the smaller megaphenocrysts and microphenocyrsts of orthopyroxene(?) have been largely replaced. The few microphenocrysts of olivine and some of the orthopyroxene(?) microphenocrysts have been totally replaced. Acicular microlites of clinopyroxene(?), however, are unaltered. The feldspars likewise show different stages of degeneration: the microphenocrysts are highly altered; the microlites show little or no alteration.

Secondary minerals in order of abundance are chlorite, calcite, albite, nontronite(?), sericite, prehnite, quartz, zeolites, and bastite. Inclusions of apatite and epidote are present in almost all feldspar crystals. Chlorite, calcite, and nontronite(?) are common in both phenocrysts and groundmass. Albite, sericite, prehnite, calcite, and chlorite have extensively replaced calcic(?) plagioclase. Secondary quartz occurs as microveinlets and as rare pseudomorphs after orthopyroxene(?) and olivine. Primary quartz (chalcedony) is extremely rare and, when present, occurs as microamygdules. Ubiquitous material of negative relief and low birefringence in the groundmass is presumed to be zeolites. The texture and mineralogy typical of lavas of the Magüeyes and Perchas are shown in figure 10.

The feldspathic lava flow of the Perchas Member contains, instead of pyroxene phenocrysts, large megaphenocrysts of polytwinned plagioclase. Megaphenocrysts of orthopyroxene(?) in this lava have been completely replaced by other minerals. The microlitic groundmass differs from that of associated lavas in having slightly more orthoclase and considerably more pyroxene.

The plagioclase megaphenocrysts in the feldspathic lava of the Perchas Member are zoned, albitic, and contain sericite and apatite inclusions; cores and interfaces between zones are lined with chloritic dust. Microphenocrysts of plagioclase have been extensively saus-

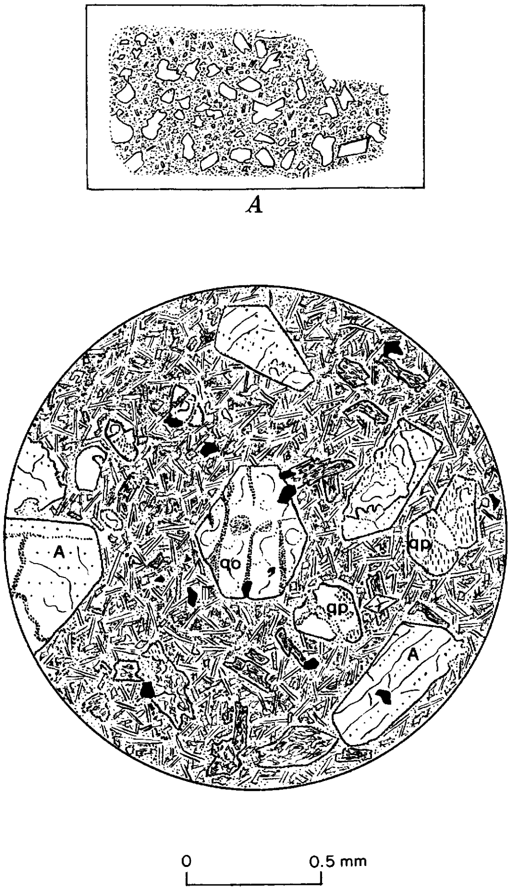


FIGURE 10.—Texture and mineralogy of lava in the Magüeyes Member, Río Orocovis Formation. *A*, Megascopic porphyritic texture. *B*, Augite (A) phenocrysts; pseudomorph of quartz (qo) after orthopyroxene(?); scattered pseudomorphs of quartz (qp) after olivine(?) and saussuritized plagioclase; microlitic groundmass with microlites of plagioclase and interstitial chloritized glass with opaque ore dust.

suritized. The orthopyroxene(?) is altered to a mixture of chlorite, calcite, quartz, serpentine(?), and a clay mineral. The microlitic groundmass consists of plagiclase, orthoclase, pyroxene, amphibole(?), ilmenite, magnetite, quartz, and interstitial dusty chloritized glass that is rich in iron and potassium oxide. Plagioclase microlites are less altered than the plagioclase phenocrysts and seem to be oligoclase or andesine. Orthoclase(?) in the groundmass forms anhedra between microlites of other minerals and contains much mineral dust.

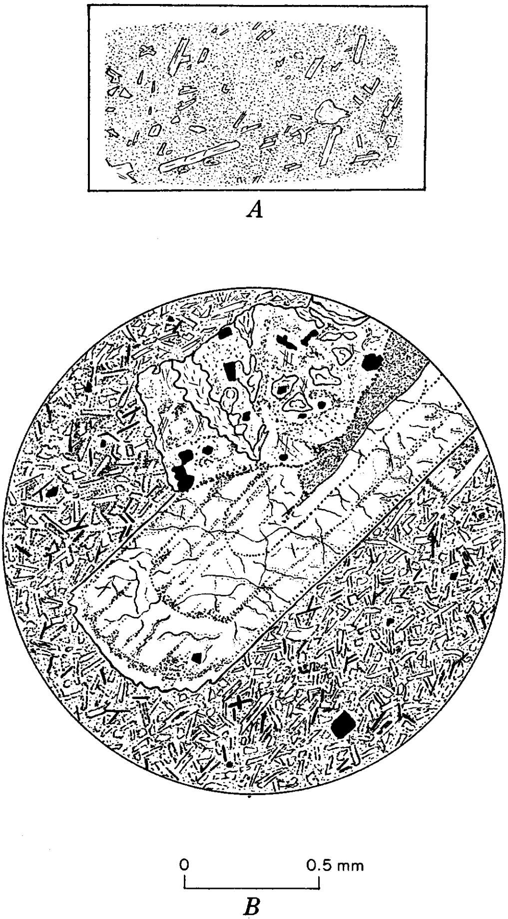

FIGURE 11.—Texture and mineralogy of feldspathic lava flow, Perchas Member, Río Orocovis Formation. *A*, Megascopic porphyritic texture. *B*, Zoned albitized plagioclase phenocrysts; pseudomorph of intermixed chlorite, calcite, quartz, and magnetite after orthopyroxene(?); microlitic groundmass with microlites of plagioclase and ilmenite and interstitial chloritized glass.

Ilmenite is especially conspicuous because of its manner of distribution through the groundmass. Microlites of ilmenite form a connecting net from one mass of chlorite (devitrified glass) to another. The scattered magnetite crystals are in both the chloritized glass and the pseudomorphs after orthopyroxene(?). Quartz (chalcedony) is a rare constituent forming microamygdules. Potash was detected in the chloritized glass by a staining process. Microscopic features of a feldspathic lava flow are shown in figure 11.

Representative specimens of the lavas of the Perchas Member were analyzed chemically. The results, together with the normative minerals and minor constituents, are shown in tables 4 and 5. For comparison, some analyses of established rock types are included.

The chemical and mineralogical similarity of the lavas of the Magüeyes and Perchas Members to the general basaltic kindred is obvious, but deviations in composition, both from typical basalt (No. 4, table 4) and also from one lava to another, are readily apparent. The potassium oxide content of all three specimens is higher than that of an average basalt, which indicates that the rocks are subalkalic. The amount of potassium oxide beyond that normal to the average basalt varies from slight in No. 3, to moderate in No. 1, to large in No. 2. Accordingly, the lavas represented by Nos. 1 and 3 are classified as basalts, and No. 1 is a potassic variant that is similar to trachybasalt. No. 2, with markedly high potassium oxide content and preponderance of normative orthoclase, is an alkalic rock rather than a normal basalt. This lava has chemical and mineralogical features similar to the lavas of Timor that De Roever (1942, p. 223–224) classified as poeneite. Poeneites are defined as rocks showing the structural and mineralogical characteristics of basalts, but in which the feldspathic constitutent is represented by potash feldspar. According to De Roever (1942, p. 224), poeneites are potash feldspar-bearing equivalents of the albite-bearing spilites. Because albite, as well as orthoclase, is prominent in the lava represented by No. 2 from the Río Orocovis Formation, the rock is called a spilitic poeneite(?), a term also used by De Roever (1942, p. 224).

TABLE 4.—*Chemical analyses and norms, in percent, of samples of the Perchas Lava Member and other "basaltic" associations*

[Analysts: P. L. D. Elmore, I. H. Barlow, S. D. Botts, and Gillison Chloe]

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Chemical analyses** | | | | | | |
| $SiO_2$ | 48.3 | 50.4 | 48.4 | 48.8 | 48.8 | 52.05 |
| $Al_2O_3$ | 14.1 | 18.8 | 13.9 | 15.8 | 16.0 | 18.35 |
| $Fe_2O_3$ | 4.7 | 2.5 | 4.3 | 5.4 | 4.3 | 10.07 |
| FeO | 6.0 | 5.5 | 5.7 | 6.3 | 6.3 | .40 |
| MgO | 8.1 | 3.7 | 9.1 | 6.0 | 5.4 | .91 |
| CaO | 10.0 | 3.8 | 10.1 | 8.9 | 8.2 | 1.96 |
| $Na_2O$ | 1.9 | 3.0 | 2.2 | 3.2 | 3.9 | 1.39 |
| $K_2O$ | 3.3 | 5.2 | 2.0 | 1.6 | 2.8 | 8.97 |
| $H_2O$ | 2.5 | 4.0 | 3.1 | 1.8 | 1.5 | 2.88 |
| $TiO_2$ | .78 | .68 | .68 | 1.4 | 1.9 | 2.24 |
| $P_2O_5$ | .50 | .75 | .45 | .5 | .7 | .94 |
| MnO | .22 | .15 | .20 | .3 | .2 | .16 |
| $CO_2$ | .14 | $<.05$ | .16 | -------- | -------- | -------- |
| $SO_3$ | -------- | -------- | -------- | -------- | -------- | .06 |
| SrO | -------- | -------- | -------- | -------- | -------- | .04 |
| $Li_2O$ | -------- | -------- | -------- | -------- | -------- | $\leqq.01$? |
| Total (rounded) | 101 | 99 | 100 | -------- | -------- | 100 |
| **Norms** [Barth modification of C.I.P.W. norm] | | | | | | |
| Quartz | -------- | 2.52 | -------- | -------- | -------- | 7.11 |
| Orthoclase | 19.46 | 30.58 | 11.68 | 9.45 | 16.68 | 52.82 |
| Albite | 16.24 | 25.15 | 17.82 | 27.25 | 31.96 | 11.53 |
| Nepheline | -------- | -------- | -------- | -------- | .85 | -------- |
| Anorthite | 20.02 | 5.00 | 22.24 | 23.91 | 17.79 | 3.34 |
| Corundum | -------- | 6.43 | -------- | -------- | -------- | 5.20 |
| Wollastonite | 10.66 | -------- | 9.63 | 7.08 | 6.26 | -------- |
| Enstatite | 8.10 | 9.30 | 16.30 | 11.20 | -------- | 2.30 |
| Ferrosilite | 2.38 | 7.00 | 4.09 | 3.43 | -------- | -------- |
| Forsterite | 8.54 | -------- | 4.48 | .70 | 9.38 | -------- |
| Fayalite | 2.65 | -------- | 1.22 | 3.88 | 3.67 | -------- |
| Magnetite | 6.73 | 3.71 | 6.26 | 7.89 | 6.26 | -------- |
| Hematite | -------- | -------- | -------- | -------- | -------- | 10.08 |
| Ilmenite | 1.52 | 1.37 | 1.37 | 2.74 | 3.65 | 1.22 |
| Apatite | 1.34 | 2.02 | 1.34 | 1.34 | 1.68 | 2.35 |
| Rutile | -------- | -------- | -------- | -------- | -------- | 1.60 |
| Calcite | .3 | -------- | -------- | -------- | -------- | -------- |

1. Basalt (potassic) Perchas Member; field No. XC-16; loc. 8, pl. 1; lab. No. 154661.
2. Spilitic poeneite(?) feldspathic lava flow, Perchas Member; field No. XC-65; loc. 9a, pl. 1; lab. No. 154663.
3. Basalt, Perchas Member; field No. XC-69; loc. 9b, pl. 1; lab. No. 154664.
4. Basalt, mean of 161 analyses (Tyrrell, 1926, p. 131).
5. Trachybasalt, mean of 28 analyses (Tyrrell, 1926, p. 131).
6. Poeneite, Noil Tobe, Timor (De Roever, 1942, p. 237).

TABLE 5.—*Minor constitutents in rocks from the Magüeyes and Perchas Members*

[Analyst: J. C. Hamilton]

| Field No. / Laboratory No. | XC-63 [1] 281012 | XC-69 [2] 281013 | XC-1012 [3] 281014 |
|---|---|---|---|
| Ba | 0. 3 | 0. 07 | 0. 15 |
| Be | . 00015 | ------------ | . 00015 |
| Co | . 0015 | . 003 | . 0015 |
| Cr | . 007 | . 03 | . 003 |
| Cu | . 03 | . 03 | . 03 |
| Ga | . 0015 | . 0007 | . 0007 |
| La | . 003 | ------------ | ------------ |
| Mo | . 0015 | . 0007 | ------------ |
| Ni | . 003 | . 015 | . 0015 |
| Sc | . 0015 | . 003 | . 0007 |
| Sr | . 3 | . 15 | . 3 |
| V | . 07 | . 03 | . 015 |
| Y | . 0015 | . 0015 | . 0015 |
| Yb | ------------ | . 00015 | . 00015 |
| Zr | . 007 | . 003 | . 003 |

[1] Basalt, Perchas Member (loc. 9c, pl. 1).
[2] Basalt, Perchas Member (loc. 9b, pl. 1). Same sample as No. 3, table 4.
[3] Basalt, Magüeyes Member (loc. 5, pl. 1).

In classifying lavas of the Magüeyes and Perchas Members, the potassium has been considered as a primary constitutent principally because of the variability in potassium content from one lava to another and because of the concentration of potassium in the groundmass. The confinement of the potassium to the groundmass of the lava indicates that the concentration was the result of deuteric effects during late stages of cooling or consolidation. The nature of occurrence of potassium suggests that the magma supplying the basaltic lava was contaminated from time to time by sialic material. Additional analyses over a wide area will be necessary to prove this tentative conclusion.

#### Lava of the Avispa Member

The microscope shows that lava of the Avispa Member has porphyritic texture and a microlitic (hyalopilitic to pilotaxitic) groundmass which in some specimens vary from the typical microlitic form. In several specimens studied, the microlites, instead of being laths or needles, are branching or sheaflike forms similar to those in the Ischian trachytes, Isle of Ischia, Italy, that were called keraunoids by Washington (1896, p. 380) because of their resemblance to the thunderbolts commonly depicted in the hand of the Greek god Zeus. Washington also referred to reported occurrences of similar texture in certain basalts of Hawaii and elsewhere. This texture, as it occurs in the lavas of the Avispa, is shown on figure 12. Keraunoids, according to Washington, have been attributed to both spherulitic growth habits and periodic splitting of growing microlite crystals as a

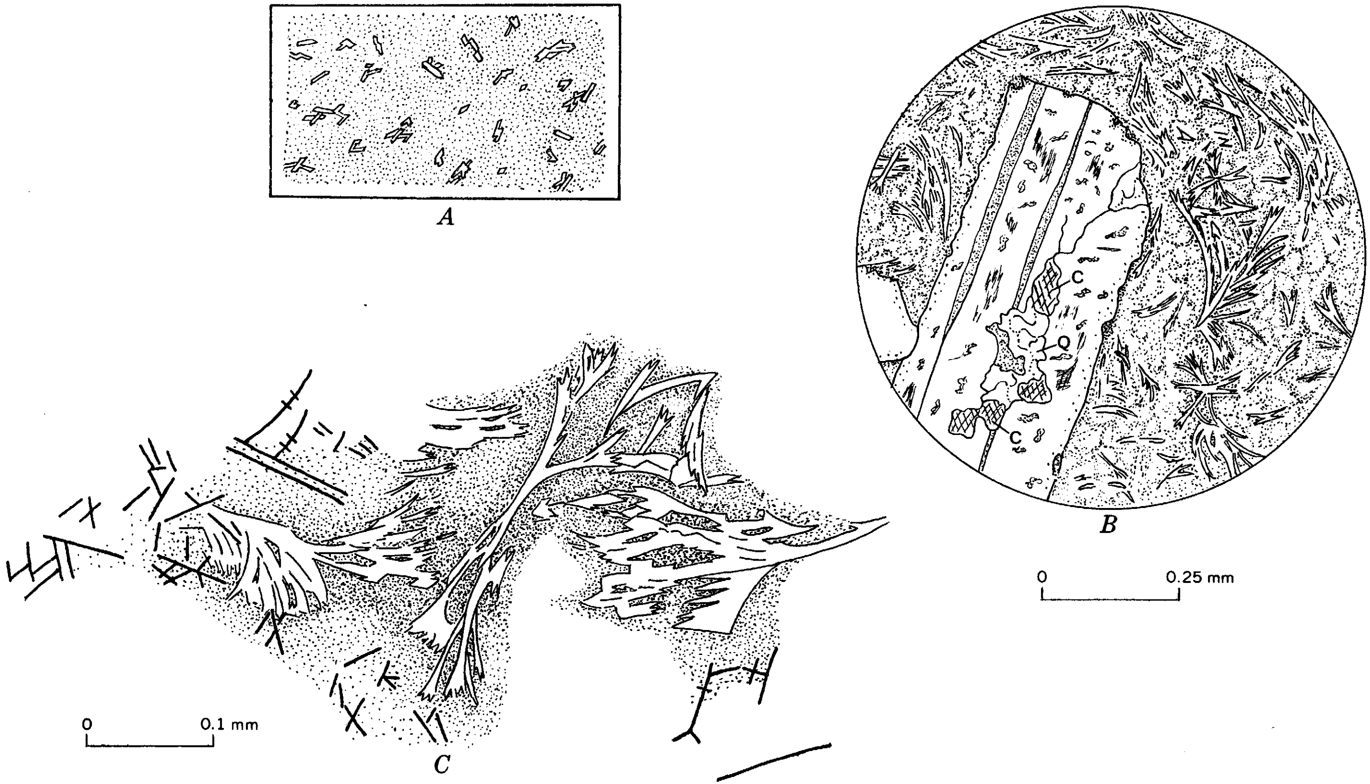


FIGURE 12.—Texture and mineralogy of lava from the Avispa Lava Member, Río Orocovis Formation. *A*, Megascopic porphyritic texture. *B*, Twinned albitized plagioclase phenocryst with resorbed edges, quartz (Q) and calcite (C) as replacing minerals, and clinozoisite(?) and chlorite dust; microlites (keraunoids) of orthoclase(?) in devitrified turbid granular groundmass having much opaque dust. *C*, Keraunoids and ilmenite microlites.

result of internal tensions caused by movements within the lava, after the lava had come to rest. Washington believed the latter explanation to be the most plausible, and he stressed the localized nature of occurrences of this texture, suggesting that such texture would form only in the inner parts of lava flows that remain liquid for some time after outer parts have cooled. Washington did not specify the nature of the internal tensions within lavas forming keraunoids, but presumably the tension was caused by convectional disturbances in parts of the lava that remained hot and liquid after outer parts had cooled.

The plagioclase phenocrysts in the Avispa Lava Member are albite, but the inclusions of clinozoisite(?), sericite, calcite, and epidote suggest albitization of a more calcic plagioclase; in some specimens the plagioclases have been partially resorbed. The subordinate and sporadic pyroxene phenocrysts, which tend to cluster around the plagioclase, have been altered completely in most specimens to a mixture of chlorite, calcite, quartz, and epidote.

Groundmass microlites are typically feldspar, both plagioclase and orthoclase(?), and ilmenite which is commonly clustered along the edges of altered feldspar microlites. Anhedral quartz and spherulitic chalcedony are moderately abundant, and devitrified glass that is now a turbid mixture of chlorite, zeolites(?), nontronite(?), occult potash, and opaque dust is a common and, in some specimens, an abundant constituent. Secondary pyrite is abundant, particularly in specimens from the central belt of rocks that have been intruded by the granodiorite stocks. Apatite needles are present in some altered feldspar. Extensive alteration of the glass, and in some specimens the microlites as well, precludes precise determination of the mineralogic composition of the groundmass.

Chemical analyses are not available for the lavas of the Avispa. Their mineralogic composition, as determined optically, is that of andesite, though the classification is provisional considering the altered condition of the rocks. The moderately high quartz content of some specimens, together with albitized plagioclase, suggests a keratophyric tendency; the relatively high potassium content of others, as revealed by staining, is suggestive of trachyandesite. Minor constituents, as determined by semiquantitative spectrographic analysis, are similar in kind and amount to those in the Magüeyes and Perchas Lava Members.

The lavas of the Avispa are clearly distinct from those of the Magüeyes and Perchas in containing more feldspar and quartz. The presence of a small amount of free quartz in the Avispa Lava Member and its rarity in the Magüeyes and Perchas Members suggest that the quartz is a product of magma differentiation; however, a secondary origin for the quartz in the Avispa cannot be discounted.

**Tuffs**

The relatively thin and lenticular tuff beds between the pillow lavas of the Río Orocovis Formation are composed of particles of lava with microlitic-fluidal texture, fragmented crystals of pyroxene, broken crystals of plagioclase, pumiceous particles, and microscopic devitrified glass with perlitic structure. Many of the lava particles have been oxidized to hematite, and a sizable percentage of all particles is rounded to some degree. Some tuff units are compact with little or no matrix; others contain a matrix that in most places has been altered and now consists of admixed calcite, nontronite(?), and chlorite.

The combination of fragile devitrified glass and pumice and rounded lava particles indicates that these units are principally accumulations of ash particles that fell directly into water and mixed with epiclastic lava particles. Some of the material is probably reworked tuff, but some may have been erupted directly into water. In every tuff unit the microscope reveals graded bedding which has probably resulted from deposition by density currents and from gravity separation of ash particles during fall through the air. Additional evidence for deposition by density currents are groove casts and penecontemporaneously deformed laminae that were truncated by scour when overlying material was carried in and deposited.

The most distinctive tuff in the Río Orocovis Formation is the basalt tuff member. When fresh, this dense rock can be recognized as a tuff only by microscopic study. The material in the basalt tuff member is mineralogically very similar to the associated basaltic pillow lavas. It consists of pyroxene (augite) crystals in great abundance, pseudomorphs of chlorite after a mafic mineral (iron-rich pyroxene and (or) olivine), spherulitic ash particles, and sporadic devitrified glass particles with perlitic structure. Feldspar as such is conspicuously absent; calcite is common as a matrix between particles. The distinguishing microscopic feature of this basaltic tuff is an extensive overgrowth of wispy amphibole (tremolite-actinolite?) as a secondary mineral around the pyroxene crystals and also around some ash particles (fig. 13). Amphibole is also common as very small acicular microlites within the chloritized groundmass. Overgrowth of amphibole around other crystals and ash particles in the basalt tuff member seems to have been a deuteric process that probably was aided by entrapment of water during submarine eruption.

Calicified remains of Foraminifera are common throughout the basalt tuff member. The tests are so grossly replaced that species

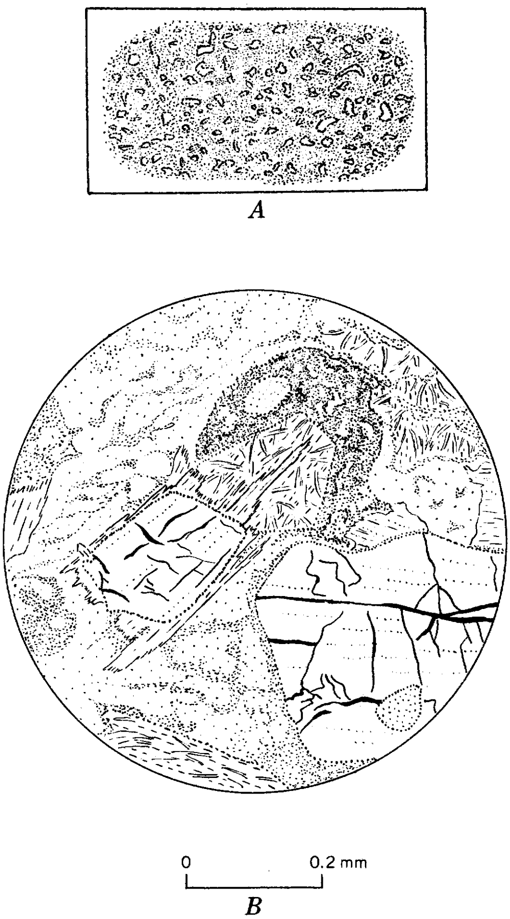


FIGURE 13.—Texture and mineralogy of the basalt tuff member, Río Orocovis Formation. *A*, Megascopic pyroclastic texture. *B*, Clastic texture with characteristic large crystals of pyroxene. The pyroxene crystal to the left of center has the typical wispy overgrowth of amphibole. The crystal in the center is a pseudomorph of chlorite after pyroxene with acicular microlites of amphibole.

identification is not possible, but most seem to resemble *Globigerina* and are probably pelagic types.

The sporadic bedded parts of the basalt tuff member show a characteristic grading of grain size under the microscope. In contrast to other parts of the member, the pyroxene crystals within the bedded tuff are highly fragmented and somewhat rounded. The rock has a more heterogeneous aspect, because the groundmass is calcareous rather than chloritic and contains no devitrified glass particles. The rounding of fragments and graded bedding were presumably accomplished by density current action resulting from submarine slumping.

## CONDITIONS OF ORIGIN

### Magüeyes and Perchas Members

The well-developed pillow structure with local interstitial limestone demonstrates that the lavas of the Río Orocovis Formation were extruded on the sea floor. Laminated tuff completely encircles pillows as rinds at some places, indicating that the lava began to form pillows in the wet sediments as it moved upward toward the ocean floor. The nature of pillowing relative to the Late Cretaceous sea floor is spectacularly demonstrated in an outcrop at locality 3a on the Río Orocovis that shows the following sequence from base to top: lava with polygonal jointing, lava in pillows surrounded by laminated rinds of tuff and limestone, and lava in pillows without rinds of tuff. The pillowed lava without rinds of tuff formed on the sea floor above the sediments and is connected with the pillows in the tuff by a large dike of basalt. A submarine origin for the sequence is further indicated by graded bedding in pyroclastic-epiclastic material between individual flows and by the abundance of pelagic Foraminifera in the thick basalt tuff member.

Two types of volcanism are represented by rocks of the Río Orocovis Formation: quiet effusion of molten material as indicated by the thick sequence of pillow lavas of the Magüeyes, Perchas, and Avispa Members; explosive, and probably submarine, ejection of a tremendous quantity of basaltic tuff as indicated by the basalt tuff member. Coeval relationship of the two types of volcanism is demonstrated by the intertonguing of the lava and the mineralogically similar tuff (pl. 2) and by the abundant lava within the tuff as randomly distributed isolated pillow-shaped masses and as contorted stringers. Obviously, lava effusion and explosive eruption were at times simultaneous. Earthquakes that must have attended the volcanism probably dislodged sizable quantities of both pillow lava and tuff, which cascaded to deeper parts of the sea as submarine slides, thus accounting for a part of the intermixing of the two types of material and for the sporadic graded bedding. The intermixed submarine pyroclastic tuff and lava of the basalt tuff member probably accumulated in part in a low area in the sea floor between an area of lava effusion to the south (present position of Magüeyes and Perchas Members) and an area of explosive activity that lay to the north and northeast of the present area underlain by the basalt tuff member. This low area presumably was created by irregular buildup of material near the sites of submarine eruption. Some tuff of the basalt tuff member may represent pile-up around submarine vents. Both types of volcanic activity seem to have persisted almost simultaneously for a long period, as indicated by the tremendous accumulation of both lava and basaltic tuff.

Submarine vents are postulated as the source of the basalt tuff on the basis of lithologic, mineralogic, and sedimentologic features that distinguish this tuff from other tuff in the area and from subaerially erupted tuff in general. The intertonguing of the lava and the basaltic tuff and the abundance of lava, both as pillows and as weirdly contorted masses within the tuff, indicate either that tuff and lava were erupted simultaneously or that they became intermixed before much of the lava cooled. Similarly, mineralogic affinity of the pillow lava and tuff and homogeneity of the tuff suggest a close genetic relationship. The presence of amphibole as an overgrowth mineral of probable deuteric origin in the tuff suggests strongly a submarine source where water and steam would be entrapped in the porous tuff and act as an agent in late stage mineralization. The massiveness of the basalt tuff with only sporadic bedding is in marked contrast to the well-defined stratification and laminations that are characteristic of most water-laid tuffs. In the absence of transporting media, other than submarine slump and short-lived currents generated around the vents during eruption, tuff from submarine eruptions would not become bedded except locally but instead would form massive accumulations such as that of the basalt tuff member.

The presence of albite in lavas of certain provinces in excess of the amount normal to basalt has led to the designation of such rocks as spilite, which, according to the definition of Dewey and Flett (1911, p. 203), is a pillowed lava with soda content in considerable excess to that in basalt. Because the spilites described by Dewey and Flett in Britain are associated with thick sedimentary rocks, they believed that spilitization is a phenomenon characteristic of lavas extruded into a geosynclinal suite of rocks.

Although the mechanism of spilitization or albitization remains controversial, Gilluly (1935), in a detailed treatment of the problem, reasoned that the excess soda in spilitic lavas was not inherited directly from a parent magma but instead either was assimilated from water stored in thick sediments as the lava moved toward the surface or was derived from albitic solutions that came from deep-seated differentiation along trondhjemitic lines. Both the geosynclinal locus of spilitic rocks and the role of water in the spilitization process were emphasized by Gilluly. He believed that availability of water rather than simple tectonic conditions governed the trend of differentiation.

Some have hypothesized that the excess soda comes directly from interaction of lava with sea water. This does not seem likely because sudden contact of hot lava with cooler sea water would cause immediate crusting of the lava, which would seal off the lava and prevent chemical exchange, except that which might take place on a small scale by absorption of sea water which was trapped, or which entered through cooling cracks in the outer crust. Besides, if an exchange did occur between the lava and sea water, compositional zoning would be expected in the lava, and no such zoning has been described in spilitic rocks. Although most lavas of the Río Orocovis Formation do not contain enough $Na_2O$ to be considered true spilites, the presence of albite in these rocks rather than calcic plagioclase indicates a spilitic tendency. The lavas of the Río Orocovis Formation were obviously extruded in a marine environment, and if it is assumed that the induced soda came from wet sediments, then a considerable thickness of subsurface sediments older than the Río Orocovis Formation is suggested for the Ciales quadrangle. Otherwise the excess soda must have been either inherent in the parent magma or derived from differentiate solutions, as suggested by Gilluly.

Although Gilluly dismissed tectonism as a controlling factor in spilitization, the juxtaposition of belts of spilitic pillow lava and non-spilitic basalt tuff that formed contemporaneously suggests not only that diastrophic movements established loci for volcanic outpourings, but that they may have controlled pressure conditions within the magma chamber(s), which in turn may have affected chemical reactions within the basaltic magma.

The excess potash in the lavas of the Perchas Member could be most easily explained by secondary introduction of potassic minerals during intrusion of the nearby granodiorite stocks, and some of the potash possibly came from this source. However, considering the variation in the amount of potash in the several lavas analyzed and considering the relatively uniform density of the entire sequence, it seems unlikely that alteration processes would have selectively introduced more potash into some lavas than into adjacent ones. Furthermore, the lava with the largest amount of both potash and soda is also the only lava in the Perchas Member with feldspar phenocrysts instead of pyroxene, a clear indication that in this lava the alkali content is associated with minerals of magmatic rather than secondary origin. This lava is mineralogically different from the lavas associated with it, suggesting eruption of independent parent magmas, contamination of a single parent magma by assimilation of sialic material, or differentiation within a single magma. A similar occurrence of an orthoclase-bearing (dacite) tuff in a sequence of basaltic rocks of probable Early Cretaceous age has been noted in southeastern Puerto Rico (Berryhill and Glover, 1960). Lacking conclusive evidence to the contrary, introduction of potash into the basaltic lavas of the Perchas Member as a secondary constituent cannot be discounted; however, both the isolated occurrences of highly

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potassic lavas within basaltic sequences and the slightly excessive potash in the associated lavas relative to that in normal basalts, suggest that sialic or continental-type material was in the subsurface during Cretaceous volcanism and that some of this material was melted and incorporated into the basaltic parent magma from time to time. Furthermore, the confinement of the potassic material to the glassy groundmass material indicates a primary constituent that cooled with the residual silicic melt at a late stage in lava solidification.

#### Avispa Lava Member

The pillow lava sequence in the Avispa is a result of prolonged extrusion of liquid magma upon the ocean floor, and this sequence marks a continuation of the phase of volcanic activity that was also responsible for lavas in the Magüeyes and Perchas. These lavas denote quiet effusion rather than explosive action.

Thickness patterns in the Avispa Lava Member are significant in terms of regional volcanism. Observed variation in thickness is probably a result in part of distance from orifices, in part of irregularities in the ocean floor, and in part of tectonic subsidence. The reef limestone in the south-central area of outcrop and the relative thinness of the lava there suggest the position of a high on the ocean bottom. Significantly, this high occurred where lavas in the Magüeyes and Perchas had previously accumulated to a tremendous thickness. The relative thinness of the Avispa Member across this high as compared to its great thickness in the northwestward-trending central belt of outcrop, plus the lack of feeder dikes, suggests that one locus of lava effusion shifted northward after Magüeyes and Perchas time. The extent of the lavas into the southern and extreme southwestern parts of the quadrangle suggests that a second locus of effusion existed farther south. Thicknesses and areal extent of lava in the Avispa south and west of the Ciales quadrangle are not known, but the extent of this lava in the Ciales quadrangle and adjacent areas suggests that a considerable area of the ocean floor was blanketed and that orifices were abundant and widespread.

Extrusion of the lavas in Avispa time must have been accompanied by crustal subsidence, for the reef limestone in the lower part of the Avispa Formation shows that the area at that time was shallow sea. Subsequent accumulation of several hundred meters or more of pillow basalt above the limestone must have been accompanied by an equivalent sinking of the sea floor during the volcanism.

### AGE AND REGIONAL CORRELATION

Fossils other than unidentifiable Forminifera, small rudistid fragments, and algae were not found in the Río Orocovis Formation.

General stratigraphic relations to older and younger fossil-bearing rocks elsewhere in eastern Puerto Rico suggest a probable Turonian(?) to late Santonian(?) or early Campanian age for the Río Orocovis Formation.

In an earlier report (Berryhill and others, 1960, p. 143–147), rocks now designated as the Río Orocovis Formation were included in the upper part of the Robles Formation as a part of a "pillow lava-volcanic breccia facies," which forms an eastward-trending belt of outcrop along the north side of the Puerto Rico anticlinorium from the Ciales quadrangle eastward almost to the northeast corner of Puerto Rico. Rocks of the same age, as well as somewhat older but lithologically related rocks in the Robles Formation along the south side of the Puerto Rico anticlinorium, are predominantly tuffaceous siltstones and subordinate amounts of pillow lava. Equivalent rocks to the northeast are also tuffs of the lower part of the Hato Puerco Tuff.

### MANICABOA FORMATION

#### DISTRIBUTION

The Manicaboa Formation is here named for exposures along the Río Toro Negro east and west of the mouth of Quebrada Manicaboa. It is restricted mainly to the southwest quarter of the Ciales quadrangle, but smaller areas of outcrop are in the east-central and northwest parts (pl. 1). Rocks of the Manicaboa Formation have been faulted and tilted in all three areas. In the southwest area, which is bounded on the north and south sides by regional faults, except for a local discordance of small extent, the Manicaboa is in conformable sequence with both older and younger formations; dip is steeply westward and northwestward, becoming southwestward in the northwestern part of the area. Rocks provisionally assigned to the Manicaboa in the northwestern part of the quadrangle just southwest of the Ciales stock are in small triangular fault blocks; similar Manicaboa(?) rocks in the east-central part of the quadrangle lie in the center of a faulted syncline. Arthur Nelson (written commun., 1961), in mapping the large patch of Manicaboa(?) volcanic breccia and reworked tuff eastward into the Corozal quadrangle, has placed these rocks in the Avispa Lava Member of the Río Orocovis Formation. Correlation of these rocks with the Manicaboa of southwest Ciales quadrangle admittedly is somewhat tenuous; but the large thickness, the abundance of well-bedded tuff, and the crude cyclic repetition of breccia and tuff are features more common to the Manicaboa Formation than to the massive breccia lenses in the Avispa Lava Member.

Excellent outcrops of the lower part of the Manicaboa are along the dirt road west of Quebrada Riachuelo from locality 15 southwest to locality 16. The upper part of the Manicaboa is well exposed along the Río Bauta from the Quebrada El Gato fault north to the confluence with the Río Toro Negro, from the confluence west along the Río Toro Negro to the base of the Minguillo Lava Member of the Pozas Formation, and on the ridge trail that runs northwest from near the confluence of the two rivers.

### THICKNESS AND STRATIGRAPHIC RELATIONS

The approximate thickness of the Manicaboa Formation in the southwestern part of the Ciales quadrangle is 2,140 meters. Because of possible repetition of parts of the formation by faulting, the computed thickness is probably greater than the true thickness. No attempt was made to determine thicknesses for the remnants of the Manicaboa Formation in the northwestern and east-central parts of the quadrangle.

The Manicaboa Formation conformably overlies the Avispa Lava Member. An intertonguing relation between the lower part of the Manicaboa and upper part of the Avispa is indicated in central Ciales quadrangle. However, because of faulting there is a possibility that the tongue of volcanic breccia that seems to be a part of the Manicaboa may be a lens within the Avispa Lava Member. An unconformable contact between the Manicaboa and Río Orocovis Formations has been postulated by M. H. Pease (written commun., 1961), but evidence for an unconformity at this stratigraphic position is lacking in the Ciales quadrangle. The Minguillo Lava and Blacho Tuff Members of the Pozas Formation conformably overlie the Manicaboa Formation with a sharp contact at most places in the southwestern Ciales quadrangle. Locally in the vicinity of Capilla del Carmen, an unconformable relation of the Manicaboa to the overlying Pozas Formation is shown by an angular discordance; however, no hiatus of consequence is indicated.

### LITHOLOGY

The Manicaboa Formation consists almost entirely of water-laid clastic debris of volcanic origin. Only a single lava flow, a basalt(?) 1 meter thick, was observed in the formation. Principal constituents are reworked fine and coarse tuff, lapillistone, reworked pyroclastic volcanic breccia, epiclastic volcanic breccia, volcanic breccia-conglomerate, and primary tuff and lapillistone. Pebbles and cobbles of both reef limestone and jasper occur sporadically.

The overall color of both breccias and tuffs of the Manicaboa Formation is dark greenish gray (5*GY* 4/1), although color of individual fragments varies. Some color variants, such as fragments that seem to have undergone oxidation, are hues of reddish brown; others are hues of yellowish and grayish olive green.

Pebbles and cobbles of lava and slabs of bedded tuff within the Manicaboa are of epiclastic origin, but the microscope reveals primary pyroclastic ash particles in both the tuff and the matrix of the breccias. Devitrified glass particles with perlitic structure, pumice particles, chloritized glass shards, and microtrachytic lava particles occur throughout the formation. The microscope also reveals fragments of feldspar crystals as an abundant constituent, both of the fine-grained units and of the matrix in breccias. The intricately jagged edge of many feldspar particles is suggestive of fragmentation by pyroclastic eruption; thus, feldspar particles of this type are probably pieces of ash that were erupted in, or fell directly into, water. Fragments of pyroxene crystals are subordinate to feldspar throughout the Manicaboa and are absent from some beds. Fragments of feldspar are chiefly plagioclase, but a small amount of orthoclase is present. Calcite is prominent in the matrix of some beds, quartz occurs as rare individual grains and sporadically as anhedra of secondary origin, and chlorite is an abundant secondary mineral.

Chemical analyses are not available for the Manicaboa Formation, but the overall mineralogy suggests an andesitic composition.

#### CONDITIONS OF DEPOSITION

The Manicaboa Formation is a marine deposit. Much of the formation is intermixed reworked pyroclastic and epiclastic debris, including oxidized fragments, that was carried from land to the sea by surface water. Primary ash that fell or was erupted directly into the depositional basin probably is an important constituent.

Significant and characteristic features of the Manicaboa are beds having graded grain size and cyclic repetition of tuff and breccia units, groove casts, penecontemporaneous slump structures, and truncated laminae. Many graded beds whose bases locally have scour markings and truncate upper parts of underlying beds indicate that much of the material in the formation was distributed across the sea floor and deposited by density currents. Deposits attributable to this mechanism range in thickness from feldspathic laminae less than 1 mm thick to massive beds of volcanic breccia about 30 meters thick. The graded beds with scour-type bases plus the great range in both grain size and thickness of beds indicate that the rate of sedimentation was highly variable and that sedimentation proceeded mainly as a series of abrupt influxes. The quantity and fragment size of the debris that entered the sea during a specific period was dependent both upon the amount of material available at the source areas and upon the carrying ability of the transporting media.

Principal source areas are thought to have been volcanic cones built of loose ash and volcanic breccia. Good bedding throughout indicates that transporting agents carried and deposited the debris of the Manicaboa. This unconsolidated material probably was carried to the sea principally by landslides and by running water during heavy rains; some ash fell into the sea from subaerial eruptions. Deposition of massive beds of reworked volcanic breccia followed volcanic eruptions that produced large quantities of loose, coarse debris. Some of this material possibly came from submarine eruptions, but the well-developed bedding, laminations, and abundant oxidized fragments in most of the material attest to subaerial eruption and subsequent transport to site of deposition. Clastic material from submarine eruptions is usually massive and relatively homogeneous because transporting media other than submarine slides are not available for spreading the material after it piles up on the sea floor.

Secondary source areas possibly were uplifted parts of the sea floor. Tectonism during Late Cretaceous time probably involved differential uplift and subsidence, and from time to time small areas of the sea floor that had received thick accumulations of volcanic sediment may have been exposed to subaerial erosion. From these short-lived sources and from the limestone reefs that formed around them came epiclastic debris, including slabs of indurated tuff and cobbles and boulders of limestone.

As the source areas were worn down by erosion, debris accumulated around them as deltaic aprons or shelves. Because the loose debris accumulated rapidly and in large quantity, outer slopes of the shelves were steep, and submarine slides, triggered by volcanic shocks, carried material from the outer edges of the shelves to deeper parts of the sea. The beds containing numerous slabs of epiclastic tuff were probably deposited by submarine slides. The restriction of slabs of tuff to a few beds in the Manicaboa Formation indicates that the areas of the sea floor uplifted from time to time by tectonic movement were small and therefore were rapidly worn down by erosion. The slabs of indurated tuff in individual units are too plentiful to have been accidental blocks torn from volcanic vents during explosive eruptions.

The lack of crossbedding in the lower half of the Manicaboa suggests that the volcanic debris accumulated in quiet water and probably below wave base. Local crossbedding in the upper half signifies deposition in shallow water and subsequent movement by waves and currents. The pebbles, cobbles, and water-worn boulders that are scattered through the upper half of the Manicaboa probably came from landmasses with fairly well-developed stream systems, in which the fragments became rounded before reaching the sea. Some of the rounding may be the result of wave action in shallow water.

To summarize, the Manicaboa Formation seems to be largely a sequence of density current deposits. Cyclic repetition of coarse and fine debris throughout probably was caused both by recurrence of volcanic activity and by seasonal variation in rainfall.

#### AGE AND REGIONAL CORRELATION

Stratigraphic relations to associated rocks suggest a Campanian to Maestrichtian(?) age for the Manicaboa Formation; positive data for dating are not available. The formation may be equivalent to the upper part of the conglomeratic Cariblanco Formation and (or) to the lower part of the Coamo Formation of central and south-central Puerto Rico and to the Frailes Formation, Tortugas Andesite, and Guaynabo Formation of northeast Puerto Rico. The Frailes and Guaynabo Formations are lithologically similar to the Manicaboa, although Kaye (1959) called the fine-grained material in them siltstone and graywacke rather than reworked tuff.

### POZAS FORMATION

*Distribution*—The Pozas Formation is here named for extensive outcrops across the Cerro Cedro graben in barrio Pozas, Municipio de Ciales. It includes a sequence of reddish tuffs, volcanic breccias, conglomerates, and lavas. Rocks of the Pozas Formation were previously referred to as the Coamo Formation by Berryhill (1961). Subsequent work has thrown doubt on a direct correlation between rocks named Pozas in the Ciales quadrangle and those named Coamo in south-central Puerto Rico by Glover (1961), although rocks in the two formations are probably in part age equivalents.

In the Ciales quadrangle the Pozas Formation crops out principally in an L-shaped area that covers the extreme west-central, southwestern, and extreme southern parts of the quadrangle. Other smaller areas of outcrops, enclosed by faults, are in the west-central and central parts of the Ciales quadrangle.

In the principal area of outcrop, rocks of the Pozas Formation have been folded into a syncline and faulted. Much of the formation lies within the synclinal Cerro Cedro graben that trends west-northwestward across the southern and southwestern parts of the quadrangle.

*Thickness and stratigraphic relation*—The Pozas Formation is about 1,400 meters thick in the Ciales quadrangle. Because of faulting, which has concealed the base of the formation over much of the principal area of outcrop, maximum thickness of material originally accumulated is not known.

The Pozas Formation overlies the Manicaboa Formation with sharp contact in the west-central part of the Ciales quadrangle north of the Cerro Cedro graben. Local discordance between the two formations was noted near Capilla del Carmen, but a conformable relation seems to exist between the two elsewhere. Along the north side of the graben from the vicinity of Quebrada Riachuelo to the southeast corner of the quadrangle, the Pozas is in fault contact with older rocks, and at the southeast corner of the quadrangle rocks of the Pozas are in juxtaposition with lavas of the Magüeyes Member that are about 5,500 meters stratigraphically below the Pozas Formation. On the south side of the Cerro Cedro graben, at the southwest corner of the Ciales quadrangle, the Pozas has been downfaulted against the Avispa Lava Member of the Río Orocovis Formation.

Other outcrops north of the Río Grande de Manatí fault are in narrow blocks that have been faulted against the Río Orocovis and Manicaboa Formations. Near the center of the quadrangle a very narrow belt of Pozas rocks lies along the Río Grande de Manatí fault.

The top of the Pozas Formation has been eroded in the Ciales quadrangle. A sequence of laminated tuffaceous siltstone with a basal reef limestone containing fragments of rudistids overlies the Pozas Formation to the west near the east edge of the adjacent Florida quadrangle.

*Lithology*—In the Ciales quadrangle the Pozas Formation is predominantly an accumulation of pyroclastic material including tuff, lapillistone, and volcanic breccia. At the base of the formation is a lens of lava, which is called the Minguillo Lava Member. A thick stratified sequence above the Minguillo, the Blacho Tuff Member, is composed of ash-flow deposits and interbedded fluvial conglomerate, and lapillistone having a reddish color and a few lavas. The poorly stratified nonred sequence of volcanic breccia above the Blacho Tuff Member has been designated the upper breccia member. The stratigraphy of the Pozas Formation is shown in composite sections on plate 2.

### MINGUILLO LAVA MEMBER

The Minguillo Lava Member is here named for outcrops along the highway west of Quebrada Minguillo, barrio Pesas, Municipio de Ciales, west-central Ciales quadrangle. It forms a lens at the base of the Pozas Formation in west-central Ciales quadrangle and is absent south of the headwaters of Quebrada Manicaboa. The lava seems to overlie conformably the Manicaboa Formation, but the brecciated nature of the lava and lack of pillow structure suggest that it was extruded in part on a land surface. In its westernmost outcrop and in the fault blocks north of the Río Grande de Manatí fault, the Minguillo Lava Member is in fault contact with the Avispa Lava Member of the Río Orocovis Formation and with the Manicaboa Formation.

Maximum thickness as measured along the Río Toro Negro is about 300 meters. From there the Minguillo thins southward and pinches out in a distance of only little more than half a kilometer.

The Minguillo Lava Member is a massive unit with no apparent internal stratification. Although the part of the member south of the Río Grande de Manatí fault seems to represent a single effusion, the lithology varies considerably along strike. From the west edge of the Ciales quadrangle southeastward to locality 17, the member is largely an oxidized dusky-red flow breccia. The lava in this part of the member is largely porphyritic with plagioclase phenocrysts. From locality 17 southward across the Río Toro Negro to locality 18, the Minguillo is a medium-gray (*N* 5) to greenish-gray (5*GY* 6/1) porphyritic lava with plagioclase phenocrysts in abundance and pyroxene phenocrysts in moderate amount. Trachytic structure is locally developed in this part of the lava. South of locality 18, plagioclase phenocrysts are absent, and the lava is dark-greenish-gray dense porphyritic rock with large pyroxene phenocrysts in abundance. The different lithologies in the Minguillo Member intergrade laterally so that locally the three types are intermixed.

North of the Río Grande de Manatí fault the Minguillo is in part an autoclastic(?) reddish breccia and in part brownish-gray (5*YR* 4/1) to very dusky red (10*R* 2/2) porphyritic lava with plagioclase phenocrysts showing poorly developed trachytic structure.

In all areas of outcrop the Minguillo is characterized by hematite which has partially replaced some of the plagioclase phenocrysts, giving them a pinkish hue. Because of the abundant hematite, powdered samples of the Minguillo are pale red purple (5*RP* 6/2) to grayish red purple (5*RP* 4/2).

Throughout its areal extent, the Minguillo contains many small veins that seem to be joint and crack fillings. Vein material, as determined by X-ray diffraction, is principally the zeolite mineral heulandite (identification by F. A. Hildebrand).

#### BLACHO TUFF MEMBER

The Blacho Tuff Member is here named for outcrops about 100 meters west of the mouth of Quebrado Blacho in the cliff adjacent to the Río Toro Negro between localities 19 and 20. It crops out within the Cerro Cedro graben and in an arcuate belt north of the graben from the Quebrada El Gato fault northwestward to the west-central edge of the quandrangle. Excellent outcrops of the Blacho are along the Río Bauta and its tributary, the Río Culebra. The structure of the Blacho Tuff Member in the Cerro Cedro graben is synclinal; dips north of the Quebrada El Gato fault are southwestward toward the graben.

The Blacho overlies the Minguillo south to the vicinity of Quebrada Manicaboa and the Manicaboa Formation south of the Quebrada Manicaboa to the Quebrada El Gato fault. The base of the member is not exposed within the Cerro Cedro graben.

The Blacho Tuff Member is a sequence of ash-flow deposits and interbedded lapillistone, reworked tuff, and volcanic breccia having an aggregate thickness of about 500 meters in the type area. Lava is a minor constituent of local extent, and impure nodular limestone was observed near the base of the member only in a single outcrop (loc. 42a). Reworked water-laid tuffs, occurring as laminated beds of thin to medium thickness, are restricted almost entirely to the basal part of the Blacho Member. The reddish color distinguishes the sequence of rocks in the Blacho from all other volcanic rocks in the Ciales quadrangle.

The lenticular ash-flow deposits,[1] which are unique to the Blacho Member in Puerto Rico, range in thickness from about 10 to 40 meters and extend laterally for as much as 4 km. These dense ash-flow deposits are relatively resistant to weathering and form ledges. Two of the more continuous ash-flow deposits were mapped to show structure and are designated on plate 1. In the type area, at least 15 ash-flow deposits seem to be in the Blacho.

The ash and lapilli of the ash-flow deposits were in part welded under heat and pressure at the time of emplacement. Distinctive megascopic features of parts of these deposits are parallelism and marked flattening of pumice bombs, denseness, and heat reaction rims formed in the ash around the lithic fragments. Although denseness is a feature of the welded component of these deposits, none possesses the glassy texture that Smith (1960a, p. 154–155) ascribed to the "zone of dense welding." Rather, the welded components of the Blacho ash-flow deposits possess a less intense degree of cohesion that would presumably place them within Smith's (1960a, p. 154) "zone of partial welding." Upper parts of the Blacho ash-flow deposits are nonwelded mixtures of tuff, bombs, and lithic fragments having a rubbly appearance. The lowest part of each of several ash-flow deposits is a granular zone composed of highly fragmented material including a notable concentration of feldspar crystals. These zones probably represent the soles of the ash flows, and pulverization was accomplished by friction as the hot gaseous avalanche moved along the ground. Mineralogy and zonation within the Blacho ash-flow deposits are described in more detail under "Petrography."

The volcanic debris between the ash-flow deposits is in part primary tuff and lapillistone, in part reworked tuff and reworked pyroclastic volcanic breccia that appears to have been emplaced as mudflows, and in part lenticular conglomerate that was deposited as fluvial gravel. Porphyritic dusky-red (5*R* 3/4) lavas with both plagioclase

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[1] Ash-flow deposit is the aggregate mass of intermixed ash, lapilli, and breccia deposited by a single avalanche of hot gas-charged material following an autoexplosive eruption. The term is applied here according to the nomenclature of Smith (1960b, p. 800).

and pyroxene phenocrysts occur sporadically in the Blacho Tuff Member.

Lithic fragments in the Blacho are principally reddish lava with small plagioclase phenocrysts. Lapilli and larger masses of hematitic blackish-red (5*R* 2/2) silica are characteristic of nonwelded parts of some ash-flow deposits and most lapilli tuff units. Chloritized almond-shaped fragments that seem to be compressed bombs are notably concentrated in some ash-flow deposits. Blocks of reworked ash-flow material occur in some of the mudflow deposits.

Small veins of zeolites (principally heulandite) similar to those in the Minguillo are also common throughout the Blacho. Most of these veins are very light pink as a result of staining by hematite.

#### UPPER BRECCIA MEMBER

The upper breccia member crops out across bario Pozas, between localities 21 and 22, in the central part of the Cerro Cedro graben and adjacent to the graben, north of the Quebrada El Gato fault.

The upper breccia member conformably overlies the Blacho Tuff Member. Lenses of reddish material within the lower part of the upper breccia member that is similar to the Blacho Tuff Member suggest an intertonguing relation between the two members. Locally along the north side of the Cerro Cedro graben in the south-central part of the quadrangle, breccia of the upper member is in fault contact with the Río Orocovis Formation.

The member is composed predominantly of poorly stratified compact volcanic breccia. Breccia fragments are typically porphyritic feldspathic grayish andesitic lava, though a mixture of fragments of both feldspathic (andesitic) and mafic (basalt) lava and reworked fragments of the underlying Blacho are common to the lower part of the member. The very pale yellowish gray color of weathered breccia is a distinctive feature of the member. Massiveness is also a feature of this breccia in the Ciales quadrangle, and bedding is restricted to sporadic lenses of reworked(?) coarse tuff. However, just to the south in the northeastern part of the Orocovis quadrangle along Highway 155, much of the upper breccia member is bedded coarse tuff, suggesting that the member becomes progressively more stratified southeastward along the Cerro Cedro graben. Lava flows are minor constituents of the member, although some of the more compact andesitic material that has been identified as volcanic breccia could be flow breccia.

Much of the breccia in the upper member seems to be reworked pyroclastic breccia, although a large part of the porphyritic lava fragments may be of epiclastic origin. The intermixed fragments of lava and tuff in the lower part of the member probably are predominantly epiclastic.

The upper breccia member is well exposed along the Río Toro Negro and along the dirt road that crosses barrio Pozas.

PETROGRAPHY

**Minguillo Lava Member**

The groundmass of the porphyritic lava of the Minguillo from the type area is microlitic fluidal. Microvesicles with colloform outlines are common to the groundmass in all specimens examined. Partial alteration of most minerals is a common feature of the Minguillo Lava Member; alteration has been so intense locally that precise identification of the original minerals is not possible.

Phenocrysts are predominantly plagioclase; many are only fragments of crystals. Originally the albitized plagioclase phenocrysts probably were andesine and oligoclase, but all have been altered to some degree, and many are nothing more than completely saussuritized relics. Nontronite(?), sericite, chlorite, chalcedonitic(?) clay, zeolites, and finely disseminated hematite are common secondary minerals. Apatite inclusions are common. Albite overgrowths containing fine opaque hematite(?) particles are widespread, and in most specimens the rinds of plagioclase phenocrysts are fritted, indicating superheating and partial remelting after original crystallization. Plagioclase phenocrysts so affected can be recognized megascopically by a gray outer rim. The subordinate pyroxene phenocrysts are of two varieties: unaltered augite and pseudomorphs after orthopyroxene(?).

Microlites of albitized plagioclase and orthoclase(?) are the principal groundmass constituents. Hematite pseudomorphs after amphibole(?) are common in most specimens. Anhedra of quartz are scattered through the groundmass. Interstices between microlites are filled with a mixture of secondary minerals including chlorite, zeolites, and nontronite(?). Calcite is locally abundant; prehnite occurs sporadically. Gas cavities (microvesicles) are commonly filled either with zeolites or chlorophaeite(?); some are filled with chalcedony.

Bulk chemical composition suggests that the Minguillo Lava Member is andesite. The chemical analysis of a specimen of Minguillo from the type area is given in table 6, column 1.

**Ash-flow deposits (Blacho Tuff Member)**

The microscope clearly reveals the welding of particles which is only suggested by megascopic examination. The ash-flow deposits consist primarily of plagioclase crystals, devitrified glass shards, fragments of feldspathic oxidized lava, accidental lithic fragments, pumice, masses of hematitic silica, and a very fine ash matrix containing abundant iron oxide dust. Magnetite is in all specimens examined. The highly fragmented plagioclase crystals are principally andesine(?); the microscopic glass shards are altered, mostly to quartz and clay; and the flattened pumice bombs and much of the matrix have been altered to a clay mineral (nontronite?), quartz, and zeolites. Welding is generally restricted to the basal third of an ash-flow deposit, and concentration of crystals is common at the base. Microscopic texture of the welded part of the deposit is fluidal, as shown on figure 14. None of the Blacho ash-flow deposits have undergone the wholesale conversion to glass that Smith (1960a) described as typical of the "zone of dense welding." Presumably the Blacho ash-flow deposits were too thin to retain the heat necessary for intense welding or were not hot enough initially.

The sequence of rock types and the zonation within an ash-flow deposit as revealed by the microscope are described in the following representative section.

*Section of ash-flow deposit measured at type locality of Blacho Tuff Member of the Pozas Formation [Base of section is 50 meters above loc. 19]*

| | *Thickness (meters)* |
|---|---|
| Ash-flow deposit of the Blacho Tuff Member: | |
| Lapilli tuff, nonwelded except for very slight welding at base, reddish-brown, compact; intermixed fragments of pumice, oxidized feldspathic lava, and iron-rich reddish-black silica. Fine-grained matrix makes up less than 20 percent of total mass; fragmented plagioclase (andesine?) crystals make up less than 15 percent. Some fragments have heat reaction rims; pumice bombs are compressed only in basal part | 26 |
| Lapilli tuff, partly welded, reddish-brown; heterogeneous mixture of partly sericitized fragmented plagioclase crystals, oxidized feldspathic lava fragments, devitrified glass shards, and compressed pumice bombs well-alined parallel to stratification. Reddish fine-grained matrix, largely altered to zeolite(?), quartz, and nontronite(?), makes up 40 percent of total mass; plagioclase crystals make up about 15 percent | 3 |
| Tuff, welded, reddish-brown; vitroclastic; contains sparse fragments of feldspathic lava as much as 5 mm long; abundant iron oxide dust; fragmented plagioclase crystals make up about 15 percent of mass; all pumice bombs compressed; feldspathic lava fragments have heat reaction rims | 5 |
| Tuff, welded, reddish-gray, vitroclastic; all pumice bombs compressed and altered to nontronite(?) and quartz; fragmented plagioclase crystals comprise about 15 percent of mass | .5 |
| Tuff, welded, reddish-brown, vitroclastic-fluidal texture; consists of pulverized andesine(?) crystals in a flour of quartz, iron oxide, zeolite(?), and nontronite(?); plagioclase makes up about 40 percent of mass | .3 |
| Crystal tuff, welded, vitroclastic-fluidal texture with much quartz; highly fragmented, cracked, and bent andesine(?) crystals make up about 50 percent of mass (represents sole of ash flow) | .7 |
| Total | 35.5 |
| Base of ash-flow deposit. | |

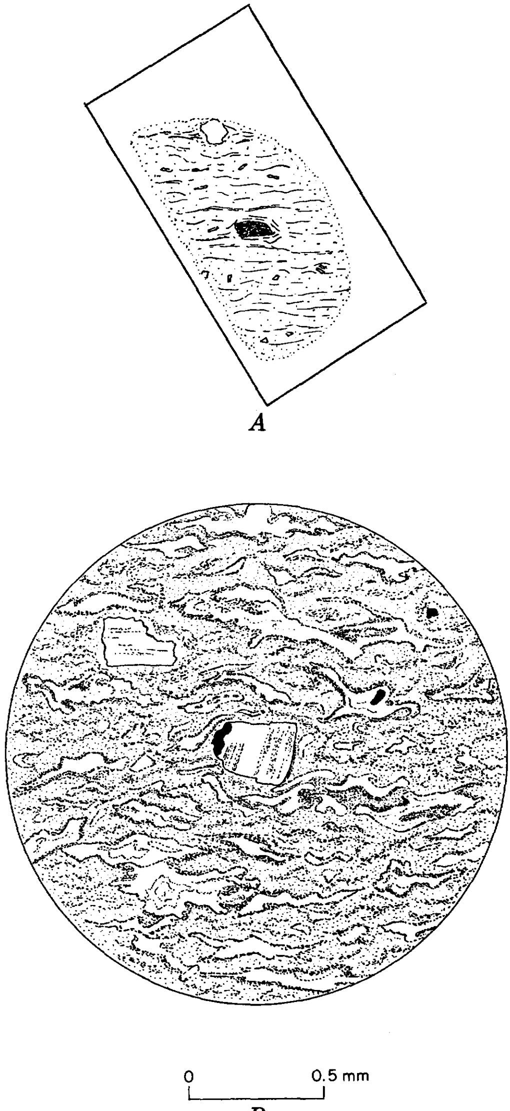


FIGURE 14.—Texture and mineralogy of welded part of an ash-flow deposit, Blacho Tuff Member. (*A*), Megascopic, banded texture. (*B*), Fluidal texture with coherent silica shards, hematite dust, and fragments of twinned andesine(?).

Concentration of fragmental plagioclase crystals in lower parts of most ash-flow deposits is notable. The separation of crystals from particles of vitric ash and the concentration of these crystals in certain parts of the glowing avalanche deposits of St. Vincent, British West Indies, and of Mount Pelée, Martinique (May 8, 1902), are ascribed by Hay (1959, p. 552–553) to different settling velocities of particles produced by the eruptions. The absence of ferromagnesian minerals in the concentration of crystals in the lower part of the ash-flow deposits of the Blacho suggests either absence of mafic crystals in the parent magma or oxidization of these crystals just before and during eruption.

Specimens from three ash-flow deposits were analyzed and the results, together with norms, are given in table 6. Chemical composition indicates that the ash flows are dacite. The analysis for sample

TABLE 6.—*Chemical analyses and norms, in percent, of samples from the Pozas Formation*

[Analysts: P. L. D. Elmore, I. H. Barlow, S. D. Botts, and Gillison Chloe]

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| **Chemical analyses** | | | | |
| $SiO_2$ | 54. 5 | 63. 7 | 69. 1 | 59. 5 |
| $Al_2O_3$ | 17. 4 | 16. 5 | 15. 7 | 16. 0 |
| $Fe_2O_3$ | 6. 6 | 3. 7 | 3. 3 | 5. 5 |
| FeO | . 91 | 1. 0 | . 26 | 1. 2 |
| MgO | 2. 5 | 1. 3 | . 24 | 2. 9 |
| CaO | 5. 6 | 2. 2 | . 84 | 3. 6 |
| $Na_2O$ | 3. 4 | 4. 2 | 7. 1 | 2. 2 |
| $K_2O$ | 3. 8 | 4. 2 | 2. 0 | 2. 2 |
| $H_2O$ | 3. 0 | 2. 2 | 1. 0 | 5. 6 |
| $TiO_2$ | . 66 | . 74 | . 64 | . 74 |
| $P_2O_5$ | . 44 | . 22 | . 17 | . 40 |
| MnO | . 21 | . 15 | . 10 | . 18 |
| $CO_2$ | 1. 0 | ---------- | ---------- | ---------- |
| Total (rounded) | 100 | 100 | 101 | 100 |
| **Norms** [Barth modification of C.I.P.W. norm] | | | | |
| Quartz | 8. 7 | 16. 8 | 17. 8 | 27. 7 |
| Orthoclase | 22. 2 | 25. 0 | 11. 7 | 12. 8 |
| Albite | 28. 8 | 36. 6 | 63. 9 | 18. 3 |
| Anorthite | 18. 1 | 10. 0 | 3. 3 | 15. 3 |
| Corundum | 1. 1 | 1. 3 | . 6 | 4. 5 |
| Wollastonite | ---------- | ---------- | ---------- | ---------- |
| Enstatite | 6. 3 | 3. 2 | . 6 | 7. 3 |
| Ferrosilite | ---------- | ---------- | ---------- | ---------- |
| Forsterite | ---------- | ---------- | ---------- | ---------- |
| Fayalite | ---------- | ---------- | ---------- | ---------- |
| Magnetite | . 9 | 1. 6 | ---------- | 2. 6 |
| Hematite | 5. 9 | 1. 3 | 3. 4 | 3. 7 |
| Ilmenite | 1. 4 | 1. 6 | . 6 | 1. 4 |
| Apatite | 1. 0 | 1. 3 | . 3 | 1. 0 |
| Rutile | ---------- | . 2 | . 4 | ---------- |
| Calcite | ---------- | 1. 3 | ---------- | 4. 5 |

1. Andesite, Minguillo Lava Member; field No. XC-100; loc. 19a, pl. 1; lab. No. 154665.
2. Dacite tuff, Blacho Tuff Member; field No. P-26; loc. 19b, pl. 1; lab. No. 154668.
3. Dacite tuff, Blacho Tuff Member; field No. XC-59; loc. 22a, pl. 1; lab. No. 154662.
4. Dacitic andesite, Blacho Tuff Member; field No. P-34; loc. 19b, pl. 1; lab. No. 154669.

3 shows that it is richer in both silica and soda than the average dacite reported by Tyrrell (1926, p. 124); the analysis for sample 4 shows that it is somewhat less salic than the average.

Minor constituents in representative samples from all three members of the Pozas Formation are given in table 7. Amounts of minor constituents in the Pozas Formation are similar to those lavas in the Río Orocovis.

TABLE 7.—*Minor constituents in rocks from the Pozas Formation*

[Analyst: J. C. Hamilton]

| Laboratory No.<br>Field No. | 281025<br>XC-100 [1] | 281019<br>XC-773 [2] | 281020<br>P-5 [3] | 281022<br>P-34 [3] | 281021<br>P-7 [3] | 281023<br>P-37 [3] | 281024<br>XC-213 [4] |
|---|---|---|---|---|---|---|---|
| Ba | 0. 15 | 0. 15 | 0. 3 | 0. 07 | 0. 15 | 0. 15 | 0. 15 |
| Be | -------- | -------- | -------- | -------- | -------- | -------- | -------- |
| Co | . 0015 | . 0015 | -------- | . 0015 | . 0007 | . 0007 | . 003 |
| Cr | . 0007 | . 0003 | . 00015 | . 0007 | . 00015 | . 0003 | . 015 |
| Cu | . 007 | . 015 | . 0015 | . 007 | . 0015 | . 007 | . 007 |
| Ga | . 0003 | . 0007 | . 0003 | . 0007 | . 0007 | . 0007 | . 0003 |
| La | -------- | -------- | . 003 | -------- | -------- | -------- | -------- |
| Mo | -------- | -------- | -------- | . 0007 | -------- | -------- | -------- |
| Ni | . 0015 | . 0007 | . 0007 | . 0007 | -------- | -------- | . 007 |
| Sc | . 003 | . 003 | . 003 | . 0015 | . 0015 | . 0015 | . 003 |
| Sr | . 15 | . 07 | . 07 | . 07 | . 07 | . 15 | . 15 |
| V | . 015 | . 015 | . 0015 | . 015 | . 003 | . 007 | . 03 |
| Y | . 0015 | . 0015 | . 003 | . 0015 | . 003 | . 003 | . 0015 |
| Yb | . 00015 | . 0003 | . 0003 | . 0003 | . 0003 | . 0003 | . 00015 |
| Zr | . 007 | . 015 | . 015 | . 007 | . 015 | . 015 | . 0015 |

[1] Andesite, Minguillo Lava Member; loc. 19a, pl. 1.
[2] Dacitic ash flow, Blacho Tuff Member; loc. 22b, pl. 1.
[3] Dacitic ash flow, Blacho Tuff Member; loc. 19a, pl. 1.
[4] Andesite, Minguillo Lava Member; loc. 20a, pl. 1.

## CONDITIONS OF ORIGIN

The Pozas Formation in the Ciales quadrangle seems to be largely a subaerial deposit, but the lower part of the Blacho Tuff Member is locally of subaqueous origin as indicated by nodular limestone.

The lack of pillow structure and the widespread brecciated nature of the Minguillo Lava Member suggest extrusion largely on land. Moreover, the nature and extent of alteration in the lava are indicative of deuteric action by hydrothermal solutions. This rock possibly was a dome lava and a source of hot springs. Although the lava of the Minguillo seems to have been extruded on land, no evidence was found that would signify a long erosional hiatus between deposition of the Manicaboa and extrusion of the Minguillo. The Minguillo could be interpreted as a small laccolith that was emplaced very near the surface in early Pozas time. However, general characteristics and specifically the brecciated oxidized parts of the lava argue against this mode of origin.

Three probable sources for the Minguillo lie within the Ciales quadrangle. One is just east of Quebrada Blacho at the site now occupied by the hornblende andesite-diorite intrusive. The lithologic similarity of the hornblende andesite and lava of the Minguillo and their proximity suggest a genetic relationship. The intrusive body may be a plug that moved upward into an orifice from which a part of the Minguillo Lava Member was extruded. Another probable site of lava emission in Minguillo time was north of the Quebrada El Gato fault at the southeast end of the faulted belt of Pozas outcrops. The brecciated lava of the Minguillo there possibly formed as an autobreccia or agglomerate within an orifice. The highly welded nature of the breccia fragments suggests superheating within a vent. The Minguillo northwest of the Río Cialitos may mark fissures that were the third source from which lava was emitted.

The bulk of the Blacho Tuff Member and most, if not all, of the upper breccia member in the Ciales quadrangle are subaerial accumulations. The bedded tuff with nodular limestone forming the basal part of the Blacho is probably of subaqueous origin, but the single nodular limestone bed observed is only a few meters above the base of the Blacho Tuff Member. Evidence for subaerial origin of all but the lower few meters of the Blacho Tuff Member is red color, preponderance of hot avalanche (ash flow) deposits, mudflow deposits, fluvial conglomerates, and casts of plant roots in the tuff. The propagation and welding of ash flows under water are not considered possible, a conclusion reached also by Rankin (1960) after considering the paleogeography of several ash-flow deposits.

The massiveness of the upper breccia member with little stratification, except locally in the basal part and in the southwesternmost outcrops, strongly implies subaerial accumulation. The lower part of the member contains lenses of reworked Blacho debris that possibly were spread by fluvial action. Most of the member seems to be a mixture of reworked pyroclastic breccia and epiclastic lava debris having the general appearance of indurated colluvium. The lack of stratification in so thick a unit suggests rapid subaerial accumulation in a restricted depression.

Deposition of the Pozas Formation seems to be directly related to regional tectonic movements. Confinement of the ash-flow deposits of the Pozas Formation within and immediately adjacent to the Cerro Cedro graben and the structural and geographic position of the graben relative to plutonic intrusives (fig. 15) suggest that the area of ash-flow accumulation was initially outlined by sagging of a crustal segment above a magma chamber. Faulting, possibly in part contemporaneous with, but largely subsequent to, ash-flow deposition, formed the present structure of the graben.

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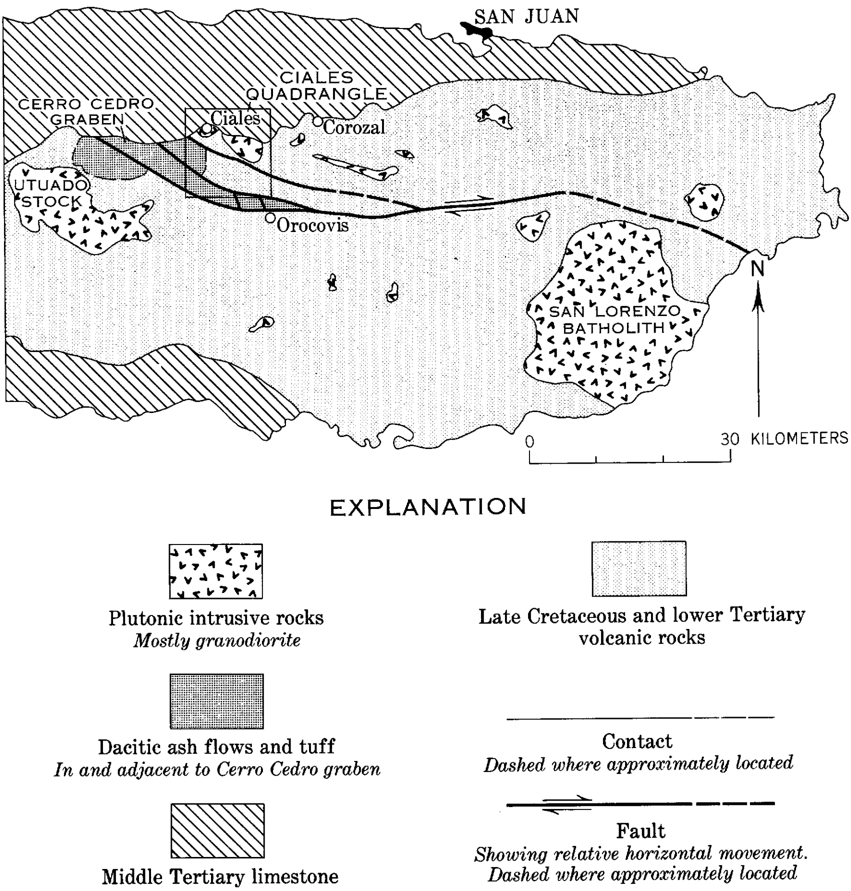


FIGURE 15.—Map of eastern Puerto Rico showing location of ash-flow deposits of the Blacho Tuff Member relative to plutonic intrusives.

That some subsidence and southeastward rotation of the Cerro Cedro graben was contemporaneous with ash-flow deposition is suggested by facies changes in the Pozas Formation from northwest to southeast along the graben. Rocks of the northwestern part, including those of the Ciales quadrangle, are largely of subaerial origin. Rocks in the southeastern part of the graben in the adjacent Barranquitas quadrangle include the prominent and thick reef limestone of marine origin in the Botijas Limestone Member of the Coamo Formation (Briggs and Gelabert, 1962), and no ash-flow deposits are reported there. Thus, the southeastern end of the graben may have undergone progressive subsidence and may have been the site of some marine deposition during Pozas time.

The chemical and mineralogical similarity between the dacite ash-flow deposits and the granodiorite in the nearby stocks suggests that the ash-flow deposits represent the expulsion of volatile-rich magmatic material after these plutonic bodies had moved upward into the near-surface crustal zone.

#### AGE AND REGIONAL CORRELATION

Means for dating the Pozas Formation were not found in the Ciales quadrangle. The age, as determined from several species of rudistids in similar rocks in other parts of eastern Puerto Rico (Berryhill and others, 1960, p. 151–152), is uppermost Cretaceous (Maestrichtian).

Notably, rocks equivalent to the Pozas Formation over most of eastern Puerto Rico seem to be of marine origin. This fact suggests that, as the sialic plutonic material moved from the magma chamber upward toward the surface beneath, a general swelling and uplift ensued. The swelling is presumed to have been largely confined to the area just above the magma chamber and to have been most pronounced along a regional west-northwest-trending belt that crossed the Ciales quadrangle.

### INTRUSIVE ROCKS

Intrusive rocks of probable Late Cretaceous age are restricted to the extreme southeastern part of the Ciales quadrangle, except for a single body in the west-central part of the quadrangle. Rock types represented are basalt, altered gabbro, and altered andesite(?), all of hypabyssal origin. A Late Cretaceous age for these rocks is based on their mineralogic composition, somewhat altered condition, crosscutting relation to country rocks, and truncation by early Tertiary(?) faults. The age relation of the several types of Late Cretaceous intrusives is not known.

#### BASALT

Basaltic rock forms several dikes, small bodies of irregular shape, and a sill. The dikes and small bodies are typically of porphyritic texture with abundant large augite phenocrysts set in a very fine grained groundmass. These rocks are a drab olive green and tend to weather to a friable mass with an abundance of loose augite crystals. All these bodies cut basaltic pillow lava of the Río Orocovis Formation, and reworked tuff layers have been deformed locally by intrusion of the basalt.

A basalt sill forming prominent cliffs adjacent to the Río Orocovis is marked by well-developed hexagonal jointing. The rock is porphyritic with phenocrysts of augite(?) and olivine in a subophitic groundmass consisting of albitized plagioclase and granular pyroxene. The sill breaks along joints into huge blocks that are scattered northward along the Río Orocovis for more than a kilometer. Some of these blocks exceed 4 meters in diameter.

### ALTERED GABBRO(?)

An intrusive rock that seems to have been a gabbro crops out near the southeast corner of the quadrangle. This sizable intrusive body, which truncates lava and tuff of the Río Orocovis Formation, is cut by faults of early Tertiary(?) age. The rock has panidiomorphic texture with abundant large crystals of both pyroxene (augite?) and feldspar. The minerals of the rock have been changed by metamorphism, but general crystal structure and relic minerals suggest gabbroic composition. Characteristically, the feldspar crystals and matrix minerals have been extensively altered to sericite and muscovite; weathered specimens of the rock are decidedly micaceous. Moreover, all pyroxene crystals show marked corrosion; this feature, together with the extensive alteration of the feldspar to micas, suggests subjection to hydrothermal alteration, probably during intrusion of the younger early Tertiary(?) augite syenite body that cuts the altered gabbro(?).

### ALTERED ANDESITE(?)

A bulbous body of andesitic(?) rock that has intruded the Manicaboa Formation crops out about half a kilometer southwest of the confluence of the Río Toro Negro and the Río Bauta. The intrusive is porphyritic with abundant phenocrysts of both plagioclase and clinopyroxene(?). The finely crystalline groundmass is largely microlites of albitized plagioclase and anhedral orthoclase(?) with interstitial iron-rich calcite. General texture and relic crystal structures indicate that the rock was intruded as an andesite.

All minerals in the rocks except the orthoclase(?) have been considerably altered. Phenocrysts of both plagioclase and clinopyroxene(?) have been intensively corroded and altered—the plagioclase to sericite and calcite, and the clinopyroxene(?) to uralite(?) and calcite. The interstitial calcite seems to be secondary.

A Late Cretaceous age is assigned to this rock because of its resemblance to the Minguillo Lava Member. Both seem to have suffered alteration of a nature that could be attributed to hydrothermal action. The country rock around the altered andesite(?) shows no appreciable alteration; therefore the alteration affecting the andesite(?) was not of a regional nature. Perhaps the body of altered andesite(?) represents one of the conduits through which the lava of the Minguillo was extruded.

## UPPER CRETACEOUS OR LOWER TERTIARY ROCKS

### SEDIMENTARY ROCKS

#### CARRERAS SILTSTONE

The Carreras Siltstone is here named for outcrops along the Río Las Carreras, east-central Ciales quadrangle. The formation is limited to a small area in the extreme east-central part of the Ciales quadrangle, but outcrops of the formation continue eastward into the Corozal quadrangle. Rocks in this formation were referred to as the Unibon Shale by Semmes (1919, p. 73–74), but as he described neither stratigraphic nor areal limits for the formation, a new name is necessary so that these rocks can be properly defined and described. The Carreras Siltstone seems to be the upper part of a thick heterogeneous sequence of sedimentary rocks that crops out in the northwestern part of the adjacent Corozal quadrangle, but because of faulting, stratigraphic continuity within the sequence is not known with certainty This sequence, which has at its base a thick reef limestone, rests on rocks that may be equivalent to an upper part of the Pozas Formation and is probably more than 1,000 meters thick. Figure 16 shows the extent of the Carreras Siltstone and its possible stratigraphic relation to underlying rocks.

The Carreras Siltstone seems to be several hundred meters thick in the Ciales quadrangle, but because of tight folding and some faulting, a precise thickness could not be determined.

The Carreras Siltstone is in fault contact with the basalt tuff member in the Ciales quadrangle. Structurally, the Carreras is in a synclinal block that has been tilted southward; the siltstone has been strongly folded and locally beds are vertical. The San Sebastián Formation of middle Tertiary (Oligocene) age unconformably overlies the Carreras. The Carreras Siltstone in the Corozal quadrangle seems to grade downward into a thick arkosic conglomerate that is characterized by granodiorite debris (fig. 16).

The Carreras Siltstone is a sedimentary deposit of very fine grained debris in thin to medium beds of light-colored bands or laminae. The detritus is extremely fine grained, but seems to be a mixture of reworked ash and epiclastic particles. Light-colored laminae are feldspathic and probably are largely of volcanic origin. The rock is dense and highly calcareous, and some beds border on impure limestone; such beds can be recognized in outcrops by small solution cavities that parallel the bedding. The siltstone is medium dark gray (*N* 4), but after weathering and leaching of the lime, the rock is grayish orange (10*YR* 7/4). Weathered debris from the Carreras is characteristically small fragments of rectangular or cubical shape. The resistance of some of the fragments to weathering suggests that they are siliceous.

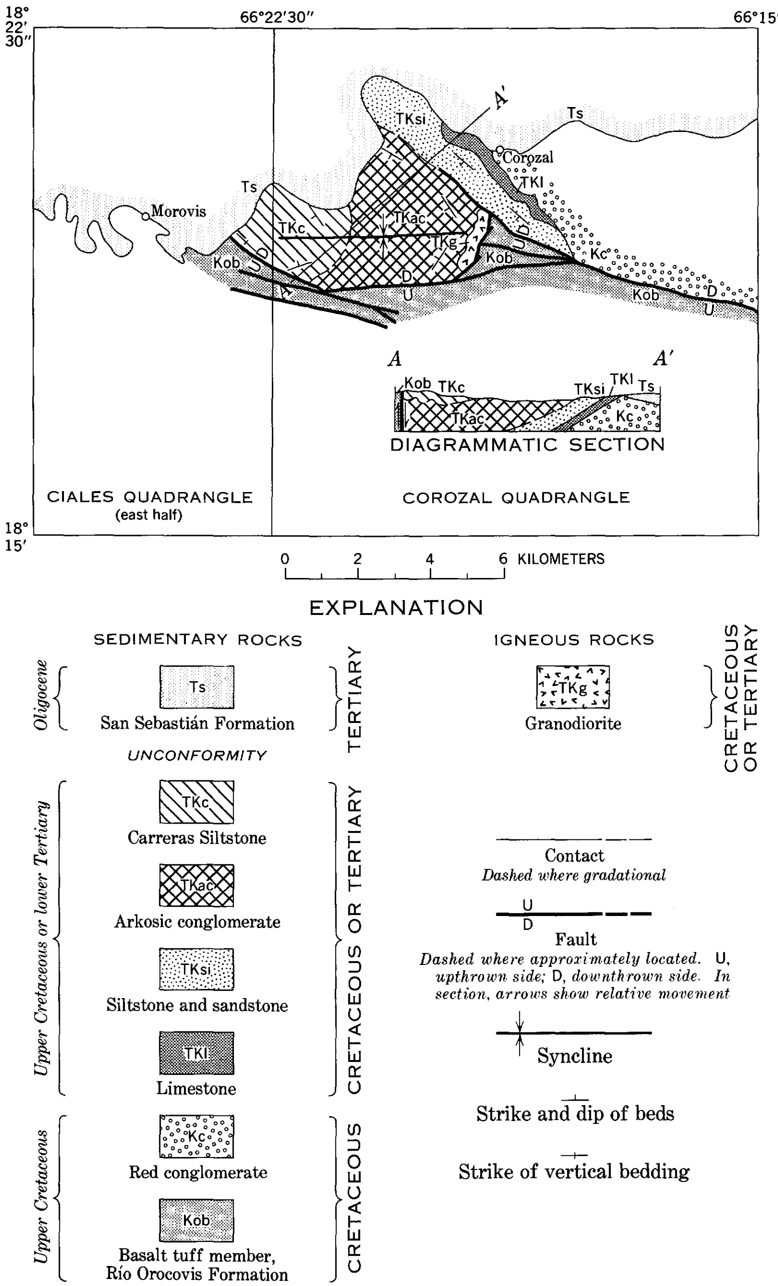


FIGURE 16.—Probable areal, structural, and stratigraphic relations of Carreras Siltstone to underlying rocks. Mapping in Corozal quadrangle is based on reconnaissance and is subject to revision.

The age of the Carreras is problematical. Foraminifera are numerous in thin sections made from rocks of the formation, but preservation is generally too poor for specific identification. Semmes (1919, p. 74) considered these rocks to be Late Cretaceous on the basis of Foraminifera that he identified from thin sections. He admitted that the species recognized were only general indicators of age and not a conclusive index. A variety of fossils from limestone and associated rocks that lie some 1,000 meters below the Carreras in the Corozal quadrangle (fig. 16) is reported by Kaye (1956, p. 115–117). Among the specimens were 22 genera of Foraminifera which Ruth Todd and Esther R. Applin identified as Paleocene forms. The limestone at Corozal (fig. 16) was considered by Berryhill and others (1960, p. 152) to be approximately at the Cretaceous-Tertiary boundary.

Rocks similar to the Carreras Siltstone and of presumed early Tertiary (Paleocene or Eocene) age are fairly extensive in northern Puerto Rico. To the west in the Florida quadrangle a thick sequence of siltstone overlies the Pozas Formation both in and adjacent to the Cerro Cedro graben. To the east a very distinctive and extensive sequence of similar siltstone in the San Juan area was called the Fajardo Formation by Kaye (1959), p. 27–29) and dated by him as late Paleocene or Eocene. However, Kaye's use of the name "Fajardo" for the siltstone near San Juan is a misnomer, as the Fajardo Formation of easternmost Puerto Rico (assigned to the Cretaceous by Berkey, 1915, p. 61) is now known to contain ammonites of Turonian (early Late Cretaceous) age (Berryhill and others, 1960, p. 143) and lies about 4,000 meters stratigraphically below the siltstone in the San Juan area.

The age of the Carreras Siltstone, as based on lithologic comparison with similar rocks in other parts of Puerto Rico, seems to be early Tertiary; meager fossil evidence suggests a Late Cretaceous age. As conclusive data are lacking for precise dating, the age of the Carreras is designated as either Late Cretaceous (Maectrichtian) or early Tertiary (Paleocene or younger).

## INTRUSIVE ROCKS

Hypabyssal dikes and plutonic bodies of various sizes crop out in the Ciales quadrangle. The dikes are not common, but the larger plutonic bodies occupy sizable areas. Most of the dikes and all the smaller plutonic bodies are associated with faults.

None of the intrusive rocks has undergone postmagmatic deformation, but most have undergone some secondary mineralization. On the bases of their mineralogic similarity and their crosscutting relation to country rocks and to faults, the dikes and plutonic rocks are classed as either Late Cretaceous (Maestrichtian) or early Tertiary (Paleocene or Eocene).

### GRANODIORITE

The principal Upper Cretaceous or lower Tertiary intrusive rocks in the Ciales quadrangle are the Morovis and Ciales granodiorite stocks. The Morovis stock occupies about 18 sq km in the central part of the quadrangle; the Ciales stock, lying about 1 km to the northwest occupies about 2 sq km. The two bodies are possibly connected at shallow depth. Weathering has reduced most outcrops to friable light-colored soil and saprolite, and fresh outcrops occur only along streambeds.

Both stocks seem to be of uniform composition. Both have typical granitic texture, although locally near borders, hornblende crystals are alined, indicating flowage during emplacement. Contacts with country rock are sharp. Texture is coarse except in prominent protuberances, which are finely crystalline. Migmatitic structures, porphyroblasts, and other evidence of intense metamorphism were observed in the adjacent country rocks only locally along the south side of the Morovis stock close to the Río Grande de Manatí fault zone. Veins, other than fracture fillings in rocks immediately adjacent to the intrusives, are notably scarce. Inclusions, both autoliths and xenoliths, occur most commonly in border areas of the stocks, but they are scattered through both. Small roof pendants lie within the Ciales stock.

### PETROGRAPHY

Minerals identifiable in hand specimens are hornblende, plagioclase, orthoclase, quartz, and biotite. The microscope shows that the granodiorite is composed chiefly of plagioclase (andesine?), hornblende, orthoclase, biotite, and quartz. Magnetite, apatite, and sphene are accessories, and zircon is a rare constituent. Most plagioclase crystals contain small inclusions, such as sericite and apatite; many hornblende crystals are cracked, corroded, and embayed by quartz and orthoclase.

A specimen from the Ciales stock, collected from an outcrop in the Río Cialitos due west of Ciales, was analyzed, and the result, together with the norm, is given in table 8, column 1. Minor constituents in this specimen are listed in table 9. These data indicate that the Ciales stock is granodiorite. The mineralogic composition of the Morovis stock indicates that it is of the same composition.

TABLE 8.—*Chemical analyses and norms, in percent, of plutonic intrusive rocks*

[Analysts: P. L. D. Elmore, I. H. Barlow, S. D. Botts, and Gillison Chloe]

| | 1 | 2 |
|---|---|---|
| **Chemical analyses** | | |
| $SiO_2$ | 61.3 | 57.3 |
| $Al_2O_3$ | 16.4 | 16.9 |
| $Fe_2O_3$ | 3.0 | 2.9 |
| FeO | 2.7 | 3.2 |
| MgO | 2.1 | 2.2 |
| CaO | 5.1 | 2.6 |
| $Na_2O$ | 3.4 | 4.1 |
| $K_2O$ | 3.4 | 6.8 |
| $H_2O$ | 1.1 | 1.9 |
| $TiO_2$ | .56 | .91 |
| $P_2O_5$ | .40 | .63 |
| MnO | .18 | .12 |
| $CO_2$ | .07 | <.05 |
| Total (rounded) | 100 | 100 |
| **Norms** [Barth modification of C.I.P.W. norm] | | |
| Quartz | 14.94 | ------ |
| Orthoclase | 20.02 | 40.03 |
| Albite | 28.82 | 34.58 |
| Anorthite | 19.46 | 7.78 |
| Wollastonite | 2.44 | .70 |
| Enstatite | 5.20 | 4.80 |
| Ferrosilite | 2.77 | 1.72 |
| Forsterite | ------ | .42 |
| Fayalite | ------ | .20 |
| Magnetite | 4.41 | 4.18 |
| Ilmenite | 1.06 | 1.67 |
| Apatite | 1.01 | 1.34 |

1. Granodiorite, Ciales stock; field No. XC-285; loc. 35, pl. 1; lab. No. 154666.
2. Alkali syenite, southeast Ciales quadrangle; field No. XC-988; loc. 43, pl. 1; lab. No. 154667.

TABLE 9.—*Minor constituents in a sample from the Ciales stock*

[Analyst: J. C. Hamilton]

| Laboratory No. | 281028 | Laboratory No. | 281028 |
|---|---|---|---|
| Field No. | XC-285 [1] | Field No. | XC-285 [1] |
| Ba | 0.15 | Ni | 0.0007 |
| Be | ------ | Sc | .0007 |
| Co | .0015 | Sr | .15 |
| Cr | .0003 | V | .015 |
| Cu | .003 | Y | .0015 |
| Ga | .0007 | Yb | .0003 |
| La | .003 | Zr | .007 |
| Mo | ------ | | |

[1] Granodiorite, Ciales stock (loc. 35, pl. 1).

### AGE AND MODE OF EMPLACEMENT

The Ciales and Morovis stocks cut Upper Cretaceous rocks, but they do not seem to have been affected by faults that cut lower Tertiary (Paleocene or younger) rocks in the adjacent Corozal quadrangle. Both are overlain unconformably by middle Tertiary (middle Oligocene) rocks. The suggested age of emplacement relative to faulting is early Tertiary (late Paleocene or Eocene). However, the faults cutting lower Tertiary rocks in the adjacent quadrangle cannot be traced with certainty to the borders of the Ciales and Morovis stocks; therefore the emplacement of the two stocks must have taken place sometime between the very Late Cretaceous and the middle(?) Eocene.

A lead-alpha age determination on zircon separated from a granodiorite in the Ciales stock yielded an age of $70 \pm 20$ million years. The lead content of the zircon was determined as 3.5 ppm by Charles Annell and Harold Westley, and its alpha activity as 133 $\alpha$ per mg per hr by T. W. Stern. The age was calculated using the formula given by Gottfried, Jaffe, and Senftle (1959, p. 19) and a value of 2,485 for the factor *c*. The low lead content of this zircon introduces an uncertainty of 20 million years in its age.

The probable age of the stock as determined from the lead-alpha age of zircon is compatible with the age range indicated by geologic relations, which is considered to be Late Cretaceous to early Tertiary. However, the structural relations of the granodiorite to country rocks favor intrustion in early Tertiary time.

The Ciales and Morovis stocks are wholly discordant to country rocks. Lineation of minerals is common in border areas and parallels the contact with country rocks where observed. The country rocks have undergone little metamorphism beyond moderate chloritization and introduction of pyrite. Updragging and general deformation of adjacent rocks seem to be restricted to a few places along the south side of the Morovis stock. Along the northwest and southeast sides of the Morovis stock and around the Ciales stock, emplacement of the granodiorite does not seem to have affected the regional west-northwest trend of the country rock, although drag would not be easily detected around the Ciales stock or around much of the Morovis stock because of massiveness of surrounding country rocks. Roof pendants of the Avispa Lava Member are present in the Ciales stock, but none was observed in the Morovis stock. Both stocks intruded volcanic rocks, and the chemical and mineralogical similarity of the stocks to the nearby dacite ash-flow deposits of the Blacho Tuff Member of Late Cretaceous age have been discussed on page 61. Emplacement of the granodioritic plutons seems to have been one of the last phases of a regional igneous cycle that began with the extrusion of great quantities of basaltic lava and ended with the intrustion of moderately salic magma into the supracrust.

Criteria noted indicate that both the Ciales and Morovis stocks penetrated the near-surface crustal zone. Roof pendants of the Avispa Lava Member indicate that the magma of the Ciales stock penetrated upward to about 4,500 meters or even less from the surface, assuming no erosion of Upper Cretaceous and lower Tertiary rocks before emplacement. Lack of roof pendants in the Morovis stock and relative size suggest that the magma penetrated considerably closer to the surface than 4,500 meters.

Parallelism and proximity of the Morovis stock to the Río Grande de Manatí fault zone suggest that the steeply dipping fault guided the upward movement of the magma. Both migmatitic structures and updragging seem to be most common along the southern side of the stock in the vicinity of the fault zone. Localization of protuberances mainly to the northwest and southeast sides of the stock indicates a tendency for the magma to penetrate along the west-northwest-trending regional fractures and faults of the Jaguas-Cuchillas faulted synclinal belt. The west-northwest orientation of the protuberances indicates that the present west-northwest structural trend of the Upper Cretaceous and lower Tertiary rocks developed in very Late Cretaceous time. Nowhere do the Ciales and Morovis stocks seem to be cut by faults, which suggests that emplacement and solidification of the granodiorite stocks occurred after the major portion of early Tertiary faulting had ceased.

The Ciales and Morovis stocks are clearly intrusive bodies and are presumed to have moved upward from considerable depth. They did not form in place by the process of granitization.

### SYENITE AND OTHER INTRUSIVE ROCKS

Smaller intrusive bodies, all associated with faults, are widely distributed in the Ciales quadrangle, although their total areal extent is small. Most are too weathered for precise mineralogic determination.

The largest of these bodies crops out along the bed of the Río Grande de Manatí near the center of the quadrangle. Two features distinguish this rock: pyroxene and potash feldspar composition and numerous thin stringers of potash feldspar. The feldspar stringers are distinctly pink, vertical, and roughly parallel but somewhat sinuous and are alined west-northwestward (N. 70° W.) through the main body of the intrusive. Average width of stringers is 1–2 cm, but locally is as much as 16 cm; similar material occurs locally as masses as much as 1 meter across. Space between stringers ranges from about 1 to 10 meters or more, and many stringers can be traced for as much as 50 meters. Chlorite and epidote are common secondary minerals within the stringers which grade into the main body of the intrusive. The potash feldspar forming the stringers seems to have been deposited along narrow channels by volatiles that were escaping from the intrusive during cooling and solidification. The orientation of the stringers parallels the west-northwest regional trend of fractures and faults, indicating that the volatiles emanated along lines of regional stress.

The microscope reveals an intersertal texture and equicrystalline intergrowth of augite, orthoclase, and scattered magnetite. Of special note are the strikingly rectangular and straight-sided interstices between crystals, which are filled with chlorite and zeolite having colloform and spherulitic structure. The shape of the interstices and the peculiar growth of the secondary mineral within them suggest that a liquid fraction was flushed from the partially crystalline magma before consolidation was complete. The orthoclase stringers previously discussed possibly formed during the escape of a volatile-rich liquid fraction. The microscopic texture of the rock and the characteristic rectangular interstices are shown on figure 17. Microscopically, the potash feldspar crystals in the stringers are highly corroded, partly resorbed, and embayed with chlorite, which is a replacement of vein material (fig. 17*B*). The mineralogic composition of the rock is that of augite syenite. This intrusive, which is probably genetically related to the Morovis stock, penetrated close to the surface along the Río Grande de Manatí fault and probably was a source for fumaroles and small-scale volcanic eruptions, as indicated by several small masses of autoclastic breccia (agglomerate) that lie within the intrusive. This syenite body may represent a volatile-changed fraction of the main mass of granodiorite magma that moved upward ahead of the main mass, using the fault as an escape route.

Another small body of syenite has intruded the older body of altered gabbro(?) near the southeast corner of the quadrangle and lies along a fault that is subsidiary to the main fault that marks the north side of the Cerro Cedro graben. This intrusive is highly feldspathic, and the microscope reveals hypidiomorphic granular (granitic) texture. Pyroxene, the only recognizable primary mafic mineral, is not common. Chlorite is an abundant secondary mineral. The composition of this rock, as indicated by chemical analysis (table 8, column 2), is alkali syenite.

Most of the other small intrusive bodies, all of which lie along faults, seem to be dioritic; some may be granodiorite, others possibly are syenites; all probably are genetically related to the Ciales and Morovis stocks. The intrusive south of the Río Toro Negro and at the edge of the Minguillo Lava Member seems to be a composite

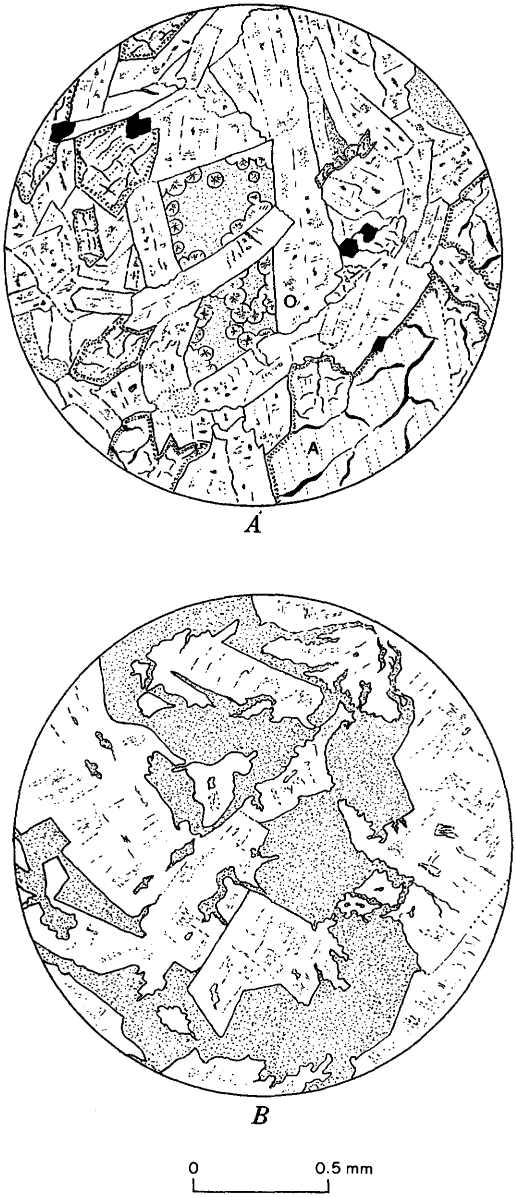


FIGURE 17.—Microscopic texture of augite syenite. *A*, Interserial texture with lattice intergrowth of augite (A) and potash feldspar (0) and rectangular interstices filled with chlorite and zeolite having spherulitic and colloform structure. *B*, Corroded and partly resorbed potash feldspar and chlorite which has replaced a vein material.

body consisting of diorite and hornblende andesite; the hornblende andesite possibly represents a chilled border phase and not a separate intrusive phase.

### DIKES

Hypabyssal dikes of diorite and hornblende andesite are in the Ciales quadrangle. The dioritic dikes lie principally along the south side of the Morovis stock and in the Río Grande de Manatí fault zone. The hornblende andesite dikes are more scattered, but are mainly in the southwestern quarter of the quadrangle. Most dikes are associated with small faults.

The largest dike in the quadrangle lies within the Morovis stock at the west edge of Morovis and is probably of early Tertiary age. On the basis of conspicuous float, the dike was mapped southward from Morovis for three-fourths of a kilometer. The gross mineralogic composition suggests that the dike rock is diorite, but, because of the fine grain, the proportions of mafic and feldspathic minerals could not be determined accurately. The color is moderately dark, but plagioclase is abundant to the extent that the rock has a mottled or slightly sugary appearance. Although contact relations along the edges of the dike are obscure because of weathering of the granodiorite, the linear shape of the body strongly suggests that it has cut the Morovis stock and is not a differentiated mass within the granodiorite. This dike may represent the last phase of igneous activity in Puerto Rico. Similar dikes are common in northeastern Puerto Rico east of San Juan and north of the San Lorenzo batholith.

The hornblende andesite dikes are porphyritic with hornblende phenocrysts. Albitization of the plagioclase is common in all these bodies. Dikes of this type are widely distributed in eastern Puerto Rico and have been described in south-central Puerto Rico by Berryhill and Glover (1960) and Berryhill (1960).

## UNCONFORMITY AT BASE OF MIDDLE TERTIARY ROCKS

A marked unconformity separates the middle Tertiary from the lower Tertiary(?) and Upper Cretaceous rocks. The hiatus represented by this unconformity is not known precisely, but the time lapse possibly extended from Paleocene to mid-Oligocene time. Older rocks were profoundly faulted, tilted, locally folded and intruded by plutonic rocks, and eroded deeply enough to expose one of the plutonic bodies over an area of about 18 sq km before middle Tertiary rocks were deposited over it. The thickness of material removed seems to have been at least a kilometer or perhaps more. The angular discordance of the rocks above and below the unconformity is everywhere large and locally as much as 90°.

Pre-middle Tertiary erosion reduced the topography of the Ciales quadrangle to a surface of moderate slope and low relief. Summit levels in the area between the middle Tertiary rocks and the Río Grande de Manatí probably closely approximate the slope of the pre-middle Tertiary surface. Maximum relief in the northern part of the quadrangle, as ascertained from elevation differences of the base of the middle Tertiary rocks along strike, seems to have been about 60 meters.

The middle Tertiary sea transgressed southward across the gently sloping surface. Means are not available for determining the maximum extent of the middle Tertiary submergence, but most, if not all, of the Ciales quadrangle probably was covered by middle Tertiary deposits.

## MIDDLE TERTIARY ROCKS

### GENERAL FEATURES

Middle Tertiary rocks ranging in age from middle Oligocene to early Miocene cover the northern third of the Ciales quadrangle, where they lie unconformably on volcanic and igneous rocks of Late Cretaceous and Late Cretaceous or early Tertiary age. These rocks are part of a thick sequence of middle Tertiary rocks that crops out along the north coastal area of Puerto Rico (Zapp and others, 1948). Areal extent of this sequence and also of rocks of equivalent age along the south coast of Puerto Rico is shown on figure 18.

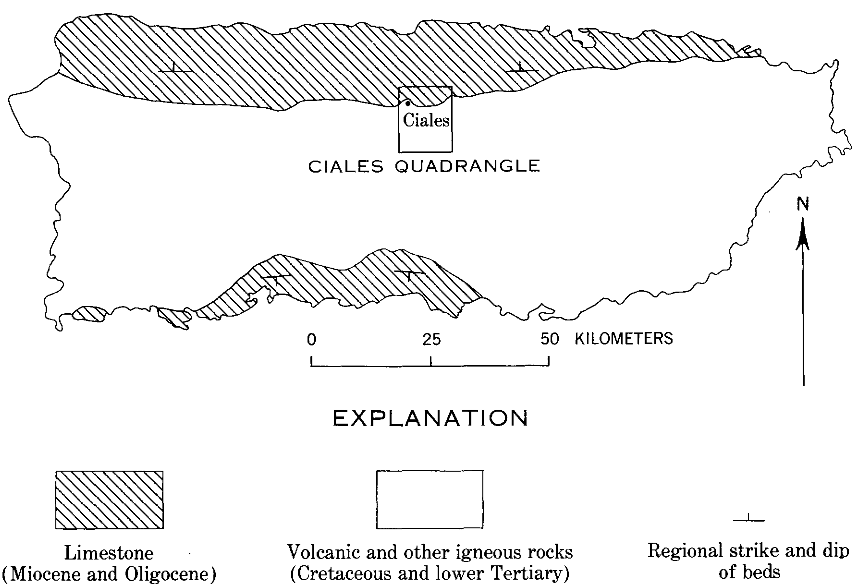


FIGURE 18.—Areal extent of middle Tertiary rocks in Puerto Rico. Modified from Zapp and others (1948).

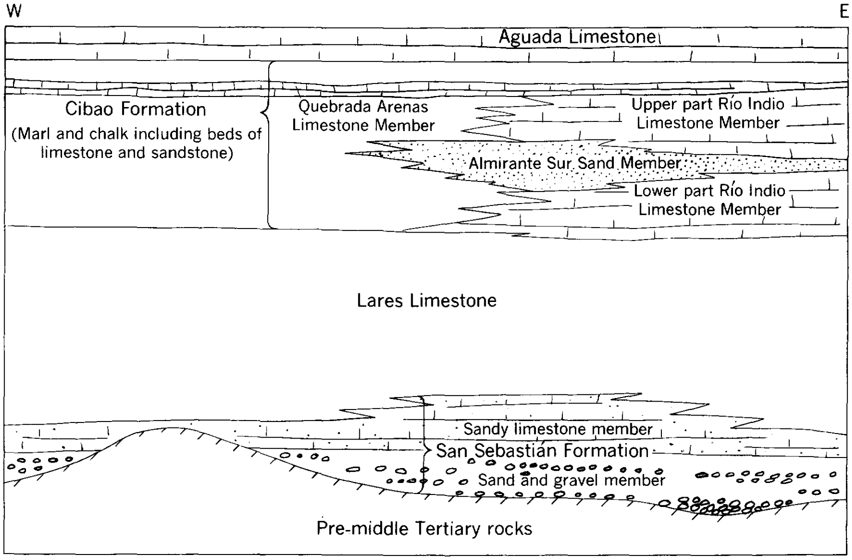


FIGURE 19.—Diagrammatic section showing stratigraphic and facies relations of middle Tertiary formations in the Ciales quadrangle.

The middle Tertiary rocks are predominantly limestone, but they also include chalk, marl, clay, sand, friable sandstone, gravel, and conglomerate. Stratigraphic units recognized are the San Sebastián Formation and Lares Limestone of Oligocene age, the Cibao Formation of late Oligocene and early Miocene age, and the Aguada Limestone of early Miocene age. Zapp and others (1948) considered the San Sebastián, Lares, and Cibao Formations to be indistinct units within an intergradational and intertonguing sequence which they named the Río Guatemala Group. In the Ciales quadrangle these formations are designated as separate units which have been locally subdivided into members.

Coarse detritus is concentrated in the lower part of the middle Tertiary sequence, but tongues of calcareous sandstone lie within limestone and marl higher in the sequence. General stratigraphic and facies relations of the middle Tertiary formations are shown on figure 19. In general, the middle Tertiary sequence becomes more clastic eastward across the Ciales quadrangle.

The estimated thickness of the middle Tertiary rocks of the Ciales quadrangle is 600 meters. The east-west trend of the homoclinal gently northward dipping middle Tertiary rocks is oblique to the general west-northwest trend of the underlying rocks.

The middle Tertiary rocks were deposited by a transgressing sea that submerged an erosion surface of gentle relief. The lower part of the sequence consists of estuarine and shoreline deposits; the upper part consists mostly of shallow-water shelf or reef-bank deposits. Waves and currents were active agents in reworking and spreading these deposits.

### SAN SEBASTIÁN FORMATION

The San Sebastián Formation, originally called "San Sebastián shales" of Tertiary age by Berkey (1915, p. 10, 17) and later redesignated as a formation of Oliogocene age by Meyerhoff (1933, p. 66–67), comprises the conglomerate, gravel, friable sandstone, silt, clay, and sandy limestone that form the lower part of the middle Tertiary sequence across most of northern Puerto Rico. In the Ciales quadrangle this heterogeneous and lenticular formation has been subdivided into two informally designated units: the sand and gravel member and the overlying sandy limestone member. The age of the San Sebastián Formation is considered to be Oligocene because of its stratigraphic relation to other middle Tertiary rocks and because of the age of the fossils.

#### SAND AND GRAVEL MEMBER

The sand and gravel member strikes east-west and forms the southernmost belt of middle Tertiary outcrops. Because of gentle dip, intricate dissection by streams, and irregularities in the pre-middle Tertiary surface, the outcrop belt is very irregular in width and fingers of gravel and sand extend southward from it. Outliers of gravel and sand preserved in shallow depressions lie south of the main outcrop belt.

Thickness of the sand and gravel member ranges from 0 to about 80 meters, the thickest part lying about half a kilometer west of Morovis. The member thins to the east and west and pinches out locally against a topographic high on the pre-middle Tertiary erosion surface 4.7 km west of Morovis. Locally the member is covered by talus from the Lares Limestone.

The lower part of the sand and gravel member is greenish, medium to coarse sand, and friable, locally crossbedded sandstone containing many lenticular beds of gravel and conglomerate from a few centimeters to several meters thick. The gravel beds are a mixture of well-rounded pebbles and subordinate subangular fragments in a friable sandstone matrix. Both composition and number of gravel beds vary vertically. Thick compact conglomeratic lenses at the base of the member are heterogeneous and contain detritus from almost every Upper Cretaceous and lower Tertiary rock unit. The number of beds diminishes upward, and the detritus becomes less varied because fragments of Carreras Siltstone predominate over detritus from other types of rock. The number and thickness of gravel beds

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also vary laterally, and both the concentration and thickness of the beds are greatest in the eastern part of the quadrangle.

The upper part of the sand and gravel member is interbedded fine-grained partly calcareous friable sandstone with subordinate thin gravels and beds of both olive-gray and pale-red silty clay.

Fossils were not found in the sand and gravel member in the Ciales quadrangle, but a few fragments of pelecypod shells were observed in the upper part of the member in the adjacent Corozal quadrangle. Thin beds of lignite and carbonized plant fragments are in beds presumed to be equivalent to the sand and gravel member elsewhere in Puerto Rico (Zapp and others, 1948).

The sand and gravel member accumulated in part as estuarine deposits in drowned valleys and in part as coastal swamp and lagoonal deposits. The member weathers rapidly, is friable, and forms a subdued topography.

### SANDY LIMESTONE MEMBER

The upper part of the San Sebastián Formation in the Ciales quadrangle is a lens of sandy, somewhat friable limestone that crops out extensively in an area that extends from a little west of Quebrada Franquez eastward to the east edge of the quadrangle. The member overlies the sand and gravel member, except for a small outlier in the west-central part of the quadrangle that lies directly on the Avispa Lava Member of the Río Orocovis Formation. The sandy limestone member is separated from the sand and gravel member on the basis of lime content and color. The pale-yellowish-orange sandy limestone makes a sharp contact with the underlying drab greenish sand and silt of the sand and gravel member. The friability of the sandy limestone member distinguishes it from the dense resistant limestone of the overlying Lares Limestone.

The sandy limestone reaches a maximum thickness of 45 meters north of Morovis and thins eastward and westward from there, pinching out locally against a topographic high on the pre-middle Tertiary erosion surface 4.7 km west of Morovis. Around the Ciales reentrant in the northwest part of the quadrangle, the sandy limestone member is generally less than 20 meters thick and is covered largely by talus from the Lares Limestone. To the east in the northwestern part of the Corozal quadrangle, W. H. Monroe (written commun., 1961) reports a thickness of 5 meters or less for the sandy limestone.

The sandy limestone member is largely a calcarenite with a few resistant lenticular beds of calcilutite. The unit is typically in massive beds and is somewhat friable, particularly in the lower part. The lower 5 to 6 meters contains glauconite and small reworked green

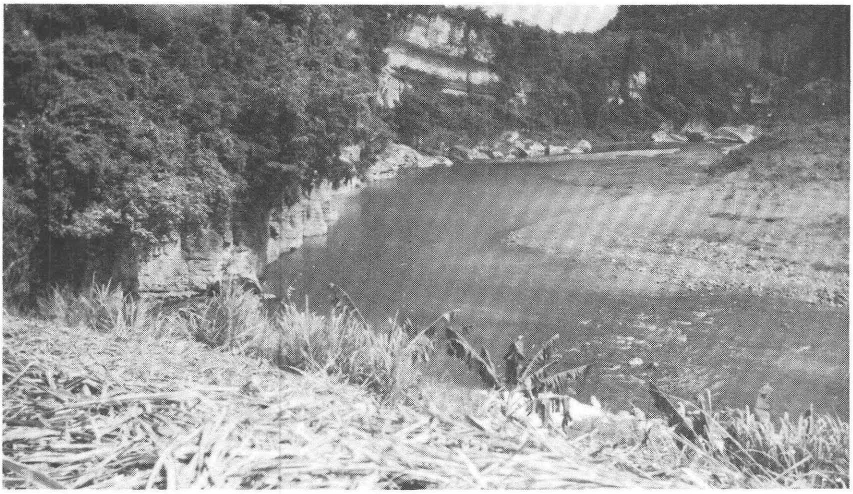


FIGURE 20.—Photograph showing outcrop of sandy limestone member of the San Sebastián Formation, west bank of Río Grande de Manatí north of Ciales (loc. 23, pl. 1).

fragments of the underlying sand and gravel member. Figure 20, which faces north from locality 23, shows the typical massive beds of the member.

Except for a few beds of dense calcilutite, the limestone consists largely of coral and shell sand of medium to coarse grain size with minor amounts of quartz and glauconite. Fragments of pelecypod shells, particularly *Pecten* sp., and *Ostrea* sp., are locally abundant, as are remains of the large Foraminifera, *Lepidocyclina* sp. The presence of *Lepidocyclina* is indicative of a late middle Oliogcene age, according to Woodring (Cooke and others, 1943, chart 12).

The sandy limestone member is a near-shore deposit that was spread seaward from a littoral and near-littoral zone that abounded in benthonic marine organisms. Parts of the member in the Corozal quadrangle are crossbedded in a way that suggests beach deposits. The thickness pattern of the lens formed by the sand and gravel and sandy limestone members suggests that these units filled a broad lowland in the pre-middle Tertiary erosion surface.

#### LARES LIMESTONE

The Lares Limestone was named in 1917 by Hubbard (1923, table 3) as the basal limestone of the north coast Tertiary sequence. At the type locality near Lares, western Puerto Rico, the Lares overlies the San Sebastián Formation and is overlain by the chalk and marl of the Cibao Formation. The Lares Limestone was considered by Zapp and others (1948) as a reef-forming unit within an intergradational sequence that included the San Sebastián and Cibao Formations, and they drew indefinite contacts between these units. In the Ciales quadrangle the contact between the Lares and Cibao Formations, as mapped by Monroe (1962), follows closely the contact shown by Zapp and others in the western part of the quadrangle, but lies somewhat lower than their contact in the eastern part. Monroe has placed the contact at the top of a sequence of hard stratified pure, whitish limestone and beneath a fragmental yellow limestone that contains grains of glauconite.

The Lares Limestone forms a broad sinuous belt across the northern part of the Ciales quadrangle. Its thickness increases from about 140 meters at the east edge of the quadrangle to about 260 meters at the west edge.

The Lares is typically a very pure limestone whose color varies from almost white to hues of pale yellow and orange. The lower two-thirds of the formation is massive limestone in layers as much as 10 meters thick, and the upper part is calcilutitic limestone in beds from about 10 to 30 cm thick. Small caverns and solution channels covered by reprecipitated calcite are common throughout the formation.

The massive lower part of the Lares is richly fossiliferous, containing corals and other forms; several small bioherms were observed. The following fossils, collected by Cooke (USGS 19252) from a quarry on the east side of Highway 149, a short distance south of Hato Viejo (loc. 24), are reported by Monroe (1962): *Lepidocyclina gigas* Cushman, *Ostrea antiguemsis?*, *Spondylus* n. sp., *Amusium antiguense* Brown, and others. On the basis of these fossils, particularly *Lepidocyclina gigas* Cushman, Cooke (in Monroe, 1962) considered the rocks here included in the Lares Limestone to be late Oligocene in age.

The Lares Limestone is resistant and forms prominent topographic features. Extensive solution by ground water has developed a karst topography of classic form, with steep-sided haystack hills, or pepinos, and intervening sinkholes, over much of the area underlain by the Lares. Along the sides of the Ciales reentrant the Lares forms almost vertical cliffs 30–60 meters high. The karst topography typical of the Lares is shown in figure 21, which includes two views: a distant view looking south from locality 25, showing the typical hummocky surface formed by the haystack hills and intervening sinkholes, and a closeup view showing individual haystacks, or pepinos.

The Lares is largely a biogenic deposit that accumulated in close proximity to reef banks which probably formed on a shallow shelf.

### CIBAO FORMATION

The chalk, marl, limestone, and sand overlying the Lares Limestone were named the Ciabo Limestone by Hubbard (1923, table 3) for

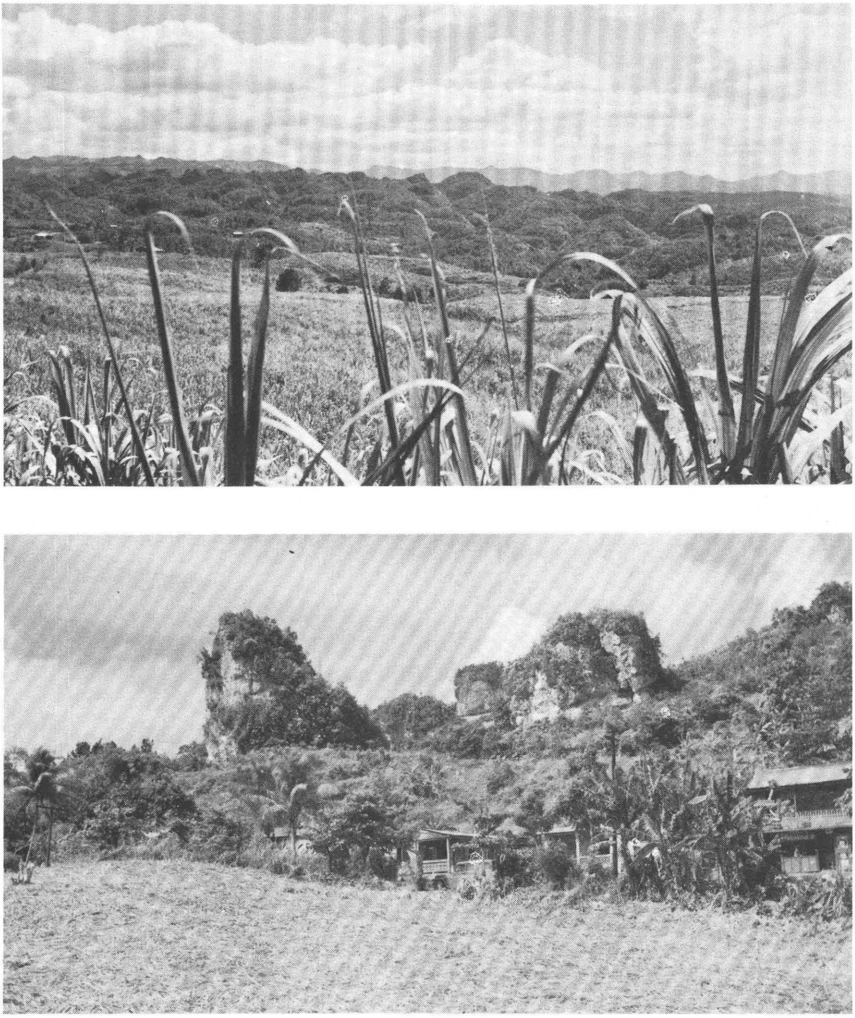


FIGURE 21.—Views of karst topography on Lares Limestone, northwest Ciales quadrangle. Upper, Distant view looking south. Lower, View of haystack hills, or pepinos, north of Ciales.

outcrops in barrio Ciabo, Municipio de Camuy, western Puerto Rico. Zapp and others (1948) renamed the unit the Ciabo Marl. Monroe (1962) changed the designation to Cibao Formation because of the varied character of its members. The Cibao Formation crops out extensively along the north edge of the Ciales quadrangle, but its contact with the overlying Aguada Limestone lies mainly to the north in the Manatí quadrangle. The indicated thickness of the Cibao is 185 meters. The soft chalk and marl of the Cibao form a gently rolling topography in contrast to the sinkholes and pepinos in the adjacent Lares and Aguada Formations.

The Cibao Formation in the Ciales quadrangle was mapped by Monroe (1962) during his work on the adjacent Manatí quadrangle. The lithologic descriptions that follow are taken from the Manatí report.

The Cibao Formation is more varied lithologically than the other Tertiary formations in the Ciales quadrangle. The lower part of the Cibao in the western part of the quadrangle consists of a few meters of moderately soft chalky fragmental yellowish-orange limestone that commonly contains grains of glauconite and quartz. The glauconite is rare in beds higher than 5 meters above the base of the formation, but it is a diagnostic feature for differentiating the basal limestone of the Cibao from uppermost beds of the Lares, which contain no glauconite. Above the basal few meters in the western and central parts of the quadrangle, the Cibao consists of sandy and silty, slightly clayey chalk or marl. Eastward the marly and chalky sequence intertongues with a sequence of alternating units of limestone, sand, and chalk. Yellowish-brown (10*YR*) tints are characteristic of the lower part of the Cibao. The age of the lower part is considered late Oligocene by Cooke (in Monroe, 1962) because of the presence of *Lepidocyclina gigas* Cushman, *Echinolampus aldrichi* Twitchell, and *Schizobrissus antillarum* (Cotteau), all well known from the West Indies in formations generally considered Oligocene.

A thick unit of hard crystalline limestone and softer chalky limestone occupies the interval from 110 to 140 meters above the base of the Cibao. The persistent hard limestone was mapped across the entire quadrangle and designated the Quebrada Arenas Limestone Member.

The Quebrada Arenas Limestone Member is overlain by about 50 meters of soft chalky limestone, chalk with calcareous concretions, and local small lenses of nearly grit-free chalk. Colors in this part of the Cibao range from almost white to pale yellowish orange (10*YR* 8/4). The upper part of the Cibao Formation above the Quebrada Arenas Limestone Member is considered early Miocene by Cooke (in Monroe, 1962) because of the presence of *Pecten vaun* Cooke, *Ostrea rugifera* Dall, and tubes of *Kuphus incrassatus* Gabb.

In the northeastern part of the quadrangle the Cibao below the Quebrada Arenas Limestone Member has been subdivided by Monroe into the Río Indio Limestone Member and the Almirante Sur Sand Member. Interbedded with these members are tongues of typical chalk or marl of the Cibao. The stratigraphic and facies relations of the members of the Cibao are shown on figure 19.

#### RÍO INDIO LIMESTONE MEMBER

The Río Indio Limestone Member, named by Monroe (1962) crops out on Highway 645 just west of the bridge over the Río Indio, southeast Manatí quadrangle, and rests on the underlying Lares Limestone with sharp contact. The Río Indio is about 90 meters thick at the southeast corner of the Manatí quadrangle, but westward the member is split into lower and upper parts by the Almirante Sur Sand Member.

At the type locality the lower part of the Río Indio is compact but chalky yellow to yellow-orange poorly bedded to massive limestone with scattered glauconite in the lower 10 meters. Broad-scale crossbedding is a notable feature in the type area in the Manatí quadrangle. The lower part is about 40 meters thick and is gradational upward into the Almirante Sur Sand Member.

The upper part, which is about 20 meters thick, is much more fragmental than the lower part. It is a porous rock consisting mostly of cemented shell fragments. The upper part rests gradationally on the Almirante Sur Sand Member and grades laterally into impure chalk; it is overlain by the Quebrada Arenas Limestone Member.

#### ALMIRANTE SUR SAND MEMBER

The lower part of the Río Indio Limestone Member is overlain by about 30 meters of sand which Monroe (1962) named the Almirante Sur Sand Member for exposures in barrio Almirante Sur on Highway 645, northeastern Ciales quadrangle (loc. 26).

At the type locality the basal 5 meters of the member is coarse grained and contains well-rounded granules as much as 3½ mm long. The granules and smaller grains are predominantly subrounded to subangular quartz, but many are angular volcanic rock debris. A persistent indurated sandstone layer lies about 5 meters above the base of the member and forms a ledge that can be traced around nearby hills. Higher beds of the member are generally fine-grained sand.

West of the Río Unibon and the Río Morovis, the Almirante Sur grades laterally into impure marly chalk similar to other parts of the Cibao Formation. Eastward in the Manatí quadrangle the sand member grades rather abruptly into the Río Indio Limestone Member.

#### QUEBRADA ARENAS LIMESTONE MEMBER

The persistent unit of interlayered hard and chalky limestone in the upper part of the Cibao Formation has been named the Quebrada Arenas Limestone Member of Monroe (1962) for outcrops in the Manatí quadrangle along Highway 645 on the slope down to Quebrada El Toro from the Escuela Quebrada Arenas.

The member is 30 meters thick in the type area. The hard beds are typically very pale orange (10*YR* 8/2) to pale-grayish-orange (10*YR* 8/4) very finely crystalline to calcilutitic limestone that contains scattered quartz grains and abundant molds of fossils. The member thins westward to about 10 meters along the valley of the Río Grande de Manatí, where the limestone mapped is apparently only the upper part of the unit.

Although the general area underlain by the Cibao Formation is one of gentle relief, the resistant Quebrada Arenas Limestone Member forms the caprock of a persistent escarpment, or cuesta inface, that parallels the north edge of the Ciales quadrangle.

#### AGUADA LIMESTONE

The Aguada Limestone of Miocene age was named by Zapp and others (1948) for the town of Aguada on the west coast of Puerto Rico. The Aguada, which has a thickness of about 90 meters, crops out across the southern part of the Manatí quadrangle and forms a well-developed karst topography. Only the lower 10–15 meters of the Aguada is exposed in the Ciales quadrangle. Outcrops are restricted to the upper part of two knolls near the north edge of the quadrangle.

The Aguada Limestone of the Ciales quadrangle is bedded, finely crystalline, and grayish orange (10*YR* 7/4), and contains scattered grains of quartz, limonite, and volcanic rock fragments. Some layers of marly limestone are interbedded with the harder layers. Monroe (1962) reports that the amount of quartz sand in the Aguada Limestone increases eastward, and that downdip to the northeast some beds of the Aguada in the eastern part of the Manatí quadrangle are almost thin-bedded calcareous sandstone.

### QUATERNARY ROCKS

The unconsolidated silt, sand, gravel, cobbles, and boulders along the streams and stream valleys and in limestone sinks and the angular rock debris and rock-slide debris on and at the base of steep slopes are the youngest deposits in the Ciales quadrangle. This material makes up alluvium, including streambed, flood-plain, and limestone sink deposits, stream terrace deposits, and colluvium, including both talus and landslide debris. No fossils or other evidence was found for precise dating of the alluvium, but it is presumed to be of Recent age. The stream terrace deposits may be of Pleistocene age.

Deep residuum, consisting of soil that accumulated from rock weathering and saprolite, lies at the higher elevations in the southeastern part of the quadrangle and at lower elevations near the east-central edge of the quadrangle. The residuum was possibly more extensive during the Pleistocene or earlier, but it has been removed by erosion during Recent time.

### STREAM TERRACE DEPOSITS

Stream terrace deposits lie along the Río Grande de Manatí in scattered patches from the east-central part of barrio Río Grande northwestward to near Ciales. These deposits are on benches that lie from 15 to 50 meters above river level. The alluvial material on the benches or terraces is a thin veneer of silt, sand, gravel, cobbles, and scattered boulders. The terrace deposits south of the river at the center of the quadrangle are thicker than those elsewhere because they also include some ancient alluvial-fan deposits.

The pattern of distribution of the terrace deposits along both sides of the Río Grande de Manatí east of the confluence with the Río Bauta suggests that these terrace deposits are remnants of an older flood-plain deposit that was more extensive than the current flood plain. All the stream terrace deposits may be of Pleistocene age.

### ALLUVIUM

#### STREAMBED DEPOSITS

Lenticular thin deposits of silt, sand, gravel, cobbles and boulders, derived from the bedrock of adjacent hills by weathering, lie along the beds of all the streams. Rejuvenation of streams and rapid erosion in Recent time have strongly influenced the rate of accumulation and pattern of distribution of streambed alluvium.

South of the Río Grande de Manatí fault alluvium is discontinuous and occurs as patches of relatively coarse material, including a large number of cobbles and boulders mixed with sand. Scattered boulders as much as 4 meters in diameter lie along the Río Orocovis. Relative scarcity of streambed alluvium south of the Río Grande de Manatí fault, where stream gradients are steep, is a result of frequent flushing of loose material seaward by the streams during heavy rains, which commonly cause stream levels to rise several meters in a fraction of an hour.

North of the Río Grande de Manatí fault, the Río Grande de Manatí flows on a bed of intermixed silt, sand, and gravel. The thickness of alluvium in the bed of the Río Grande de Manatí probably does not exceed a few meters anywhere in the Ciales quadrangle.

#### FLOOD-PLAIN DEPOSITS

Stratified deposits of silt, sand, gravel, cobbles, and boulders lie adjacent to the channels of some of the larger streams in the Ciales quadrangle. These deposits are laid down during floods or high-water stages when the water rises above the top of the banks of the stream channels and spreads laterally across adjacent flat areas, carrying silt, sand, and gravel that is spread across the flood plains in layers.

In most places south of the Río Grande de Manatí fault the streams are enclosed by narrow valleys or rock walls, and flood-plain deposits, most of which are too small to map, are confined to crescent-shaped patches on the inside of intrenched meanders. North of the Río Grande de Manatí fault zone in the central part of the quadrangle, flood-plain deposits, which have a maximum width of a little more than half a kilometer, have accumulated locally along the Río Grande de Manatí. North of Ciales, as the river approaches the coastal plain, the flood plain becomes continuous but is narrow because of confinement by the vertical limestone cliffs of the Lares Limestone.

The flood-plain deposits of the Río Grande de Manatí are predominantly silt, sand, and gravel; but boulders are concentrated in the lower part of these deposits, suggesting that erosion at present is somewhat less active than in the recent past. The thickness of the flood-plain deposits is variable because of both irregularities in the rock floor beneath the deposits and terracing in the upper surface. Maximum thickness probably does not exceed 15 meters anywhere along the Río Grande de Manatí. The level of the river lies in most places from 5 to 10 meters below tbe level of the lowest part of the adjacent flood-plain deposits.

### LIMESTONE SINK DEPOSITS

The bottoms of many of the limestone sinks in the area of karst topography are covered by accumulations of alluvium. These sinks are so numerous, and the alluvium in most of them is so thin, that no attempt was made to map the limestone sink deposits over the entire belt of Tertiary limestone outcrops. Several of the thicker and more extensive limestone sink deposits are shown on the geologic map.

The alluvium in the limestone sinks is largely reworked residuum from the limestone. In general, this material is less sandy than other alluvium.

### COLLUVIUM

Colluvial deposits of the Ciales quadrangle include talus and small landslides that occur mainly on the steep slopes in the southernmost part of the quadrangle. Landslides or slips are numerous, but most are too small to map.

The most extensive unconsolidated material in the Ciales quadrangle is the talus which forms a wide, thick, and continuous belt along the base of the limestone cliffs that outline the reentrants cut by the Río Grande de Manatí and the Río Unibón and its tributary, the Río Carreras. The talus is a mixture of limestone debris that ranges from clay size to huge blocks many meters across. Because of the clay and limestone residuum, the talus accumulation becomes soft and plastic when wet and creeps downslope as a mudflow. Along the west valley wall of the Río Cialitos, tongues of talus debris, moving as mudflows, have migrated down ravines to the level of the river. Maximum thickness of the talus is about 30–40 meters. Some of the limestone rubble that is intermixed with alluvium in limestone sinks is actually a talus accumulation.

Landslides occur mainly in areas underlain by a fairly thick mantle of weathered residuum or soil. Slides originate at or near the heads of steep ravines and are most numerous in the southwest quarter of the Ciales quadrangle.

### RESIDUUM

Deep residual material, including soil and saprolite, are relatively restricted in the Ciales quadrangle. The soil is characteristically thin and contains many rock fragments. The general lack of deep residuum in a tropical area where formation of deep soils would be expected is a result of rapid erosion. Both high relief and high rainfall are factors in the rapid removal of rock debris and soil. A measure of the rapidity of erosion in areas of moderate to deep residuum was afforded by comparing ground level beneath the floors of houses with ground level beyond the shelter of the house. The typical rural house is supported by four pillars. Usually, after a period of about 5 years, the ground level around the house is ⅓–½ meter lower than the ground beneath the house where it has been protected from rainfall. In one example where a house was built at the crest of a narrow ridge, extensions more than a meter long had been added to the original pillars after 20 years. Even allowing for accelerated erosion of the barren ground around the houses, largely as a result of the pounding action of raindrops which loosen the soil, the removal of ⅓–½ meter in 20 years must be considered a rapid rate of erosion.

The most extensive areas of deep soil and saprolite are in the southern half of the quadrangle along the crests of the ridges that lie east and west of Quebrada Riachuelo, and along the ridge that parallels the boundary between Municipio de Morovis and Municipio de Orocovis. A small area of deep soil lies near the east-central edge of the quadrangle and extends eastward out of the quadrangle. In these areas soil and saprolite locally exceed 4 meters in depth. These general areas of deep residuum are shown on figure 22. Soil and saprolite are moderately deep (2–3 meters) in the belt between the middle Tertiary deposits and the Río Grande de Manatí fault. The thicker soils in this part of the quadrangle are preserved because of more gentle relief and a thicker cover of vegetation than are found in the southern part of the quadrangle. Some of the residuum in the central belt may have been on the pre-middle Oligocene surface.

The areas of deep residuum coincide with areas underlain by lava, except for the large area near Morovis which overlies granodiorite. Color is commonly reddish, but ranges from brick red to hues of light

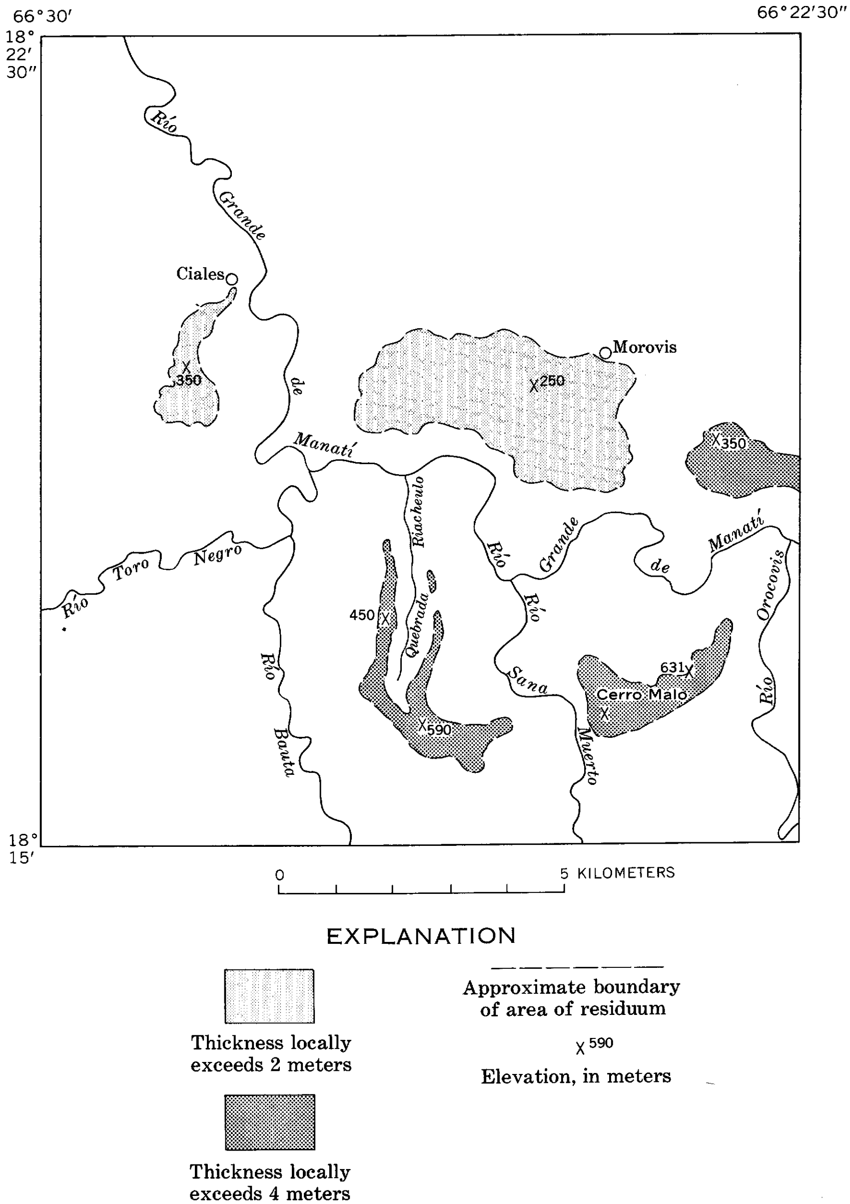



FIGURE 22.—Map showing areas in Ciales quadrangle where thickness of residuum locally exceeds 2 meters.

reddish brown. The soil layer at the top is silty clay with rock fragments, and its thickness seldom exceeds 1 meter. The soil grades downward into clayey saprolite that may be as much as 3–4 meters or more thick.

Although some soil is being formed today on the flatter upland summits of the quadrangle, the topographic position of the more extensive areas of deep residuum in the southern part of the quadrangle suggests that this residuum is remnant material of Pliocene and early Pleistocene age that as yet has not been removed by Recent erosion. The former extent of deep residuum over the quadrangle is not known but possibly such material developed extensively in Miocene and early Pliocene time when relief was much more subdued than it is today.

Saprolite that formed on the pre-middle Oligocene surface was observed at one place in the quadrangle, and both soil and saprolite were observed at one locality in the adjacent Corozal quadrangle. The thickness of soil and saprolite at the Corozal locality (2 meters) is roughly comparable to the depth to which Miocene to Recent weathering has proceeded in the central belt of the Ciales quadrangle.

## STRUCTURE

The structure of the Ciales quadrangle is marked by elements of strikingly diverse character. The Upper Cretaceous and the Upper Cretaceous or lower Tertiary volcanic rocks of the southern two-thirds of the quadrangle have been subjected to profound diastrophic movements and in the process have been extensively faulted and warped and injected with plutonic intrusives. The middle Tertiary rocks, which rest unconformably on the volcanic complex, form a homocline that reflects gentle uplift. The structural relations of the rocks in the quadrangle are shown in the geologic sections on plate 3.

The structural features of the Ciales quadrangle are the result of two main periods of movement. Although local uplifts and related collapse or sag features probably accompanied Late Cretaceous volcanism, the earliest period of deformation for which there is positive evidence occurred either in very Late Cretaceous or in early Tertiary time. Inconclusive evidence suggests either a Paleocene or early Eocene age for this diastrophism. The diastrophism was of orogenic intensity and Upper Cretaceous or lower Tertiary eugeosynclinal(?) deposits were elevated to form part of a mountainous belt. The early Tertiary(?) deformation was in part differential vertical movement and in part compressional movement with a significant amount of strike-slip faulting and warping of separate blocks. Since middle(?) Miocene time the Ciales quadrangle has undergone gentle regional uplift, presumably as a part of a broad anticlinal arching of the entire island.

In a regional sense, the Ciales quadrangle is on the north side of the Puerto Rico anticlinorium. The relation of structures in the Ciales quadrangle to the anticlinorium is shown on figure 23.

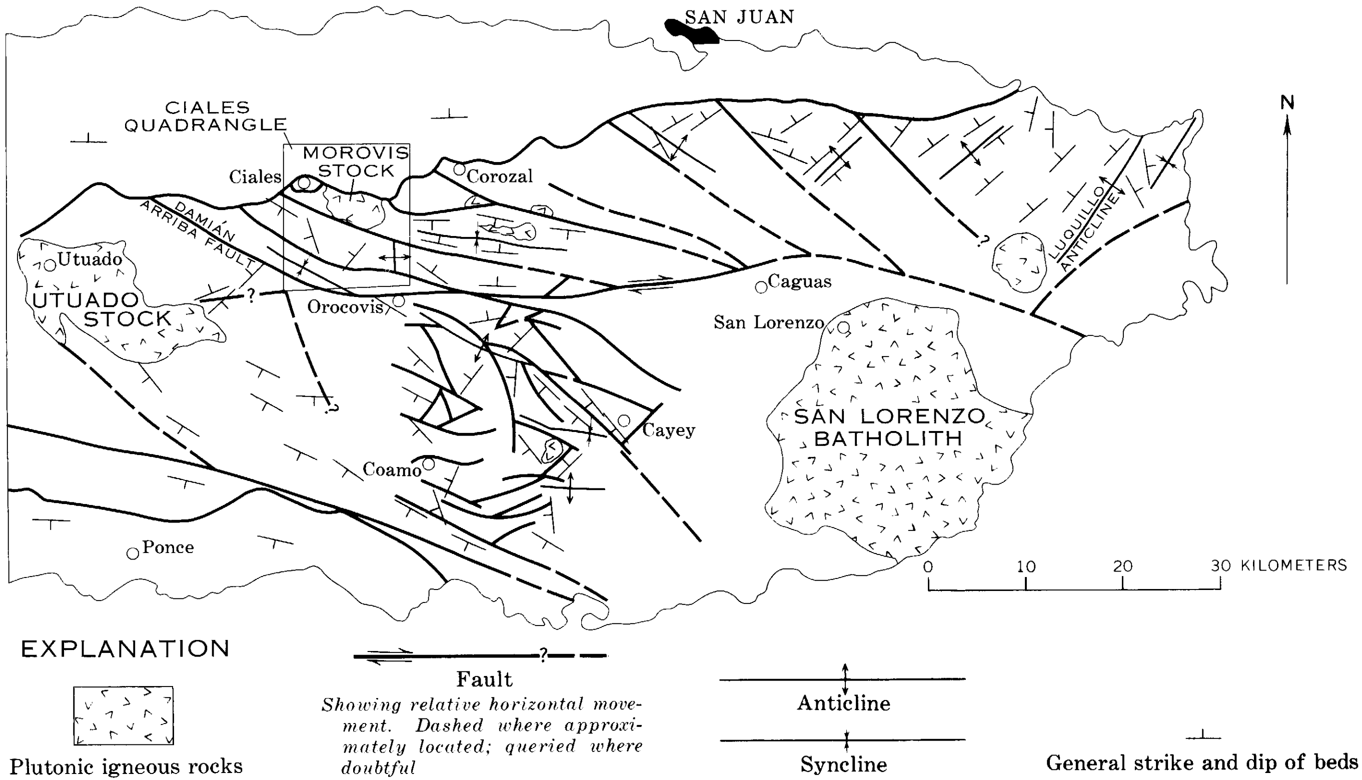



FIGURE 23.—Tectonic map of eastern Puerto Rico.

## STRUCTURE OF UPPER CRETACEOUS AND UPPER CRETACEOUS OR LOWER TERTIARY ROCKS

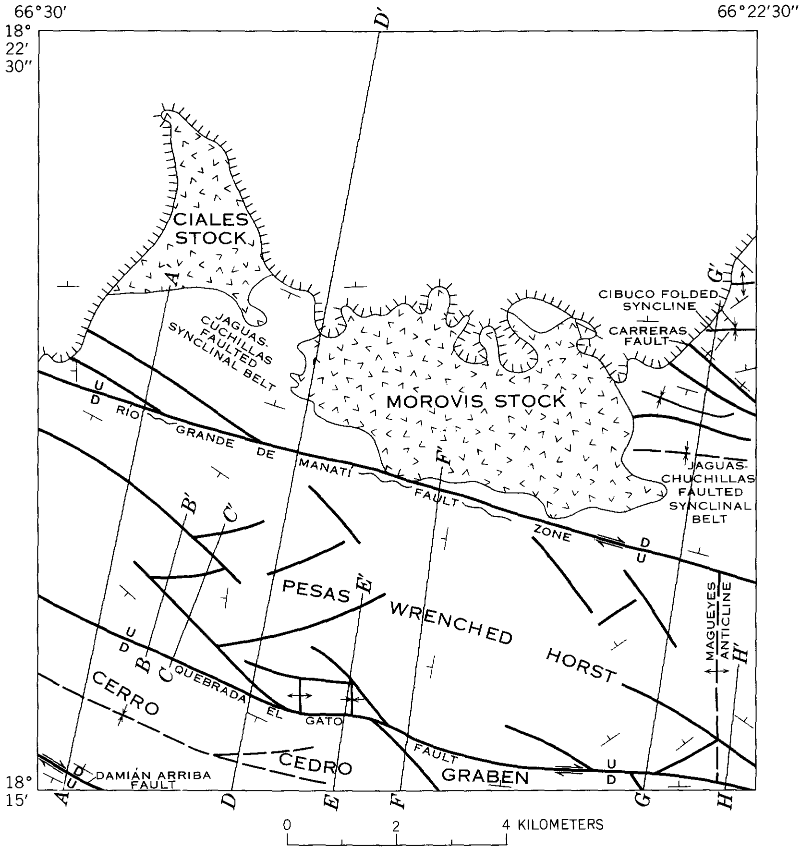
The Upper Cretaceous and Upper Cretaceous or lower Tertiary rocks have been separated into three linear west-northwestward-trending blocks by regional faults that also trend west-northwestward. These blocks, which extend beyond the Ciales quadrangle, are from south to north: the Cerro Cedro graben, the Pesas wrenched horst, and the Jaquas-Cuchillas faulted syncline. At the east-central edge of the quadrangle is a small part of a fourth block, the Cibuco tilted syncline whose southern limb has been strongly folded. The relations of the blocks are shown on figures 24 and 25 and on plate 3. The faults between the crustal blocks are really fault zones, or fault complexes that have been loci for both vertical and strike-slip movements.

The general west-northwest structural trend in the Ciales quadrangle probably was inherited from structural trends established during Late Cretaceous volcanism. For example, belts of thick pillow lavas trend west-northwest across eastern Puerto Rico, roughly parallel to the regional faults, and suggest that centers of Late Cretaceous volcanism developed along a northwest-trending belt of regional weakness. This belt subsequently became a belt of intensive faulting and a passageway for rising sialic magma very late in the Cretaceous or early Tertiary time. The rising magma possibly also caused regional doming and tensional faulting. Descriptions of the principal early Tertiary(?) structures of the Ciales quadrangle follow.

### CERRO CEDRO GRABEN

The subsided block that underlies the southernmost part of the Ciales quadrangle is a segment of an arcuate collapsed structure that trends west-northwest for 30 km across north-central Puerto Rico (fig. 5). In the Ciales quadrangle it lies between the Damián Arriba and Quebrada El Gato faults (fig. 24). The term "graben" is applied to this block with some qualification because, in addition to having subsided relative to adjacent blocks, it has been folded, rotated southeastward, and highly faulted. The present shape and structure of the graben were formed by the same lateral movements that shaped the adjacent warped crustal block to the north. (See pl. 3, section *H–H′*, and pl. 1.)

The Cerro Cedro graben possibly originated in very Late Cretaceous time as a crustal sag (volcano-tectonic collapse) above a magma chamber, for it seems to have been a locus for accumulation of ash-flow deposits. (See discussion of Blacho Tuff Member, this report, and Berryhill, 1961.) The present shape of the graben was subsequently determined largely by early Tertiary(?) diastrophism.




## EXPLANATION

Contact between area of gently dipping rocks and structurally complex area

Fault
*Dashed where approximately located. U, upthrown side; D, downthrown side. Arrows show relative horizontal movement. Wavy line indicates fault zone containing several fault planes*

Anticline
*Dashed where approximately located*

Syncline
*Dashed where approximately located*

Strike and dip of beds

Strike of vertical beds

*A*———*A'*
Line of section
*See geologic section plate 3*

FIGURE 24.—Tectonic map of Ciales quadrangle.

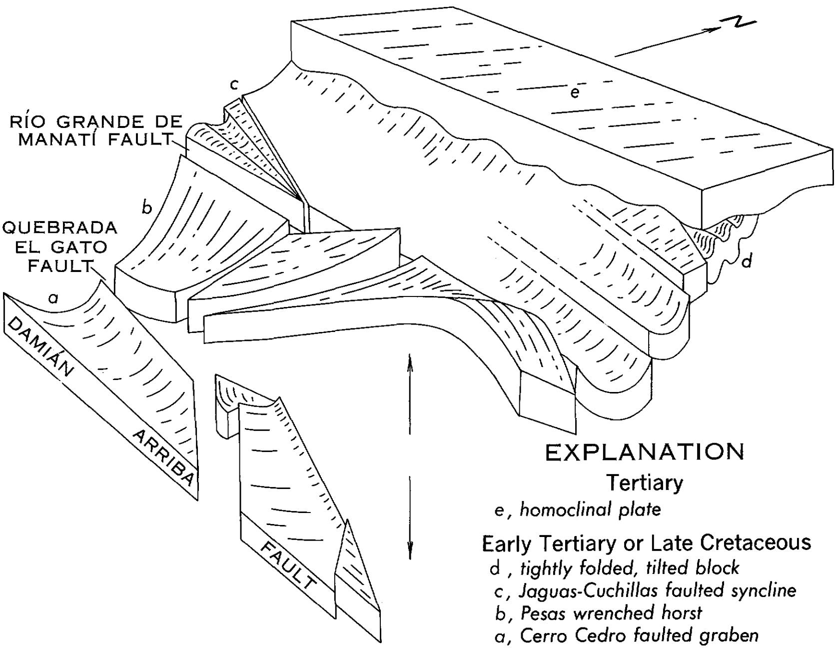



FIGURE 25.—Diagram showing configuration and relations of principal structural elements.

The Cerro Cedro graben has a width of about 3 km in the Ciales quadrangle, and is bounded on the southwest by the regional Damián Arriba right-lateral(?) transcurrent fault and on the northeast by a subsidiary tear fault that bends southeastward and intersects the main transcurrent fault in the adjacent Barranquitas quadrangle. The graben plunges toward the southeast, and at the southeast corner of the Ciales quadrangle stratigraphic displacement along the northeast side of the graben is more than 3,000 meters. This displacement seems to have resulted from a combination of subsidence of the graben and upbuckling of the anticline in the Pesas wrenched horst. A diagonal northwest-trending tear fault crosses the graben in the south-central part of the quadrangle, dividing the graben into two main parts. The western part is a depressed, roughly symmetrical but faulted syncline having steep dips along the outer edges. Toward the northwest the syncline becomes wider, displacement along the northeast side decreases, and the graben merges with the western part of the Pesas wrenched horst (pl. 1; fig. 25).

The eastern part of the graben is for the most part a subsided block with a northward tilt, except locally along the north edge where strata in the block are upturned. This block has been subdivided by a diagonal tear fault so that the part of the block west of highway

155 has been downfaulted more than the part east of the highway. Rocks in the northwest corner of the block west of Highway 155 have become detached from the main block and compressed into a small syncline. Figure 26 shows the structural relations in the Cerro Cedro graben from west to east.

Although the Cerro Cedro graben could be interpreted as a ramp formed by northeast-southwest compression, the wedge shape of the southeast end of the graben, the rotation of the graben toward the southeast, and the shape of the adjacent wrenched horst are not readily explained by this type of force. Greater displacement of the southeastern part of the graben possibly resulted in large part from tension created at the juncture of the Damián Arriba and Quebrada El Gato faults (fig. 27). Movement along the Damián Arriba fault is considered to have been right lateral; the Quebrada El Gato fault is thought to have formed later as a subsidiary tear. Thus bounded on both sides by strike-slip faults, the Cerro Cedro graben became a detached block that was dragged westward with the larger crustal block south of the Damián Arriba fault. The westward movement tended to pull the southeast end of the graben away from the Quebrada El Gato fault, thus causing tension and gravity sag at and near the juncture of the faults. Because of the west-northwest to east-southeast orientation of the force causing strike-slip faulting, compression was also exerted against the graben and some high reverse movement accompanied the normal faulting. The mechanism of displacement is shown on figure 27, which is based upon the mechanical analyses of Lensen (1958). Lensen's interpretations are drawn from studies of

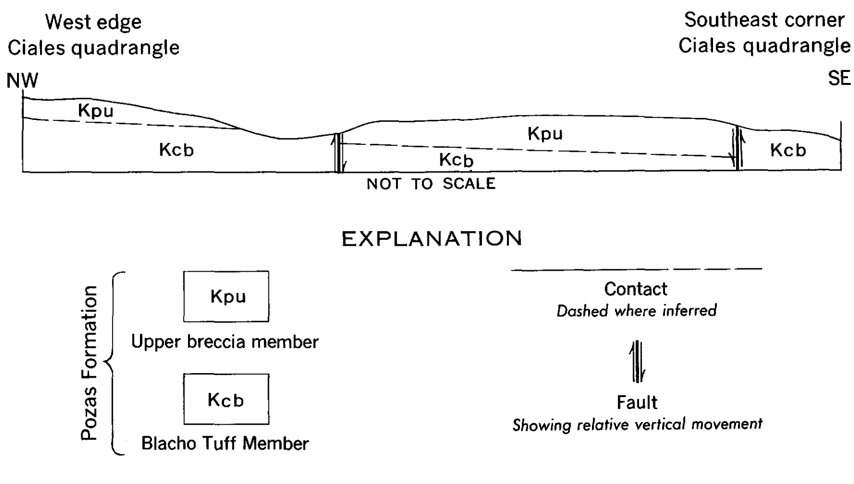



FIGURE 26.—Diagram showing generalized northwest to southeast structural relations in the Cerro Cedro graben.

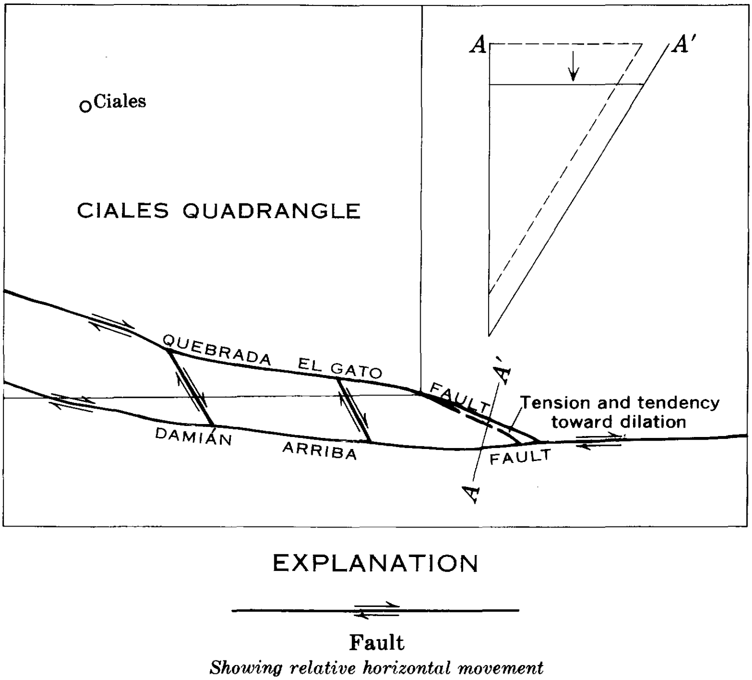



FIGURE 27.—Relation of fault movements and displacement mechanism for southeastern part of the Cerro Cedro graben.

graben and horst structures along the great Alpine transcurrent fault of New Zealand, though the structures described by him are smaller and less complicated than those in Puerto Rico.

### PESAS WRENCHED HORST

The principal features of the Pesas wrenched horst in the Ciales quadrangle are the cross buckle, here called the Magüeyes anticline (fig. 24); the torsional faults and fractures that trend in general either northwest or northeast and form a crisscrossed mosaic pattern; and the crude rhombohedral blocks that were formed by faulting during torsional movement. The Magüeyes anticline plunges sharply northward and is terminated by the Río Grande de Manatí fault. Folding of the Magüeyes anticline is believed to have resulted from horizontal stress acting on the Pesas horst block. A matching part of this fold is not present in adjacent structural blocks, and there is no evidence that the anticline is a truncated prefaulting structure. The faults in the Pesas wrenched horst were formed by torsional movement, and their pattern is similar to the pattern of tension cracks that form in a piece of safety glass when subjected to torsional twisting. The criss-

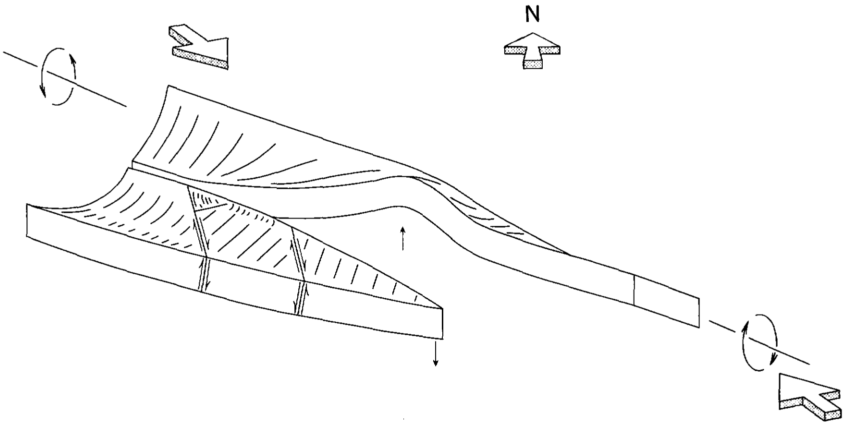



FIGURE 28.—Diagram of mechanism for deformation of the Pesas wrenched horst. Small arrows indicate relative vertical movement; large arrows indicate direction of compressional forces.

crossed tension faults seem to be concentrated in the eastern and western parts of the horst where wrenching was most pronounced.

The Pesas wrenched horst is interpreted as a regional compressional feature formed as a result of strike-slip movements along the Damián Arriba fault. To the writer's knowledge, a structure of this type has not been previously described. Wrenching of the horst probably was caused by torsional movement reacting to horizontal couples from the west-northwest and east-southeast. Thus the northwestern part of the horst is tilted toward the southwest and merges with the Cerro Cedro graben; the southeastern part is inclined in the opposite direction or toward the north and northeast (fig. 25). The horst is a wedge-shaped block that was segregated by tear faulting along the regional Damián Arriba transcurrent fault (fig. 23); uplift is attributed to horizontal compression which squeezed the horst block in a west-northwest-east-southeast direction, causing it to warp and buckle. This buckle or anticline, which lies at the southeast corner of the Ciales quadrangle, is a cross structure that trends northward almost perpendicular to the trend of the horst. The mechanism for the deformation of the horst and its relation to the Cerro Cedro graben are shown on figure 28.

### JAGUAS-CUCHILLAS FAULTED SYNCLINAL BELT

The west-northwest-trending Jaguas-Cuchillas belt is structurally complex, but it seems to be either a syncline or several narrow synclines that have been almost obliterated by faulting and intrusion of the Morovis and Ciales stocks. The syncline has been split lengthwise into a series of narrow blocks by high-angle strike-trending faults.

(See figs. 24, 25.) In view of the complexity of the Jaguas-Cuchillas belt, it is questionable whether the synclinal structure of the narrow blocks between faults is a result of splitting of a syncline, or whether the narrow blocks were compressed into down flexures and tilted after faulting.

The synclinal structure of the Jaguas-Cuchillas belt is well demonstrated by plate 3, section *G–G′*. To the west the belt has been cut into slices by tear faults that branch northwestward from the Río Grande de Manatí transcurrent fault, and the synclinal structure is less obvious. The southernmost of these slices seems to have rotated clockwise by strike-slip movement. The adjacent small graben is interpreted as a gravity feature formed by the same general process as that described for the Cerro Cedro graben.

Faulting within the Jaguas-Cuchillas belt was probably due in part to pressure from rising magma during upward movement of the Morovis and Ciales stocks and in part to strike-slip faulting that took place before emplacement was complete. However, the general absence of upturned rocks around the stocks suggests that the Jaguas-Cuchillas belt was already a highly fractured zone that served as a relatively easy passageway for rising magma. That the Jaguas-Cuchillas belt was under stress from a general east-west horizontal couple during intrusion of the granodiorite of the Morovis and Ciales stocks is indicated by the orientation of roof pendants and of joints in these stocks. The west-northwest and east-northeast trend of the pendants and joints is similar to the trends of tension faults in the Pesas wrenched horst.

In the Ciales quadrangle the Damián Arriba fault (pl. 3, *A–A′*) is attended by a sheared and crushed belt at least a hundred meters wide. Including the associated faults that form a mosaic pattern, the Damián Arriba fault zone is at least a kilometer wide. Fault planes in the zone are inclined from near vertical to about 45°, and high-angle reverse, normal, and strike-slip movements have taken place on them. Striations on all slickensided surfaces observed along the fault are horizontal, indicating that the final movement along the Damián Arriba fault was strike slip. Local pyritization, silicification, and small-scale veining in the fault zone indicate possible hydrothermal action along the Damián Arriba fault zone.

### CIBUCO SYNCLINE

The Cibuco syncline, which lies mostly in the Corozal quadrangle, is an asymmetrical tilted faulted flexure that is bounded by faults, along which Late Cretaceous or early Tertiary rocks are in juxtaposition with the basalt tuff member of the Río Orocovis formation of Late Cretaceous age. Figure 16 shows the areal extent and generalized structure of the syncline. Along the eastern edge of the Cibuco syncline in the Corozal quadrangle, granodiorite has emplaced itself along the fault that has truncated the east end of the syncline.

The small part of the Cibuco syncline within the Ciales quadrangle is a part of the tightly folded southern limb of the syncline (pl. 3, section *G–G′*).

### DAMIÁN ARRIBA FAULT

The Damián Arriba fault, which crosses the southwestern part of the Ciales quadrangle, is the northwestward extension of a regional arcuate transcurrent fault that crosses eastern Puerto Rico in a general east-west direction (fig. 23a). The regional relations of the fault have been described by Berryhill and others (1960) and by Berryhill (1959). The crustal block south of the fault seems to have moved westward relative to the block north of the fault, although both blocks have been extensively broken by tear faults, and subsidiary blocks formed by the tear faults have been tilted and deformed.

### QUEBRADA EL GATO FAULT

The Quebrada El Gato fault, which is the boundary between the Cerro Cedro graben and the Pesas wrenched horst, is a tear fault that probably formed as a subsidiary to the Damián Arriba fault. The Quebrada El Gato fault is a sinuous structure with numerous associated branching mosaic faults and small tear faults that locally offset the main fault. The Quebrada El Gato fault in the southern part of the Ciales quadrangle splits into a series of secondary tear faults that form a horsetail pattern, indicating a decrease in strike-slip toward the northwest. These secondary tear faults merge with tensional faults in the Pesas wrenched horst. The Quebrada El Gato fault is offset by two cross faults in the southeastern part of the area, which indicates that normal faulting attended strike-slip movement locally. It is possible that the part of Quebrada El Gato fault from the middle of the quadrangle to the southeast corner is either a normal or high-angle reverse fault rather than a strike-slip fault. The branch that continues about S. 40° E. into the Orocovis quadrangle may be the strike-slip part.

### RÍO GRANDE DE MANATÍ FAULT ZONE

The Río Grande de Manatí fault zone, whch separates the Pesas wrenched horst from the Jaguas-Cuchillas faulted syncline, is a complex of faults forming a zone in which small-scale drag folds and tear fractures are common. The fault zone probably is a tear feature that formed as a result of strike-slip movement along the Damián Arriba fault. Secondary mineralization has occurred along the faults of the zone, probably in large part as a result of hydrothermal action, and injection of granodiorite along cleavage planes within the fault zone has formed gneissic or migmatitic structures locally. Pyrite, epidote, chlorite, and silica are locally abundant.

At its eastern and western extremities in the Ciales quadrangle the Río Grande de Manatí fault zone is well defined, but its central part seems to have been in part obliterated by the Morovis stock. Near the east edge of the quadrangle in the saddle north of Cerro Magüeyes the fault zone is marked by a wide belt of highly foliated rocks and low-grade schist. In the western part of the quadrangle a well-defined fault can be traced from the Río Bauta northwestward to the edge of the quadrangle. Elsewhere, along the south side of the Morovis stock between the Río Bauta and Highway 155, the Río Grande de Manatí fault is a complex consisting of many faults that form a mosaic pattern, and no single fault plane can be traced with certainty for any great distance. Locally, deformation along this part of the fault has been very intense, and the mechanism by which slices of dissimilar rock have become so oddly associated in the fault complex is not easily explained. This is especially true west of Quebrada Riacheulo, where the fault complex seems to flare into a series of secondary tear faults. Possibly in this area the Río Grande de Manatí fault complex cuts through older fissures and orifices that served as outlets for expulsion of lava and tuff of the Pozas Formation. Other blocks in the fault complex seem to be horses whose positions are the result of drag.

Because the structural blocks north and south of the Río Grande de Manatí fault zone reacted differently to regional stress, movement along fault planes within the zone differed in direction from southeast to northwest along the zone. Rocks within the Jaguas-Cuchillas synclinal block north of the fault zone have a general west-northwestward strike and are virtually in the same stratigraphic position all along the fault zone. Rocks within the Pesas wrenched horst south of the fault zone were warped into cross buckles that are perpendicular to the west-northwest-trending long axis of the horst, and stratigraphic displacement on the fault varies more than 3,000 meters. Upbuckling of the Magüeyes anticline raised rocks south of the fault zone relative to those north of the fault zone; downbuckling of rocks in the Pesas block in west-central Ciales quadrangle lowered rocks south of the fault zone relative to those to the north. Strike-slip displacement that accompanied the vertical displacement along the fault zone was of the magnitude necessary to accommodate the southeast-northwest shortening of the Pesas wrenched horst caused by crossbuckling. The segment of the fault zone that extends roughly 1.5 km east and west of Quebrada Riachuelo is at a pivotal point between the Magüeyes anticline to the east and the downbuckle to the west. Consequently, relative displacement of rocks in this segment was small, as is indicated by the slight offset of the distinctive reef limestone of the Avispa lava member on opposite sides of the fault zone. Significantly, this is the area of most intense fracturing along the fault zone, and it is also the part of the zone where tracing of a throughgoing fault plane is most difficult.

The development of the Río Grande de Manatí fault zone is believed to have been controlled by stresses acting along the Damián Arriba fault (fig. 23*A*). Just south of the Ciales quadrangle, the Damián Arriba fault bends about 45° from a northwest trend to an east-west trend. The many tear faults in the western part of the quadrangle, including those associated with the Río Grande de Manatí fault zone and those in the Jaguas-Cuchillas block south of Ciales, lie directly north of this bend and probably reflect changes in the pattern of stresses in the region of the bend. As this type of faulting is not present along the Río Grande de Manatí fault farther east, the rocks on the south side of the Damián Arriba fault may have acted as a buttress against stress acting from the northwest through the rocks in the Ciales quadrangle. The resulting strain took the form of the many tear faults and the general mosaic fault pattern.

## METAMORPHISM

Most of the metamorphism in the Ciales quadrangle is associated with diastrophism and therefore must be attributed either directly or indirectly to dynamic movement. A low-grade chloritization is common to most volcanic rocks in the quadrangle, but it is difficult to say whether this is secondary or deuteric in origin. In general, metamorphism induced by igneous intrusives seems to have been mild and localized. Where igneous action has played a part, either directly or indirectly, in rock alteration, as along faults and near intrusives, its role, largely in the form of hydrothermal emanations, was probably concomitant with dynamic movements.

Mechanical transformation of rocks from one form to another has taken place along all the principal faults, although the extent of alteration varies. Highly foliated rocks, including low-grade schists, are the most prevalent metamorphic forms. Rocks along the Damián Arriba fault and also along the part of the Río Grande de Manatí fault complex south of the Morovis stock seem to have been pulverized and subsequently annealed to the extent that the fault zone has been virtually healed. Heat for the annealing of these rocks might have developed by intense dynamic pressure along the faults, but more likely the heat came from underlying magma and was escaping along the faults. Where the rocks have been annealed, mineralogic transformation has occurred as a result of heating and perhaps also as a result of the action of escaping volatiles. Ferromagnesian minerals have been altered to chlorite and epidote; plagioclases have been highly sericitized; and pyrite, silica, calcite, and orthoclase have been introduced. Pyrite is especially abundant, particularly along all major fault zones, near the larger intrusives, and along the Jaguas-Cuchillas faulted belt where emanation from the Morovis and Ciales stocks seems to have penetrated the faulted country rocks. The healed condition of the faults strongly suggests that faulting and intrusion of plutonic igneous rocks were contemporaneous, and that the faults acted locally as escape routes for volatiles and excess heat. General conformity of veins and secondary mineralization to the shape of drag folds and fractures in the fault zones further suggest that mineralization was contemporaneous with faulting and not with postfaulting. The relative scarcity of veins in the fault zone suggests either that the rising magma was deficient in water or that the present erosion surface is still well up in the epizonal region and large veins which might lie at depth have not been reached. Possibly most of the volatiles associated with the stocks were expelled during eruption of dacitic ash flows in very Late Cretaceous time.

Rocks that seem to have undergone intense hydrothermal alteration are restricted to a small band about 7 meters wide that crops out in the west bank of Highway 155 about 1.4 km north of the south edge of the Ciales quadrangle. The rocks in this outcrop have a conspicuous red and brownish-white color and are rich in hematite and silica. A small amount of copper oxide was found in these rocks.

Except along the faults and immediately adjacent to large intrusives, rocks of the Ciales quadrangle show little megascopic evidence of metamorphism. However, when viewed with the microscope, most of the rocks, except the Morovis and Ciales stocks, show extensive albitization and some secondary silicification, which is most pronounced in the Jaguas-Cuchillas faulted belt near the Morovis and Ciales stocks. Source of the albite has been discussed on pages 42 and 43. Much of the microscopic silica is presumed to have been introduced during invasion of granodioritic magma; however, it is possible that some of the silica is of deuteric origin and was an end product "sweated out" of thick piles of slowly cooling pillow lavas.

## STRUCTURE OF THE MIDDLE TERTIARY ROCKS

The structure of the middle Tertiary rocks is a simple homocline having a northward dip of about 4°–5° (pl. 3, section *D–D′*). The northward dip is in part a result of deposition on a gently inclined surface and in part a result of mild regional uplift in post-early Miocene time.

Deformation of these rocks is confined to a single normal fault in the northeastern part of the quadrangle. Displacement along this fault is less than 10 meters. A gentle east-west-trending flexure, which Monroe (1958) has called the Quebrada Arenas anticline, lies a short distance northeast of the Ciales quadrangle in the Manatí, Corozal, and Vega Alta quadrangles.

The conspicuous alinement of sinks and the narrow linear form of sinks and ridges in the areas of well-developed karst topography suggest that solution of the limestone has been controlled to a considerable degree by a system of joints. The joints(?) are most pronounced in the massive relatively homogeneous Lares Limestone. Two general directions of lineation are evident, N. 20°–40° W. and N. 50°–60° E. The two lineations are of about equal prominence west of the Río Cialitos; the N. 50°–60° E. lineation is the more prominent between the Río Cialitos and the Río Morovis, and a N. 21° W. trend is predominant east of the Río Morovis. The abruptness with which the lineation changes from N. 50°–60° E. to N. 20° W. in the central part of barrio Franquez suggests a fault having a trend of about N. 20° W. A fault plane was not found, but considering the extensive solution of the limestone and cover of sugar cane in the area, a fault of small displacement would be difficult to detect.

The lineations in the middle Tertiary rocks possibly formed during post-early Miocene uplift as a result of a mild regional horizontal couple.

## GEOMORPHOLOGY

The topographic features of the Ciales quadrangle are related to the structure of the underlying rocks. Development of the topography is the result of two periods of uplift. The general drainage pattern of the southern two-thirds of the quadrangle, including courses of master streams, probably has been inherited from the pre-middle Oligocene erosional surface. Present land forms have been sculptured by post-early Miocene uplift and erosion.

### EARLY TERTIARY(?) SURFACE

Orogenic movements, probably in early Tertiary(?) time, uplifted the general Ciales region to form a mountainous belt with a surface marked by prominent fault scarps and a trough (Cerro Cedro graben). Considering that these structural features still have prominent topographic expression, and considering the lithologic similarity of the rocks involved, it seems possible that erosion during the early Tertiary(?) orogeny was not sufficiently rapid to modify completely the structural features as they developed.

Drainage on the rising early Tertiary(?) surface formed as a series of northward-flowing consequent master streams whose tributaries adjusted themselves to the rock structures; thus the control of streams by faults is very evident.

As erosion progressed, the early Tertiary(?) surface was at first deeply dissected and then worn down to moderate to gentle relief. The northern part of the Ciales quadrangle seems to have been reduced to a gently northward sloping peneplain that lay very near sea level. A few low hills or monadnocks dotted this peneplain. Remnants of this peneplained surface can still be seen south of Morovis and south of Ciales. According to Lobeck (1922, p. 304–306), the period of pre-middle Oligocene erosion included two stages of uplift and development of two peneplained surfaces in northern Puerto Rico. If two such surfaces developed in the Ciales quadrangle, evidence for them has been destroyed by erosion. Topographic profiles across the quadrangle show a series of summits whose elevations decrease progressively northward and merge with the northward-sloping surface at the base of the middle Oligocene rocks.

Before middle Oligocene submergence, the geomorphic cycle in the Ciales quadrangle had proceeded to late maturity or old age. Relief was relatively low and streams had formed meandering courses across the gentle surface. The quantity of rock removed during the early Eocene to middle Oligocene erosional interval seems to have been large, for plutonic intrusives were extensively exposed. The thickness of cover carried away may have been as much as 4 km.

### EFFECTS OF POST-EARLY MIOCENE UPLIFT

After middle Oligocene submergence, stream valleys of the Ciales quadrangle became drowned and ultimately filled with estuarine sand and gravel. Possibly all the Ciales quadrangle ultimately was covered by middle Tertiary deposits.

With the beginning of uplift in early Miocene time, the landward edge of the middle Tertiary coastal plain appeared above sea level and extended consequent streams developed across the newly uplifted surface. These streams subsequently adjusted themselves to pre-middle Oligocene channels, and, as post-early Miocene uplift and erosion proceeded, the pre-middle Oligocene drainage was resurrected. In the earlier stages of uplift, erosion consisted of stripping of middle Tertiary deposits from the landward edge of the coastal plain and removal of the limestone and estuarine gravels from the buried stream valleys. Resurrection of the pre-middle Oligocene drainage pattern probably was not the simple process of streams downcutting into their older buried channels. Instead, a system of underground drainage probably developed in the porous gravel and soluble limestone that filled the buried valleys. The valleys that now trench the coastal plain probably were formed largely by collapse of beds above the subterranean drainage lines. This process has been described by Lobeck (1922, p. 329–330).

In later stages of uplift, possibly in Pliocene time, the resurrected drainage system became rejuvenated, and incisement occurred along the meandering courses that had been established in pre-middle Oligocene time. During Recent time, downcutting along major streams has been so rapid that small tributaries to main courses have been left to run in hanging valleys in much the same manner as hanging valleys are formed adjacent to principal glacial valleys. Hanging valleys lie north of the Río Grande de Manatí near the confluence with the Río Orocovis. As a result of rejuvenation some early Tertiary structures that had been modified by pre-middle Oligocene erosion were once again etched into relief; others, such as the Cerro Cedro graben, that had been buried beneath middle Tertiary deposits were uncovered.

Erosion of the northward-dipping middle Tertiary deposits has formed a belted coastal plain that consists of a main cuesta, a secondary cuesta, and an intervening broad lowland marked in places by karst topography.

Strath terraces along the Río Grande de Manatí indicate that post-early Miocene uplift was not steady but progressed in stages. The prominent terraces that lie at an elevation of 90–100 meters indicate temporary cessation of uplift and stream aggradation probably in early Pleistocene time. A few level surfaces or shoulders adjacent to streams at elevations of 200–250 meters suggest an earlier stage of aggradation during Pliocene time. Minor adjustments of drainage are evident from the abandoned meanders of the Río Toro Negro and the Río Bauta near their confluence.

## PRINCIPAL GEOMORPHIC FEATURES

In the foregoing sections the historical development of the land surface of the Ciales quadrangle was discussed. Several of the more prominent geomorphic features will now be described and related to geologic structures.

Dissected scarps clearly outline the faulted north and south boundaries of the Cerro Cedro graben. The southwestward-facing scarp north of the graben is more subdued than the scarp south of the graben. Entrenchment of some streams, such as the Río Matrullas and the Río Culebra, along the fault zones, and the development of short ravines, such as Quebrada Quintero and its eastern unnamed counterpart, parallel to faults have further accentuated the boundaries of the graben. The landforms associated with the graben, although re-etched following post-early Miocene uplift, probably have been inherited from early Tertiary(?) deformation and uplift. Since uplift in post-early Miocene time, the central part of the graben has been deeply trenched by the Río Bauta, leaving dissected remnants of the pre-middle Oligocene surface in the southwestern and southeastern parts of the quadrangle. A view of the easternmost of these two remnants of the pre-middle Oligocene surface and also of the prominent northeastward-facing scarp along the Damián Arriba fault are shown in figure 29, which was taken from locality 27 on Highway 155 looking southwest. The Quebrada El Gato fault, which is the northeast boundary of the graben, lies in the northwest-trending valley in the foreground of figure 29. The camera was located at the top of the subdued scarp along the northeast side of the graben. A more extensive view of the Damián Arriba fault scarp and of the deeply dissected central part of the Cerro Cedro graben is shown on figure 5.

Outstanding examples of fault control upon stream development are the adjustment of the Río Grande de Manatí to the Río Grande de Manatí fault and the Río Matrullas to the Damián Arriba fault. From the confluence with the Río Bauta southeastward into the Corozal quadrangle, the Río Grande de Manatí meanders along this fault. That part of the Río Grande de Manatí east of the confluence with the Río Bauta apparently formed in early Tertiary time as a subsequent tributary to the Río Bauta. With progressive erosion in pre-middle Oligocene time, the Río Grande de Manatí developed a

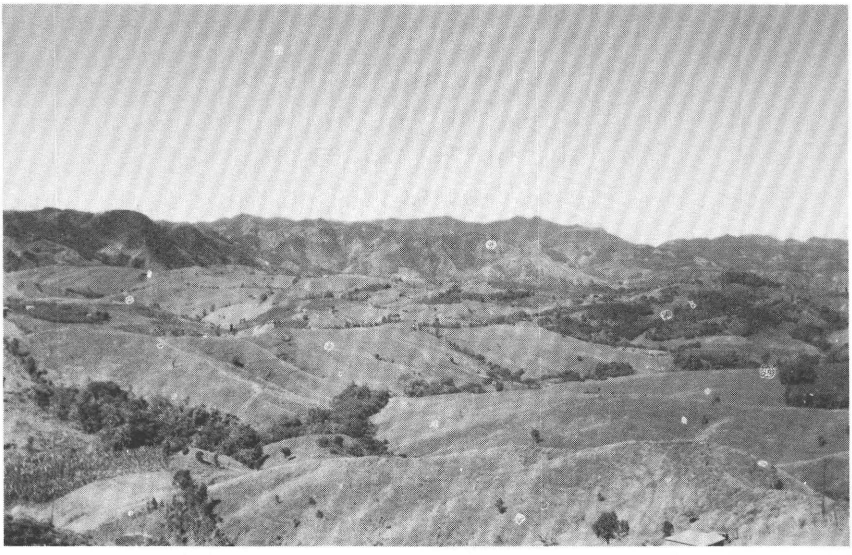


FIGURE 29.—View toward southwest of a probable remnant of the pre-middle Oligocene surface in the eastern part of the Cerro Cedro graben. Taken at locality 27 (pl. 1). Northeast boundary of graben lies in the northwest-trending valley in foreground. Prominent scarp in distance parallels Damián Arriba fault along southwest boundary of graben.

meandering course. Incisement along this course followed post-early Miocene uplift.

The karst topography of the coastal plain limestone belt has been formed by the subterranean percolation of ground water and the removal of limestone by solution. Collapse of limestone above the underground drainageways has been the principal mechanism by which the karst has developed. Degree of karst development has been largely determined by the type and purity of the limestone. Karst development is most pronounced over the massive pure Lares Limestone. Karst topography has not developed over the clayey and sandy marl of the Cibao Formation.

The principal or inner cuesta at the southern edge of the Tertiary limestone expresses the resistant nature of the massive Lares Limestone. As the stripping action of erosion has progressed, this cuesta has gradually retreated northward across the quadrangle to its present position. The absence of this feature in the vicinity of Torrecillas and the absence of a karst topography north of Torrecillas is not readily explained. Possibly the Lares Limestone in this area was less pure and more easily eroded. It is remotely possible that in early(?) Pliocene time the part of the Río Grande de Manatí east of the Río Bauta confluence turned northeastward, following a course that roughly paralleled the present courses of Quebrada Grande and the Río Morovis. Assuming such a circumstance, the Lares Limestone of the Torrecillas area would have been removed at that time. Such a circumstance would also have resulted in the subsequent capture of the part of the Río Grande de Manatí east of the Río Bauta confluence by the Río Bauta-Río Toro Negro system.

## ECONOMIC GEOLOGY

The mineral resources of the Ciales quadrangle include copper, galena, barite, limestone, and sandstone. Gold reportedly was taken from the general Ciales region during Spanish colonial days, but no evidence of its presence was found during fieldwork for this report. Sulfides, mainly pyrite, have been deposited along the major faults and along the Jaguas-Cuchillas faulted belt adjacent to the Morovis and Ciales stocks.

The metalliferous minerals copper, galena, and barite lie within the volcanic rocks and plutonic igneous rocks. The distribution of the metalliferous occurrences relative to the structural elements in the Ciales quadrangle is shown on figure 30 and plate 1. All these occurrences are small, and none have been worked commercially.

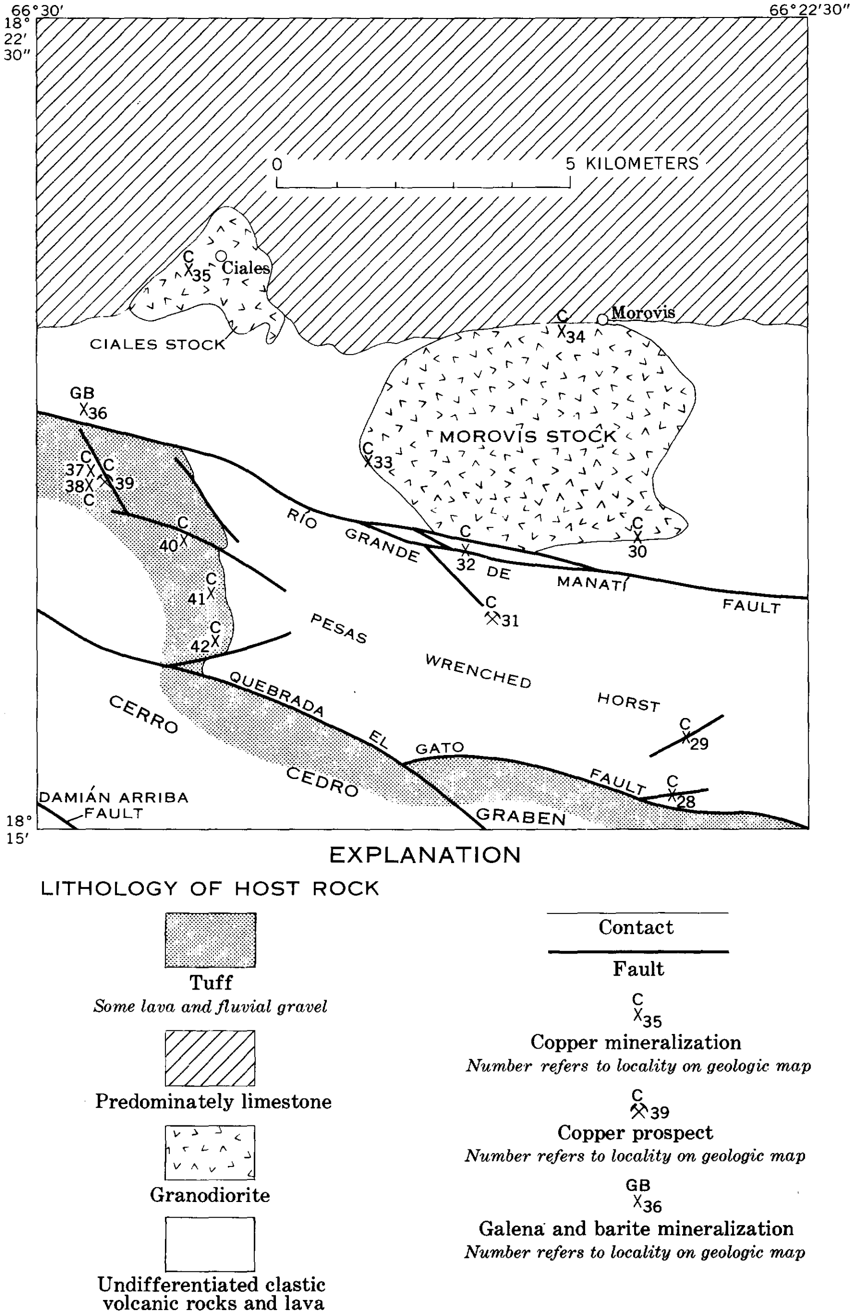



FIGURE 30.—Localities of metalliferous rocks in the Ciales quadrangle.

### COPPER

Copper is the most widespread mineral of possible economic importance in the Ciales quadrangle. It occurs both within the Ciales and Morovis stocks and within the volcanic rocks. The deposits are small veins along faults and fractures and small irregular masses in the Ciales and Morovis stocks and in the volcanic rocks. Associated gangue material is a mixture of zeolites and calcite. No quartz was observed with any of the deposits.

The largest copper-bearing vein observed lies on the east side of Quebrada Honda near the west-central edge of the quadrangle along a small fault that strikes N. 40° W. and cuts the Pozas Formation (loc. 39). The vein has a thickness of 2 meters at the surface and contains what appears to be malachite. The vein thins rapidly toward the northwest, but it can be traced for a distance of more than 100 meters. A small prospect opening was made at one time at locality 39, and about 40 tons of material was removed for analysis.

Several prospects have been opened near the head of Quebrada Minas (loc. 31) along fractures in the Avispa Lava Member. Presumably the copper was in small veins along the fractures, but no trace of copper was found within any of the small prospect openings. Copper oxide stains were observed on pieces of lava rubble that had been removed during prospecting.

Copper oxide stains were seen in the small zone of hydrothermally altered rocks at locality 28 and in basaltic amygdaloidal lava at locality 29. The occurrence at locality 41 consists of disseminated grains of native copper in the Minguillo Lava Member. Other occurrences are small copper-bearing masses within the Morovis or Ciales stock or the Pozas Formation that have been reduced to copper oxide. Chalcopyrite was identified in a few of these masses.

The prevalence of the copper-bearing minerals in masses in the stocks and in the Pozas Formation further substantiates the genetic relationship between the stocks and the Pozas tuff, as discussed on pages 61 and 68.

In view of the indicated structural relations of the faulting to the copper-bearing plutonic bodies and in view of the tendency toward sulfide enrichment along the major faults, prospecting along the larger fault zones, both geochemically and by drilling, might prove profitable in locating larger deposits of copper at depth. This is particularly true of the Río Grande de Manatí fault that crosses the central part of the quadrangle where pyrite has been introduced in moderate amounts. The proximity of this fault zone to the Morovis stock is another favorable factor to be considered in choosing sites for copper prospecting.

### GALENA AND BARITE

Galena and barite are known only from one prospect in the north bank of the Río Cialitos near the west-central edge of the quadrangle (loc. 36). The galena and barite, together with zeolite and calcite, are in a small vein along a fracture that formed as a part of the Río Grande de Manatí fault complex. Several fist-sized pieces of intermixed galena and barite were removed.

## LIMESTONE

The Lares Limestone contains a tremendous quantity of very pure limestone that is suitable for agricultural lime. It might be suitable for manufacture of cement, but should be tested thoroughly before any attempt at such use is made. A quarry for agricultural lime is in operation just east of the Río Grande de Manatí at locality 24. Although the Lares Limestone possesses the massiveness and hardness necessary for building stone and the attractiveness required for ornamental stone, widespread solution channels and cavities render most of the formation useless for these purposes. However, the hardness of the limestone makes it ideal for road metal, both for surfacing and base-course material, and for concrete aggregate. Furthermore, it can be crushed easily and compacted with a roller to form a smooth surface on a strong base course.

The limestone unit at the base of the Avispa Lava Member is a potential source of ornamental stone. Parts of this unit east of the Río Grande de Manatí are thick, the abundance of fossil debris gives the stone a pleasing appearance, and it is free of impurities that cause discoloration on weathering. However, outcrops are relatively limited, and drilling might be necessary to determine whether the limestone is of sufficient quantity to be quarried. This limestone might be suitable for the manufacture of cement, but it should be tested thoroughly before any effort is made to use it for this purpose.

## SANDSTONE

The Almirante Sur Sand Member in the extreme northeastern part of the quadrangle consists of relatively pure sandstone that is ideally suited for use in concrete or building cement. Moreover, the sandstone is friable and easily excavated. Large quantities of sandstone are available in the Almirante Sur Member.

## MISCELLANEOUS BUILDING MATERIALS

The Río Orocovis Formation contains great quantities of lava that could be crushed for use as aggregate and as highway base-course and surfacing material. The lava is somewhat more difficult to crush than limestone, however, and when crushed, it is not so good for a base course as limestone because it is harder, more brittle, and resists compaction. The lava of the Avispa Member should not be used with alkali cement. Andesitic lavas such as those of the Avispa tend to react chemically with the alkali cement, causing structural damage.

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Intermixed alluvial sand and gravel, a commonly used material for concrete aggregate, is limited in quantity within the Ciales quadrangle. Relatively small amounts of this material are obtainable along the Río Grande de Manatí from the central part of the quadrangle northwest to Ciales.

## ENGINEERING GEOLOGY

Almost any civil engineering problem requires a knowledge of the properties of earth materials. Accurate and detailed knowledge of the geologic structure, the occurrence of geologic formations, and properties such as foundation stability, ease of excavation, and slope stability are of great economic importance, whether the problem be selection of sites for dams, tunnels, or buildings; selection of routes for highways; or selection of building materials.

Because the geology of the earth's surface varies from region to region, the problems encountered in engineering practices also vary greatly from one area to another. Consequently, engineering planning is usually guided by economic feasibility, and accurate estimates of engineering costs are dependent upon sound knowledge of the geology of an area.

The engineering properties of the geologic formations in the Ciales quadrangle are tabulated in table 10, which deals with the general characteristics of certain rock types. Detailed tests of rock characteristics should be made where specific sites have been selected for either building materials or excavation. For maximum usefulness, data in table 10 should be supplemented by reference to descriptions of rock types and geologic structures given elsewhere in this report.

TABLE 10.—*Engineering properties of rocks in the Ciales quadrangle, Puerto Rico*

| Lithologic type | Distribution | Excavation | Strength and stability | Utilization | Miscellaneous |
|---|---|---|---|---|---|
| Massive lava | Widely distributed in the Río Orocovis Formation; some in basal part of Pozas Formation. Available for construction throughout much of quadrangle. | Requires blasting and power tools for removal. | Foundation strength generally good for all types of construction. Slope stability is good except along faults and fractures. Mostly impermeable and not susceptible to water seepage except along faults and fractures. | Provides base-course and surfacing material for roads. Possible source for concrete aggregate with low alkali cement. Can be used as fill for earth dams. | Compacts less readily than limestone when applied as road surfacing. The more andesitic lavas should be tested for deleterious reaction with high alkali cement. Weathering loosens pillows near the surface. Consequently, terracing should be considered for high cuts for highways to prevent rock slides. Weathers to clay. Not susceptible to mechanical weathering except at clifflike outcrops. |
| Massive volcanic breccia. | Extensive in the Manicaboa and Pozas Formations. Occurs as thick layers in the Río Orocovis Formation. | Requires blasting and power tools for removal. | Foundation strength generally good for all types of construction. Slope stability is good except along faults and fractures. Mostly impermeable and not susceptible to water seepage except along faults and fractures. | Rock fill for earth dams. Possible source for base-course material. | Weathers spheroidally. Boulders of varied sizes tend to work downslope on steep inclines. Material of small fragment size tends to weather friable. |
| Bedded tuff | Abundant in Manicaboa Formation. Occurs as lenticular layers in Río Orocovis and Pozas Formations. | Requires less blasting than more massive volcanic rocks. The dense welded tuffs of the Pozas Formation require extensive blasting and power tools for removal. | Foundation strength generally good for most construction in fresh rock. Slope stability is poor where rocks dip steeply. Where beds dip into a highway cut, slopes must be as low as the dip angle for stability. Susceptible to seepage along bedding planes and fractures. | Can be used for road metal and concrete aggregate. Welded tuff suitable for both base-course and surfacing material. | Tends to weather to slabs and angular pieces which become scattered over sloping surfaces. Forms talus at base of steep slopes and roadcuts. Welded tuffs are resistant to weathering. |
| Consolidated clay, sand, and gravel. | Makes up much of San Sebastián Formation. | Easily excavated with hand tools. | Foundation strength poor. Sand and gravel are highly permeable and subject to much seepage. | Thicker lenses of gravel could be used for secondary road surfacing. Screened fractions suitable for base-course and surfacing material. | Weathers readily to friable clayey soil with many loose pebbles. Susceptible to creep on steep slopes and where clay content is high. |

TABLE 10.—*Engineering properties of rocks in the Ciales quadrangle, Puerto Rico*—Continued

| Lithologic types | Distribution | Excavation | Strength and stability | Utilization | Miscellaneous |
|---|---|---|---|---|---|
| Limestone | Covers most of northern third of Ciales quadrangle. Lares Limestone is massive hard limestone. A lens of hard limestone occurs at base of the Avispa Lava Member. | Massive hard limestone of the Lares Limestone and at the base of the Avispa Lava Member requires blasting. Marly limestone of Cibao Formation easily excavated with hand tools. | Foundation strength generally good except where limestone is cavernous. Slope stability is good. Permeable and subject to seepage because of extensive development of solution cavities. | Excellent for road metal and concrete aggregate. Possible source of material for manufacture of cement. | |
| Intrusive igneous rocks. | Morovis and Ciales stocks | Fresh rock requires blasting and power tools for removal. Weathered rock can be removed by hand tools. | Foundation strength generally good for most types of construction. Slope stability is good. Impermeable but subject to some seepage where joints are well developed. | Weathered material is suitable for surfacing secondary roads. Suitable for use in small earth dams. | Weathers to granular soil and saprolite. |
| Alluvium | Locally along all streams; mainly along Río Grande de Manatí. Not extensive anywhere in quadrangle. | Easily removed by either hand tools or power shovel. | Foundation strength generally poor. Highly permeable and subject to much seepage during heavy rains. | Screened fractions suitable for surface metal. | Most areas of alluvium subject to flooding. |
| Colluvium | Chiefly along base of cuesta inface formed by Lares Limestone. Includes small local landslides mainly in southern part of quadrangle. | Easily worked by small power shovel. Includes large masses of rock that would require blasting. | Foundation strength nil. Permeable and subject to seepage. | | Susceptible to intermittent mass movement, especially during heavy rains. |
| Deep soils | Chiefly in the upland areas in central barrio Vaga Pasto, central barrio Pesas, and central barrio Gato, southern Ciales quadrangle, and barrio Cuchilla, east-central part of quadrangle. (See fig. 22 for general distribution.) | Easily worked with hand tools. | Foundation strength generally poor. Because of good porosity and poor permeability, soils absorb and retain much water following heavy rains. | | Subject to landslides on steep slopes. |

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