Geology of the Middle Tertiary Formations of Puerto Rico

GEOLOGICAL SURVEY PROFESSIONAL PAPER 953

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

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By WATSON H. MONROE

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Description of the stratigraphy and structure of formations of Oligocene and Miocene age near the northern and southern coasts of Puerto Rico

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GEOLOGY OF THE MIDDLE TERTIARY FORMATIONS OF PUERTO RICO

By Watson H. Monroe

ABSTRACT

Rocks of Oligocene and Miocene age crop out in both northern and southern Puerto Rico. They rest with angular unconformity on volcanic and related sedimentary and intrusive rocks that range in age from Early Cretaceous to middle Eocene. The older rocks crop out on the upland that extends east–west through the center of the island between the belts of rocks of middle Tertiary age. The surface on which the middle Tertiary rocks were deposited is very irregular, having a local relief of at least 200 m.

Although the rocks of northern and southern Puerto Rico are approximately the same age, there was no nearby marine connection during Oligocene time; as a result, neither the lithologic characteristics nor the faunas contained in the rocks permit exact correlation from one side of Puerto Rico to the other. During Miocene time, there may have been a connection of the two seas around the western end of present-day Puerto Rico, for outcrops of rocks of Miocene age are found near Rincón and in the Lajas Valley and have been reported from wells near Mayagüez.

In northern Puerto Rico, the basal stratigraphic unit is the San Sebastián Formation, which consists mostly of pale-red and gray clay that locally contains abundant pebbles and cobbles of volcanic rocks. In some places, the San Sebastián also contains lenticular layers of fossiliferous earthy limestone. The thickness varies inversely with the relief on the underlying erosional surface of rocks of Cretaceous to Eocene age. Fossils contained in the formation indicate a middle Oligocene age.

The San Sebastián Formation grades upward into the Lares Limestone, which consists mainly of hard finely crystalline fossiliferous very pure limestone that is generally stratified in beds 10–30 cm thick. The Lares ranges in thickness from featheredges at the eastern and western extremities to a reported maximum of about 310 m. Between San Sebastián and Moca, the Lares intertongues with sand, gravel, and cobble beds that are indistinguishable from the San Sebastián Formation and that are mapped with that formation. Between Ciales and Toa Alta, the Lares grades laterally into sand and sandy clay of the Mucarabones Sand. The Lares Limestone is mostly made up of limestone deposited during middle to late Oligocene time in fringing reefs on the northern side of the Puerto Rican landmass.

The Lares Limestone is overlain sharply, but apparently conformably, by the Cibao Formation, the most heterogeneous formation in northern Puerto Rico; the Cibao varies in lithology from sand and gravel to very pure limestone. The formation in the type area consists of chalky, slightly clayey limestone and calcareous clay, both ranging from very pale orange to grayish orange. Between the Río Guatemala and the Río Grande de Manatí, the formation consists largely of relatively pure calcarenite, which interfingers both to the west and to the east with the typical limestone and clay. In western Puerto Rico, the upper half of the Cibao Formation contains many thick lenses of sand and gravel, interbedded with more typical calcareous clay and soft limestone. East of the Río Grande de Manatí, most of the lower three quarters of the formation consists of limestone. The Cibao Formation is late Oligocene to early Miocene in age. The formation represents deposition, in and near the sea, of sediments brought northward by rivers from the highlands of Puerto Rico while the highlands were being arched upward. Increases in terrigenous clastic deposits record at least two episodes of uplift.

The Lares Limestone and most of the Cibao Formation grade laterally eastward into the Mucarabones Sand, which consists mainly of sand but which includes beds of earthy limestone and calcareous clay. The formation apparently represents sand brought into the sea by rivers near the eastern edge of the depositional basin present during Oligocene and early Miocene times.

The Cibao Formation is overlain gradationally by the Aguada Limestone of early Miocene age, which consists of chalky and indurated calcarenite that increases upward in hardness. In the Bayamón–San Juan area, the lower part of the Aguada apparently merges into chalky, sandy clay and impure chalky limestone indistinguishable from the Cibao Formation. The Aguada consists largely of limestone deposited on reef flats in shallow water, so shallow in some places that bedding of the limestone is scored by desiccation cracks, recording times when the limestone was temporarily exposed to the air.

The Aguada Limestone is overlain sharply, perhaps disconformably, by the Aymamón Limestone, which consists of very pure limestone, ranging from very pale orange to white. Near the coast, some of the Aymamón has been altered to dolomite. Most of the Aymamón is fossiliferous and apparently was formed by deposition of calcium carbonate on a fringing reef off the northern coast of the Puerto Rico landmass.

The Aymamón Limestone is overlain unconformably by ferruginous sandy chalk and limestone of the Camuy Formation. The Camuy Formation records an uplift of the mainland of Puerto Rico in middle or late Miocene time that caused rapid erosion of quartz-bearing intrusive rocks and transport of this sand to the sea. Before Camuy time, the area of the Utuado batholith had been drained by streams that flowed northwest and northeast to the sea, but during the short erosion interval between deposition of the Ayma-

món Limestone and the Camuy Formation, streams flowed for the first time directly north to the sea from the batholith. The Camuy is the youngest formation of Miocene age in northern Puerto Rico. It is overlain by more or less sandy surficial deposits of late Tertiary and Quaternary age.

In southern Puerto Rico, the volcanic complex of central Puerto Rico is overlain unconformably by the Juana Díaz Formation, which consists of basal beds of sand, pebbles, and cobbles overlain by calcareous, sandy to silty clay or mudstone. The clastic beds intertongue south and southwest of Peñuelas with coralline and algal limestone, deposited in Oligocene time as fringing reefs. The upper part of the Juana Díaz Formation at most places consists of more or less chalky limestone, formerly considered a basal member of the Ponce Limestone. At the top of the formation is a channel-filling unit of crossbedded sand, carbonaceous clay, and calcareous clay, which is separated from the underlying limestone by an unconformity.

The Juana Díaz is overlain unconformably by the very pale orange to grayish-orange, highly fossiliferous Ponce Limestone. Westward from Guayanilla, the Ponce overlaps all the Juana Díaz and rests unconformably on rocks of Cretaceous age. The Ponce was deposited in fringing reefs, much like those off the southern coast of Puerto Rico today.

In the western part of the Lajas valley in southwestern Puerto Rico are small outcrops of fossiliferous, yellow limestone, mostly weathered to compact silt, and of sand and gravel; these deposits are correlated with the Guanajibo Formation, which was first observed in well samples from Mayagüez. Thus far, little is known about the Guanajibo except that it is probably of late Miocene, possibly Pliocene age.

The structural features of northern Puerto Rico. contrast markedly with these of southern Puerto Rico. In the northern belt, the strike at almost all points is within a few degrees of east, and the dip ranges from about 6° near the boundary with the rocks of the older complex to about 1° or less near the coast. This regular homocline is interrupted by a few small anticlines and synclines, some near the west coast near Aguadilla, others near Quebradillas, and smaller ones south of Vega Baja and near Vega Alta. Very few faults have been observed, and most of these have vertical displacements of 30 m or less.

By contrast, in southern Puerto Rico, the strata commonly dip in a southerly direction some 10°–30°; strikes vary from north to east but are generally easterly, and the strata are cut by many normal faults having vertical displacements of as much as several hundred meters. The boundary of middle Tertiary strata with the older complex is most commonly along a fault contact. Within the belt of Oligocene and Miocene rocks, several large faults have been observed that have the upthrown side to the south. One of these near Central San Francisco raises serpentinite and Cretaceous volcanic rock up against the Ponce Limestone of Miocene age.

The limestone units of middle Tertiary age produce rock that is used for cement, agricultural limestone, and concrete aggregate. Several areas near the coast are underlain by dolomite of sufficient purity to be used in the manufacture of refractories. Several small anticlines in northern Puerto Rico could serve as structural traps for any petroleum that may be present.

INTRODUCTION

Puerto Rico is the easternmost island of the Greater Antilles in the northeastern part of the Caribbean Sea. Puerto Rico has a generally rectangular shape, extending about 175 km (110 mi) east–west and 65 km (40 mi) north–south and covering an area of 8,497 km^2. Included in its political territory are several smaller islands including Vieques and Culebra to the east, Desecheo and Mona to the west, and Caja de Muertos to the south. These satellites and Puerto Rico itself are all in the area between lat 17°37′ and 18°31′ N., and long 65°14′ and 67°56′ W. Puerto Rico is about 160 km (100 mi) south of the Puerto Rico Trench, which reaches depths of about 8,365 m—the deepest known part of the Atlantic Ocean (fig. 1). The island is bounded on the east by the Vieques Passage and on the west by the Mona Passage, which separates Puerto Rico from Hispaniola.

This report has been condensed from a longer one (Monroe, 1975a), which contains many more local details of the stratigraphy and descriptions of samples from wells.

GENERAL GEOGRAPHIC AND GEOLOGIC FEATURES

Puerto Rico can be divided into three main geographic divisions (fig. 2): (1) a mountainous core that makes up the southern two-thirds of the island (except for a wide coastal plain between Guayama and Ponce), (2) a belt of rugged karst topography in the north-central and northwestern parts of the island, and (3) a discontinuous fringe of relatively flat coastal plains.

The mountainous core of Puerto Rico extends from the Mona Passage on the west to the Vieques Passage on the east. The relief is dominated by the Cordillera Central from Mayagüez to Aibonito and farther east by the Sierra de Cayey near the southern coast and by the Sierra de Luquillo in the northeastern part of the island. The Cordillera Central is only 15–20 km (9–13 mi) from the south coast through much of its length, and it includes the highest peaks in Puerto Rico—the highest Cerro de Punta is 1,338 m above sea level. The mountainous area has been deeply eroded by streams, and valley sides are steep, slopes of 30° to 45° being not uncommon.

The rocks in the mountainous core consist predominantly of Lower Cretaceous to middle Eocene volcanic formations and are bordered by a fringe

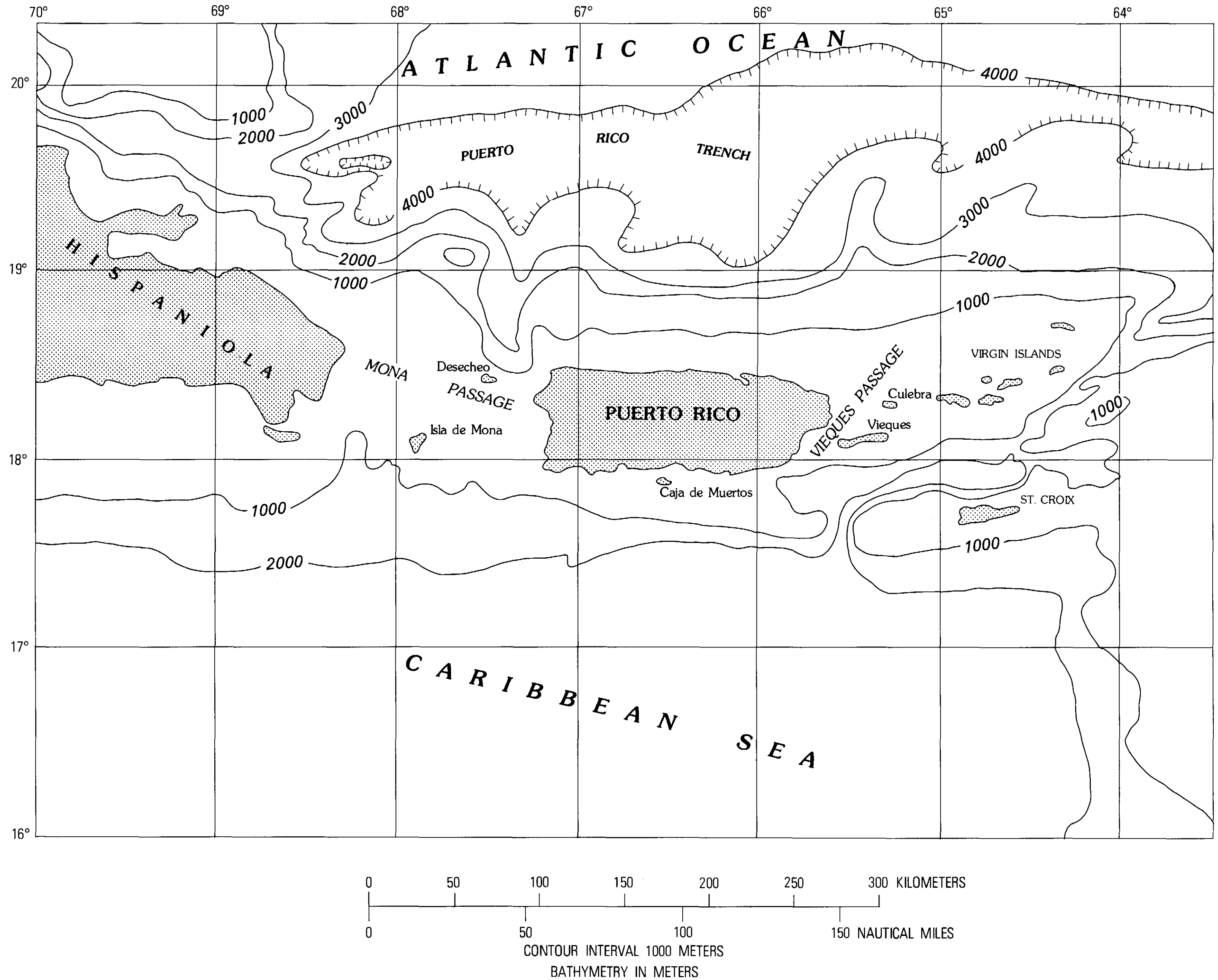

FIGURE 1.—Bathymetric map of northeastern part of the Antillean islands arc, showing relation of Puerto Rico to the Puerto Rico Trench and to other islands. Depths in fathoms. Modified from U.S. Hydrographic Office Chart H.O. 5487, published in 1939.

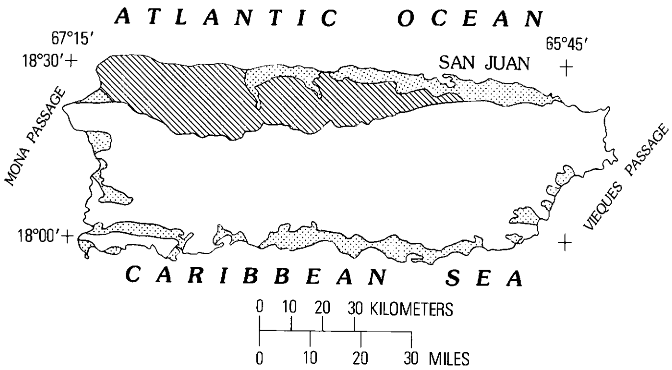

FIGURE 2.—Map of Puerto Rico showing principal geographic divisions. Unpatterned area is the central mountainous core; the ruled area is the karst region; the stippled areas are the coastal lowlands.

of sedimentary rocks of Oligocene and Miocene age along the south coast. Most of the Lower Cretaceous rocks are submarine, deep-water volcanic-ash deposits interspersed with pillow lava. In the western part of the island are several linear bodies of serpentinite that underlie Upper Cretaceous volcanic rocks. The Upper Cretaceous rocks consist of interbedded volcanic and sedimentary rocks, the latter including discontinuous reef limestone, and sandstone and conglomerate derived from volcanic rocks. The Cretaceous rocks are intruded by masses of granitic rock, generally of granodioritic to dioritic composition, which probably were emplaced in very Late Cretaceous to Eocene time. Paleocene and lower Eocene rocks are volcanic and sedimentary. These rocks are present principally on the northern and southern flanks of the central core but are also found in a faulted belt that extends west-northwest across central and western Puerto Rico (Briggs and Akers, 1965). The Cretaceous and early Tertiary rocks have been folded into an anticlinorium and have been intensely faulted into hundreds of fault blocks (Briggs and Akers, 1965). In the south-central and southwestern parts of the island, the central core extends to the Caribbean Coast and includes rocks of middle Tertiary age resting unconformably on the older rocks and in most places faulted against them. The younger rocks consist of conglomerate, sand, clay, chalk, and limestone, which will be described in the present report in the discussion of the Juana Díaz Formation and the Ponce Limestone.

The karst region in the north-central and northwestern parts of Puerto Rico varies in relief from extremely rugged terrain to rather gentle rolling hills. Most of the drainage is underground except along the courses of several rivers that flow across the belt from the central mountainous area to the Atlantic Ocean; parts of two of these rivers are underground. The region is bounded on the south from Aguadilla eastward nearly to Bayamón by a steep south-facing escarpment (Blume, 1968), which has a limestone wall at the top and clay below; the steepness of this scarp has been accentuated by landslides (Monroe, 1964a) of limestone blocks that have collapsed as the clay is squeezed out beneath them. The highest altitudes within the karst region are on peaks along this scarp, which are commonly higher than 400 m; the highest point, 530 m, is on a hill (50,900 N., 117,300 E., Bayaney quadrangle)[1] about 2 km (1¼ mi) east-southeast of the bridge of Highway 111 over the Río Tanama. Several smaller cuesta scarps, held up by limestone, interrupt a general northerly slope from this scarp to the Atlantic Ocean.

The region contains a great variety of landscape features resulting from solution of limestone (Monroe, 1968c, 1976), including hundreds of caves, solution sinks or dolines, collapse sinks, interior valleys, steep-sided mogotes or haystack hills, and zanjones. These features are alined in roughly east-trending belts that in places are separated by gently rolling hills underlain by sedimentary rocks not subject to rapid solution. In the northern part of the region, the karst features are separated by wide valleys floored by sandy clay or blanket deposits (Briggs, 1966) that rest on the limestone and that apparently have been lowered by subsoil solution (Monroe, 1969a; Miotke, 1973).

The rocks cropping out in the karst region are principally limestone and secondarily subordinate amounts of gravel, sand, clay, chalk, and dolomite. These rocks are of Oligocene and younger age and are the principal concern of the present report. The rocks are divided into lithologic units, each of which has a distinctive geomorphic expression, which will be described in this report with the stratigraphy.

The coastal plains are nearly flat areas that slope very gently upward from the shore to the foothills. At most places, the relief is very low, but projecting out of the plains at places are isolated hills of volcanic, intrusive, or sedimentary bedrock material, which are similar to inselbergs. The coastal plains

[1] Exact locations in this report are given in terms of the Puerto Rico metric grid coordinate system, marked by ticks on the sides of the geologic map accompanying this report (pl. 1) and on the sides of all U.S. Geological Survey topographic quadrangle maps of Puerto Rico. The numbers show the meters north and east of an arbitrary reference point south of Isla Mona and southwest of Puerto Rico. The location of the quadrangles is shown on figure 3.

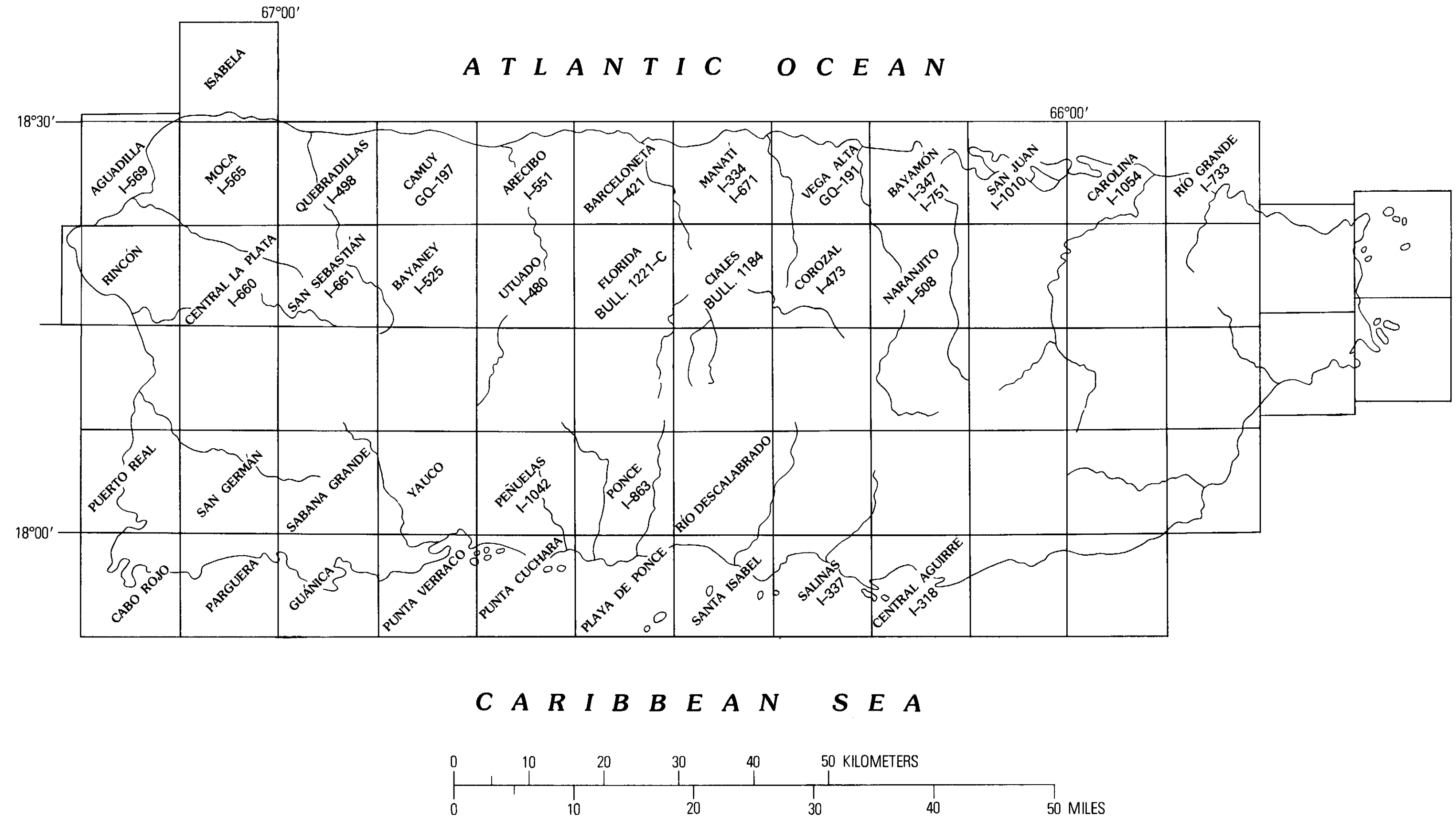

FIGURE 3.—Index map of Puerto Rico showing location of quadrangles and detailed geologic maps referred to in this report.

grade into alluvial plains of the larger rivers. In the interfluve areas, the plains reach altitudes of less than 10 m (33 ft) in northern Puerto Rico, but in southern Puerto Rico, the plains consist of a wide belt of coalescing alluvial fans that rise to 25 m (82 ft) or slightly more in the area east of Ponce. Except for the isolated hills, the deposits of the coastal plains are mostly of Quaternary age and consist of sand, clay, and gravel deposited in flood plains and alluvial fans of rivers, in coastal and river swamps, on beaches, and as dunes of beach sand blown up by the wind. Many of the features have been well described by Lobeck (1922), Kaye (1959b), Briggs (1965, 1968), and Monroe (1962, 1963a, 1967).

PREVIOUS INVESTIGATIONS

In 1913, the Council of the New York Academy of Sciences (Britton, 1919) proposed that the Academy sponsor a scientific survey of Puerto Rico, which would include geology, paleontology, botany, zoology, and anthropology. The geological investigations began with a reconnaissance by C. P. Berkey and C. N. Fenner in August and September 1914. The following year, Berkey (1915) desribed the principal geologic features of Puerto Rico, grouping "a complex association of tuffs, ashes, shale, conglomerate, limestones and a very great variety of intrusives and occasional lava flows" (Berkey, 1919, p. 17) into an Older series that he considered of late Mesozoic age, overlain probably unconformably by a Younger series of Cenozoic age. He divided the Younger series into two formations—the San Juan Formation, "confined to the immediate coast margins * * * and the adjacent small islands," (Berkey, 1919, p. 16) and the Arecibo Formation, consisting of a "great series of reef limestones and shell limestones preceded by shales that form a belt of considerable width along the north coast and a portion of the south coast of the island" (Berkey, 1915, p. 12). In 1919, he suggested that the Arecibo Formation might be divided on the north side of the island into the Quebradillas reef limestone—the upper limestone member—and the San Sebastián shales—a lower shale member. On the south side of the island, the formation might be divided into the Juana Díaz shales and marls exposed near Juana Díaz, the Guánica coral reefs, and the Ponce chalky limestones (Berkey, 1919).

The New York Academy of Sciences decided to make detailed studies of the geology of Puerto Rico by dividing the island into seven districts. Middle Tertiary rocks are in the districts studied by Semmes (1919), Hodge (1920), Hubbard (1923), Mitchell (1922), and Meyerhoff (1931). At the same time, the Academy sent A. K. Lobeck (1922) to study the physiography of the island. The geologic studies completed by these geologists are remarkable considering that each was allowed only about 3 months in which to construct a reconnaissance topographic map, study and plot the geology, and determine the mineral resources of his district. The work done since 1955 by the U.S. Geological Survey has required much more time to map a 7.5-minute quadrangle—each of the New York Academy districts was about the size of nine such quadrangles.

Hubbard (1923) made a remarkably detailed study of the middle Tertiary rocks in northwestern Puerto Rico and divided them into a succession starting with the San Sebastián shale at the base, overlain by the Lares limestone, the Cibao limestone, the Los Puertos limestone, and at the top of the succession the Quebradillas limestone. He also made an extensive collection of fossils in both northern and southern Puerto Rico, which he identified and described (Hubbard, 1920b); he considered that the fossils range in age from middle to late Oligocene. Galloway and Heminway (1941) described and figured all the Tertiary Foraminifera that had been collected by the field expeditions of the New York Academy of Sciences.

The geologic investigations of the New York Academy of Sciences were summarized by Meyerhoff (1933) in a general account of the geology of Puerto Rico, which included the first geologic map of the island. This work has been quoted for many years as the general geologic reference on Puerto Rico.

Very little geologic work was done on the middle Tertiary rocks between Meyerhoff's studies in 1924–26 and the end of World War II. In 1944, the Puerto Rico Development Company asked the U.S. Geological Survey to investigate the oil and gas possibilities of the island. As the coastal plains of Puerto Rico offer the best possibilities, a team composed of C. R. Thomas, A. D. Zapp, and H. R. Bergquist spent 4 months during the fall and winter 1944–45 making stratigraphic studies and preparing an overall geologic map of the belts of middle Tertiary rocks on both the north and south coasts of Puerto Rico. The stratigraphy of the northern coastal belt, worked out at that time largely by Zapp and Bergquist (Zapp and others, 1948), has been adopted with minor modifications in the present report. Zapp and Bergquist accepted most of Hubbard's

(1920a) stratigraphy, but were unable to ascertain the stratigraphic limits of his Los Puertos and Quebradillas limestones. Accordingly, they divided the rocks younger than the Cibao into the Aguada and Aymamón Limestones. They chose as the type area of the Aguada the rocks near the town of Aguada that had been mapped as Lares by Hubbard; these rocks are now considered a part of the Cibao (Monroe, 1968a).

Zapp, Thomas, and especially Bergquist, collected fossils from many Oligocene and Miocene horizons in both coastal belts; Bergquist's work of classifying these fossils has never been published (referred to in the present report as "Bergquist, written commun., 1945"). Zapp, Bergquist, and Thomas (1948, sheet 2) explained much of the complicated stratigraphy of the rocks older than the Aguada Limestone by describing "two areas occupied largely by great bioherms of predominantly pure reef-type limestone; and by an area between the bioherms in which sediments contain a much higher proportion of clastic material than the bioherm areas". Both east and west of the bioherm areas, the limestone grades laterally into predominantly clastic deposits. The present work confirms the conclusions about the distribution of limestone and clastic deposits, but the stratigraphic nomenclature has been modified appreciably by considering the upper parts of the bioherm masses as members of the Cibao Formation. The geology of the middle Tertiary rocks in southern Puerto Rico is much more complicated than supposed by Thomas (Zapp and others, 1948), who mapped that area, and the presently accepted stratigraphy differs appreciably from his.

The present investigation began in 1955 when C. Wythe Cooke spent 3 months in Puerto Rico studying the stratigraphy of the middle Tertiary rocks of both northern and southern Puerto Rico and making large collections of fossils. Cooke's stratigraphic report was not published, but it has proved useful, especially with respect to his fossil determinations and correlations with other parts of the world (referred to in the present report as "Cooke, unpub. data, 1956").

Detailed mapping of the middle Tertiary rocks began in 1957 as a part of a cooperative geologic investigation by the U.S. Geological Survey and the Department of Industrial Research of the Puerto Rico Economic Development Administration (PREDA). Various areas have been mapped by W. H. Monroe, R. P. Briggs, A. E. Nelson, H. L. Berryhill, Jr., O. T. Tobisch, M. D. Turner, D. H. McIntyre, and J. M. Aaron. The mapping of these rocks was completed in 1970. The geologic maps (pl. 1) accompanying this report are based on published and unpublished geologic maps by the authors listed above, modified by more recent observations made by Monroe. The principal changes in stratigraphy from that of Zapp, Bergquist, and Thomas (1948) have been assignment of the upper part of the eastern bioherm to several members of the Cibao Formation (Monroe, 1962), designation of the clastic equivalent of the Lares Limestone east of Ciales as the Mucarabones Sand (Nelson, 1966), recognition of the upper part of the western bioherm as the Montebello Limestone Member of the Cibao Formation (Nelson and Monroe, 1966), separation of the unconformably overlying Camuy Formation from the Aymamón Limestone (Monroe, 1963b), and transfer of the middle Tertiary rocks between Aguadilla and Rincón from the Aguada to the Cibao (Monroe, 1968a). These changes will be discussed in detail in this report in descriptions of the formations involved.

While studying the ground-water resources of southern Puerto Rico, Grossman (1962) learned that sand and gravel previously considered of Quaternary age in the Yauco area is an overlap of the Juana Díaz Formation. He also called attention to major faulting that juxtaposed Cretaceous rocks and Ponce Limestone (Grossman, 1963).

Studies of foraminifers published since 1959 have helped solve some of the stratigraphic problems in the middle Tertiary rocks. Sachs, in his work on the larger foraminifers, has shown that the San Sebastián Formation is of late Oligocene age (Sachs, 1959), and Sachs and Gordon (1962) have shown that in the longitude of Puerto Rico a land barrier separated the Atlantic Ocean from the Caribbean Sea throughout the period of deposition of the middle Tertiary rocks. Pessagno (1963) and Seiglie and Bermúdez (1969) have been able to correlate foraminifers in beds now considered a part of the Juana Díaz Formation with lower Oligocene zones in Trinidad and Cuba. Bold (1965) has studied ostracodes from northwestern Puerto Rico and has proposed correlation with various other areas bordering the Caribbean and in the United States. Statigraphic studies by Seiglie and Bermúdez (1969) and Moussa and Seiglie (1970) have proved of major importance in understanding the rocks of southern Puerto Rico and will be referred to in detail later in this report.

In 1973, Monroe (1973b) summarized the stratigraphy of the middle Tertiary rocks, described in greater detail in the present paper, and discussed the petroleum possibilities of Puerto Rico. This paper was critically discussed by Meyerhoff (1975) and by Moussa and Seiglie (1975), all of whom objected to the Geological Survey's abandoning Hubbard's names Los Puertos limestone and Quebradillas limestone and substituting Aguada Limestone, Aymamón Limestone, and Camuy Formation. Moussa and Seiglie pointed out that Berkey (1915) and Hubbard (1923) both designated the town of Quebradillas as the type locality of the Quebradillas limestone; because rocks of the Camuy Formation underlie the town, they contended that these rocks should be called the Quebradillas Formation. Monroe (1975b) refuted this contention, pointing out that all Hubbard's measured sections of the Quebradillas are predominantly in the Aymamón and that only two include any Camuy. Furthermore, almost all Hubbard's Quebradillas fossils are from the Aymamón. Moussa and Seiglie (1975) also proposed that the name Los Puertos be revived for the rocks now known as the Aguada Limestone. They also disagreed with Monroe's age assignments in both northern and southern Puerto Rico and with the classification of the rocks in southern Puerto Rico. The stratigraphic classification used in the present report, however, is the same as in Monroe's (1973b) earlier paper, as justified in his (Monroe, 1975b) reply.

DEFINITIONS

The classification of rock types used in this report is essentially that of Pettijohn (1957). Grain size both of clastic rocks and of crystals has been classified according to the Wentworth (1922) scale. Folk's (1959) classification of carbonates has been used for petrographic description of limestone. Colors of rocks have been determined by use of the Rock-Color Chart (Goddard and others, 1948). The karst terms used in describing physiographic expression of the limestone formations have been defined by Monroe (1970). Bedding thickness is classified as follows: laminated—paper thin to about 5 mm; thin bedded—5 mm to about 5 cm; medium bedded—5 cm to 20 cm; thick bedded—20 cm to 1 m; very thick bedded—noticeable stratification, beds mostly thicker than a meter; massive—no discernible stratification. The term "marl" is used for rock that ranges from calcareous clay to soft earthy or clayey limestone. The term "chalk" refers to unindurated nearly powdery limestone, and the adjective "chalky" refers to a condition of almost powdery. The adjective "earthy" is used for limestone that contains appreciable quantities of sand, silt, and clay but is more indurated than marl.

STRATIGRAPHY

The middle Tertiary rocks in northern and southern Puerto Rico are similar only in that they consist largely of calcareous materials, including much limestone. The rocks in the northern province range in age from middle or late Oligocene to middle or late Miocene or possibly Pliocene; in contrast, the rocks in the southern province range from early Oligocene to probable late Miocene. The rocks in western and southwestern Puerto Rico are all Miocene. The faunal assemblages in northern, southern, and western Puerto Rico are distinct, although a few species are common to all three areas; on the basis of the differences in fossils, Hubbard (1923, p. 76) suggested that during Oligocene time a landmass must have extended east–west between the northern and southern depositional basins "with no connecting passages close at hand." More recent studies by paleontologists have confirmed this opinion (Sachs, 1959; Sachs and Gordon, 1962). The Miocene sediments in the Lajas Valley (Gordon, 1961b) and the Miocene or younger sediments, called Guanajibo by McGuinness (1948), suggest that the two basins may have been connected in later times. Because of the great differences in stratigraphy and age relations in the two regions, however, they will be described separately in this report.

NORTHERN PROVINCE

In northern Puerto Rico, rocks of middle Tertiary age crop out in a belt (pl. 1) that extends west from Loíza Aldea, just east of the Río Grande de Loíza, to the west coast near Rincón. The belt is only 4 km wide at Loíza Aldea, but it widens westward to a maximum of about 26 km near Arecibo; still further west, the belt becomes narrower. The thickness of these rocks has been determined only at an oil test well drilled on the coast between Arecibo and Barceloneta, where Briggs (1961) reported 5,527 ft (1,684 m) or possibly 5,580 ft (1,701 m) of sedimentary rocks above Eocene(?) volcanic rocks. As this well was drilled near what is believed to be the deepest part of the northern depositional basin, the total thickness of the rocks of middle Tertiary age in northern Puerto Rico is probably not much more than 1,700 m.

The rocks range in age from late Oligocene (possibly middle Oligocene) to middle Miocene, although there is some evidence (Bermúdez and Sieglie, 1970) that the youngest strata, the Camuy Formation, may be late Miocene or even Pliocene. In ascending order, the rocks are divided into six formations: the San Sebastián Formation, the Lares Limestone, the Cibao Formation, the Aguada Limestone, the Aymamón Limestone, and the Camuy Formation. In the Bayamón area, a seventh formation, the Mucarabones Sand, is recognized as the clastic equivalent of the normally more calcareous Lares Limestone and most of the Cibao Formation.

BASEMENT

The middle Tertiary rocks rest on a basement of highly faulted and folded rocks of Cretaceous and early Tertiary age. The rocks include lava, tuff, lenticular limestone, sandstone composed of detritus from volcanic rocks, and several large masses of granodiorite and related rocks that have intruded the older basement rocks.

The surface on which the middle Tertiary rocks were deposited is irregular, having a local relief of more than 200 m. Without boreholes, it is difficult to determine the details of this ancient topography, for the contact of the middle Tertiary rocks with the older rocks is concealed for much of its length by large landslides (Monroe, 1964a) at places where the relatively weak San Sebastián Formation has slipped under the weight of the overlying Lares Limestone. The surface can be observed directly, however, at several places where the ancient hills were so high that they persisted as islands in the Oligocene sea throughout San Sebastián time into Lares and locally into Cibao time. Conditions are particularly favorable for mapping the topography of the basement in the Utuado quadrangle (Nelson, 1967b) both east and west of the Río Grande de Arecibo. A ridge of volcanic rocks of the Jobos Formation, mostly volcanic breccia but including some conglomerate and volcanic sandstone, extends west-northwest from Lago Dos Bocas nearly to the Río Tanamá. The ridge was buried by sediments deposited in the Lares and Cibao seas, but it has been partially exhumed by recent erosion. The volcanic rocks are highly weathered, probably weathered before burial, but the contact with the overlying rocks is sharp enough so that a sketch contour map (fig. 4) could be prepared to show the relief. Unfortunately, no information is available about the altitude of the surface in the area immediately to the south where it is deeply buried by Lares Limestone. However, it reappears 2.5 km farther south where Lares Limestone is resting on hydrothermally altered tuff of the Alonso Formation, and again about 1.5 km still farther south where a relatively thick sequence of clay of the San Sebastián Formation is resting on weathered granodiorite of the Utuado pluton. The total relief on the basement surface in this area is not known, but the hills must have been at least 230 m high at the beginning of deposition of the San Sebastián, for both the San Sebastián (about 50 m thick) and the Lares Limestone (about 180 m thick) are missing at places on the crest of the ridge. Nelson's map (1967b) shows that the surface is very irregular in the area of outcrop of the San Sebastián, but at some places, the clay of the San Sebastián has slipped downhill in small landslides that obscure the original topography.

Two other exhumed hills, now overlain by Lares Limestone, are well exposed east of the Río Grande de Arecibo. On one of these hills (130,210 E., 56,260 N., Utuado quadrangle), corals are present in the Lares Limestone (fig. 5) a few centimeters above the ancient surface of tuff of the Jobos Formation, which indicates that the water was very clear at time of deposition of the limestone. The tuff at this place was weathered to a friable saprolite before deposition of the Lares. On the ridge between the Río Grande de Arecibo and the Río Limón, south of Dos Bocas dam, Lares Limestone rests on early Tertiary volcanic rocks according to Nelson (1967b).

Similar irregularities, although perhaps of less magnitude, are present throughout the outcrop belt at the base of the middle Tertiary rocks. At most places, the irregularities are indicated by variations in the thickness of the San Sebastián. West of the Utuado area, the San Sebastián Formation is about 80 m thick over the western part of the Utuado pluton; but about 3 km east-southeast of Lares, a northwest-trending buried hill of basaltic rocks of the Robles Formation is present beneath the San Sebastián, reducing its thickness to 30 m (Nelson and Tobisch, 1968). From San Sebastián westward to Aguadilla, the basement rises rapidly, so that the total thickness of rocks of the Guatemala Group is less than half that farther east. Between Aguadilla and Rincón, a sequence of rocks—identified by Hubbard (1923) as Lares, by Zapp, Bergquist, and Thomas (1948) as Aguada, and by Monroe (1968a) as Cibao—rests on the hilly basement surface; an inlier of volcanic rocks projects through the Cibao at Aguada.

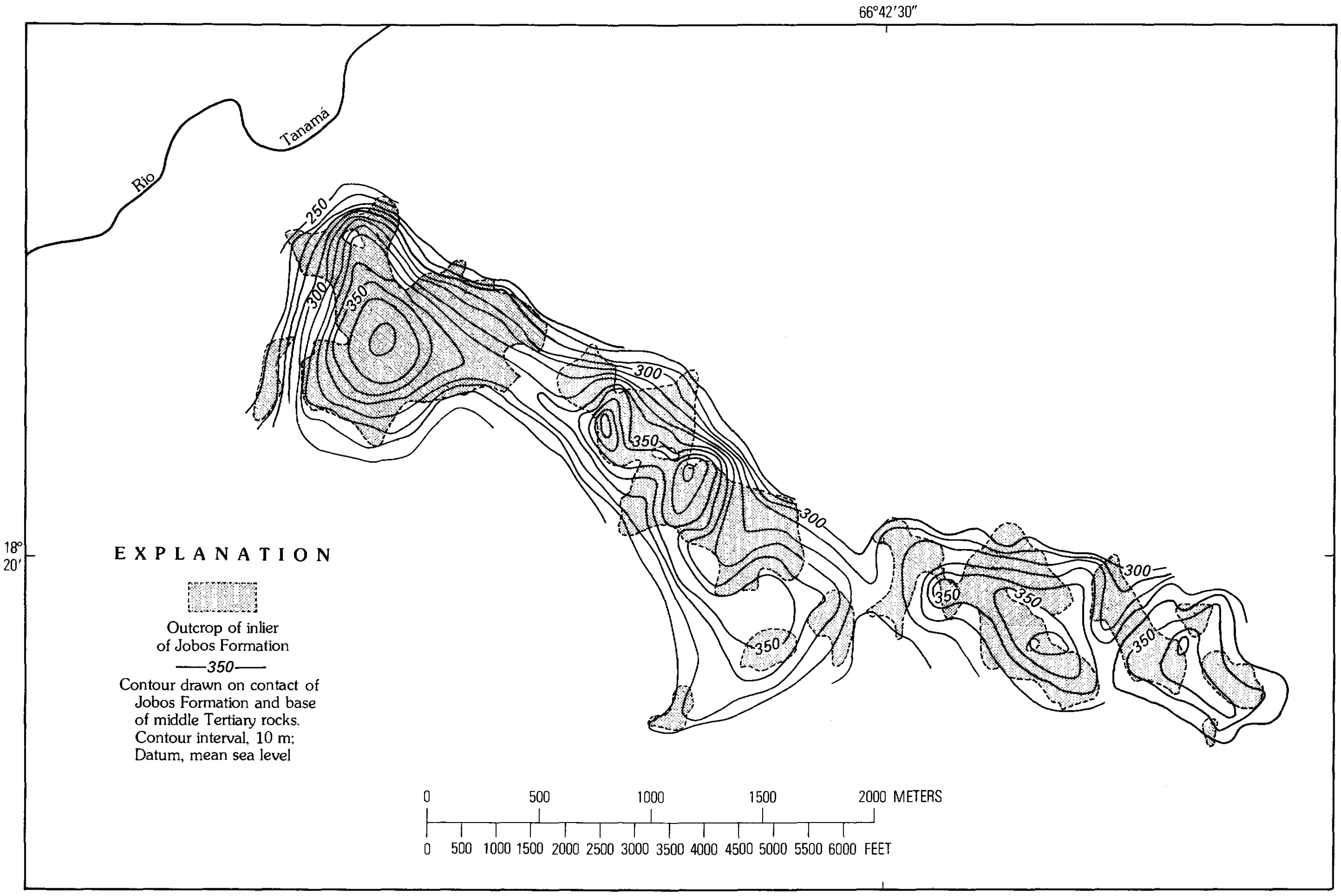

FIGURE 4.—Map of the exhumed hill of volcanic rock between Lago Dos Bocas and the Río Tanamá. Contours drawn on the trace of the contact between the Jobos Formation (Eocene) and the overlying middle Tertiary rocks.

The basement surface east of the Río Grande de Arecibo is as irregular as it is to the west, as shown by thick sequences of San Sebastián in ancient valleys and thin sequences over hills. East of Ciales at the crest of the valley wall of the Río Grande de Manatí, Berryhill (1965) showed an exhumed hill of volcanic rock, mainly lava, that projects through the San Sebastián Formation and the Mucarabones Sand (called sandy limestone member of the San Sebastián by Berryhill) into the limestone of the Lares. Both to the east and to the west, Berryhill mapped thick deposits of San Sebastián at places where the top of the basement is granodiorite of the Morovis and Ciales stocks. This hill was at least 100 m high at the time of submergence and formed an island throughout the time of deposition of the San Sebastián and Mucarabones Formations.

In the Bayamón and San Juan areas, the basement rises toward the east, and successively younger sediments overlap eastward as far as Loíza Aldea, which is east of the Río Grande de Loíza, where the Aymamón Limestone probably rests directly on the basement rocks.

The irregularities of the basement surface correlate fairly closely with the resistance to tropical weathering of the rock that cropped out in the Oligocene at the time of submergence of the old land surface. Differential erosion throughout early Oligocene time resulted in a very irregular surface consisting of steep-sided hills having a local relief of more than 200 m.

Another factor in determining the basement relief is the location of the ancient river valleys that extended from the hilly interior to the sea. Data are insufficient to locate these ancient streams accurately, but apparently one stream flowed northward from Barranquitas and persisted as a source of sediments through Cibao and probably Aguada time (Monroe, 1966b). Another persistent valley is that of the present Río Matrullas (Briggs, 1971). The high hills on the basement north of Utuado (pl. 1 and fig. 4) in the Oligocene probably diverted all

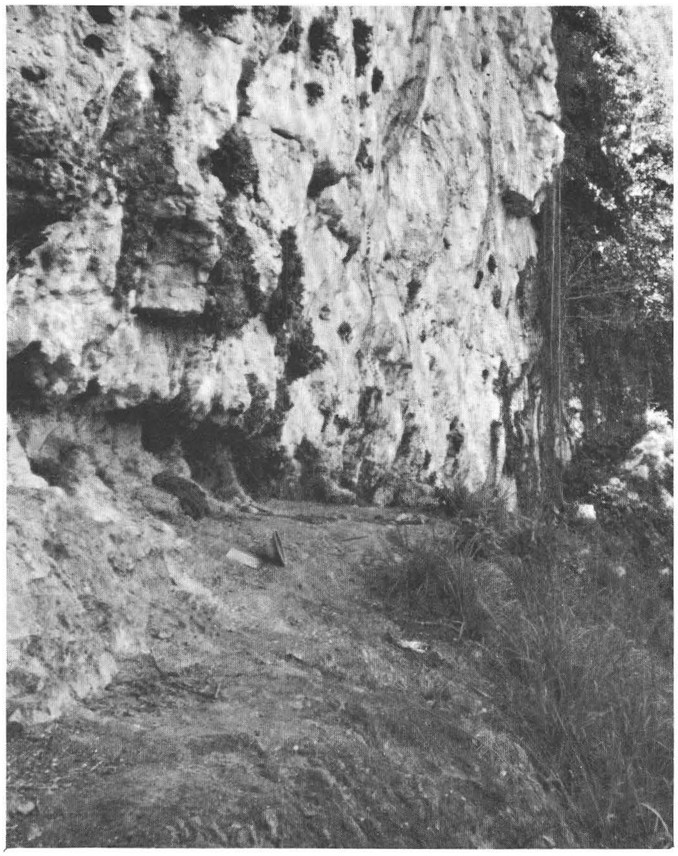

FIGURE 5.—Unconformity between Lares Limestone and Jobos Formation (Eocene) at side of trail, 4.8 km east of east side of Dos Bocas dam (November 1966).

drainage from that part of Puerto Rico toward the east or toward the west. Furthermore, some evidence suggests that a very large river flowed northwest to the sea between San Sebastián and Aguadilla; this is borne out more by the thick mass of cobbly sand that represents the San Sebastián Formation and the Lares Limestone in that area than by evidence of a great valley on the basement surface.

The steep-sided hills and the marked local relief on the basement surface do not support the apparently preconceived ideas of many earlier geologists, such as Lobeck (1922, p. 304), that the middle Tertiary rocks were deposited on a peneplained surface. Instead, the surface seems to have had a relief similar to that found today along the east and west coasts of Puerto Rico where the mountains plunge into the sea.

RIO GUATEMALA GROUP

The basal part of the middle Tertiary rocks in northern Puerto Rico—constituting the San Sebastián Formation, the Lares Limestone, the Cibao Formation, and the Mucarabones Sand—consists of an intertonguing, lenticular sequence of limestone, sand, gravel, and clay, to which Zapp, Bergquist, and Thomas (1948) gave the name Río Guatemala Group. Their Río Guatemala Group represents the deposits of an initial interval of predominantly clastic deposition, the San Sebastían Formation, followed by an interval of quiescence during which reef limestone was the dominant deposit, their Lares Limestone, followed, in turn, by another interval of clastic deposition, the Cibao Formation. In a wide area between the Río Guajataca and the Río Grande de Manatí, the entire Río Guatemala Group is represented by limestone, which Zapp, Bergquist and Thomas (1948) designated the western bioherm of the Lares. A similar but thinner sequence of limestone between Morovis and Corozal was designated the eastern bioherm. Between the Río Manatí and the Río Morovis, their western and eastern bioherms are separated by an interbioherm area, in which the upper limestones of the bioherms are replaced by clastic sediments they assigned to the Ciabo marl.

More recent studies by Monroe (Monroe, 1962; Nelson and Monroe, 1966) have shown that the upper limestones of the bioherms can be distinguished from the Lares Limestone, and they have been placed in the Cibao Formation, to which they are lateral equivalents. The intertonguing of lithologies, however, suggests the advisability of retaining the name Río Guatemala Group. The name "is taken from the Río Guatemala, which flows its entire course in the outcrop belt of the group north and west of San Sebastián" (Zapp and others, 1948 sheet 2).

SAN SEBASTIAN FORMATION

NAME

Berkey (1915) used the name San Sebastián shales to refer to sedimentary rocks below the limestone sequence for which he used the name Arecibo limestone. Hubbard formally defined the San Sebastián shale in his description of the geology of the Lares district (1923, p. 39). No type locality was designated, but Hubbard apparently had in mind the fresh exposures in the bed of the Río Guatemala that extend 4 km upstream from the bridge of Highway 111—these beds are here designated as typical. Because the unit contains a variety of rock types, Zapp, Bergquist, and Thomas (1948) used the name San Sebastián Formation.

AREAL DISTRIBUTION

The San Sebastián Formation has been traced from the type area westward to a point midway between Moca and Aguadilla, beyond which it is overlapped by the Cibao Formation (see pl. 1). In the area west of the Río Guatemala, however, it includes sand and gravel that intertongue with the Lares Limestone farther east. East of the type area, the San Sebastián is exposed continuously, varying in thickness, to the vicinity of the Río Grande de Arecibo. Near the river, however, it is locally missing at places where the Lares or Cibao rests directly on volcanic rocks. East of the Río Grande de Arecibo, the formation is generally present, cropping out or beneath a cover of landslide material to the San Juan area where it becomes indistinguishable from the overlying Mucarabones Sand and Quaternary deposits. The San Sebastián has not been recognized farther east and probably is overlapped by strata of Cibao age.

STRATIGRAPHIC RELATIONS

The San Sebastián Formation rests unconformably on a very irregular surface of folded and faulted rocks of Cretaceous to Eocene age, as described under the section on the basement. It is overlain gradationally by the Lares Limestone.

West of the type area, the overlying Lares Limestone intertongues with beds of clay, marl, sand, gravel, and cobbles that are indistinguishable from the underlying San Sebastián and hence are mapped with the latter. These beds grade upward within a distance of 5 m into the Cibao Formation.

Eastward from the valley of the Río Grande de Manatí, the San Sebastián Formation is overlain gradationally by sand and sandy limestone of the Mucarabones Sand. This sequence was called the sandy limestone member of the San Sebastián Formation by Berryhill (1965, p. 76, 77) in the Ciales quadrangle, and it was included in the San Sebastián by Monroe (1963a) and by Monroe and Pease (1962).

LITHOLOGIC CHARACTER

The San Sebastián Formation consists predominantly of vari-colored (5R to 10YR) clay and sandy clay, commonly in such thin beds that it has been called shale by many workers. Locally it consists of conglomerate, composed of particles ranging from pebbles to boulders, and contains beds of lignite or carbonaceous clay. It also contains abundant fossils in clay, marl, and soft limestone, especially near the top.

Hubbard (1923, pl. 2) shows graphically four sections of San Sebastián, which are all predominantly blue, blue gray, green, gray green, and red shale and sandy shale and subordinate amounts of conglomerate, marl, and soft limestone.

No specific type locality was designated by either Berkey or Hubbard, but Hubbard (1923, p. 39) stated that the "maximum development of this basal shale is near San Sebastián." The thickest section near San Sebastián, designated in this report as the type section, is in the valley of the Río Guatemala, where a series of small waterfalls and rapids affords an excellent series of outcrops of gray shaly clay, sandstone, and conglomerate from the transitional beds at the top nearly to the base of the formation. Unfortunately, these exposures are not continuous.

In the type area, the best outcrops of the base of the formation are along Highway 119 from 1–2.5 km south of Highway 111 at San Sebastián. Here the basal few meters of the San Sebastián consists of red and yellow mottled clay containing lenses of pebbles and cobbles of various volcanic rocks. Cobbles are larger and more common above the basal beds, which resemble closely a reworked pebbly soil; a typical cobble bed is exposed in the bank of Río Culebrinas (93,170 E. 55,520 N., San Sebastián quadrangle), 500 m south-southwest of San Sebastián.[2]

Above the basal beds, the San Sebastián in the type area is characteristically mottled gray, blue gray, or green clay and silty clay that weathers to mottled red and yellow clay interbedded with thin-bedded silt. As mentioned by Hubbard (1923) and by Zapp, Bergquist, and Thomas (1948), lenses of earthy limestone are present in the upper half of the formation. Fossil shells and prints of fossils are found sporadically throughout the formation and particularly in the classic collecting beds on the walls of the gorge of Quebrada Collazo.

In 1967, the U.S. Geological Survey drilled a test well at the power substation (93,650 E., 56,430 N., San Sebastián quadrangle) at the north edge of the city of San Sebastián. D. H. McIntyre studied the cuttings from this well. He reported (written commun., 1967) that the boring penetrated about 170 ft (52 m) of San Sebastián and 130 ft (39 m) of the early Tertiary Río Culebrinas Formation to

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[2] Distances in this report are given in meters or kilometers measured in an airline distance from some point recognizable on the geologic map accompanying the report. Distances from a town are from the town plaza, which generally is near the center.

a total depth of 300 ft (90 m). Samples were not available for the first 100 ft (30 m). McIntyre reported about the San Sebastián part of the cuttings:

Fossil debris scattered throughout the San Sebastián Formation in this hole suggests that the formation is mostly, if not entirely, marine in this area.

Sand grains and pebble fragments in the San Sebastián Formation were derived from a variety of sources. Near the base of the formation, of course, Río Culebrinas Formation detritus predominates. Higher in the well, however, occur black chert (possibly from Yauco Mudstone), epidote-bearing red porphyritic volcanics from the Río Blanco Formation, and green porphyritic rocks resembling those that intrude the Río Blanco Formation. These formations are exposed chiefly south of the well site; the exposures closest to the well are about 7 km due south. One sample (140-145) contained a chip of serpentinite. The serpentinite exposures nearest the well are about 18 km distant, also to the south.

Fresh, transparent, colorless feldspar and quartz (bipyramidal in one instance) may be volcanic eruption products penecontemporaneous with deposition of the formation. Most feldspars derived from older volcanic rocks are cloudy. Surface exposures of the San Sebastián Formation near the mouth of Quebrada de Loro, 6 km west-northwest of San Sebastián contain fresh volcanic glass fragments, strongly suggesting peneconteporaneous volcanic activity.

On Highway 445, 800–1,700 m north of Highway 111, the upper part of the San Sebastián and the lower part of the Lares Limestone are exposed (92,400 E., 58,600 N., Central La Plata quadrangle). The upper part of the San Sebastián here consists of thin-bedded gray glauconitic marl containing abundant fossils, especially oysters and several species of *Pecten*. The base of the Lares consists of hard limestone that rests on compact gray glauconitic sand.

Between San Sebastián and Moca, the entire sequence of the Lares Limestone intertongues with clastic rocks indistinguishable from the San Sebastián Formation, and it has not been possible to trace a horizon in these rocks equivalent to the base of the Lares Limestone farther east. Hence, the rocks in that area are both of San Sebastián and Lares age. The rocks in the basal 20 m of the sequence are probably entirely of San Sebastián age; they consist largely of cobbles and boulders as much as 60 cm long of various volcanic rocks in a sandy clay matrix (fig. 6). Many of these boulders have weathered to a soft saprolite on the present surface of the volcanic rocks. Above the basal conglomerate, the San Sebastián consists of a lenticular sequence of sand, silt, and clay, derived from volcanic rocks, commonly light yellowish brown to red, interbedded with lenses of sand and gravel, containing pebbles generally less than 2 cm in diameter. Some of the sand beds are cemented by calcium carbonate. These sand beds and some of the silt beds contain oysters and other shells, and locally they contain coral heads.

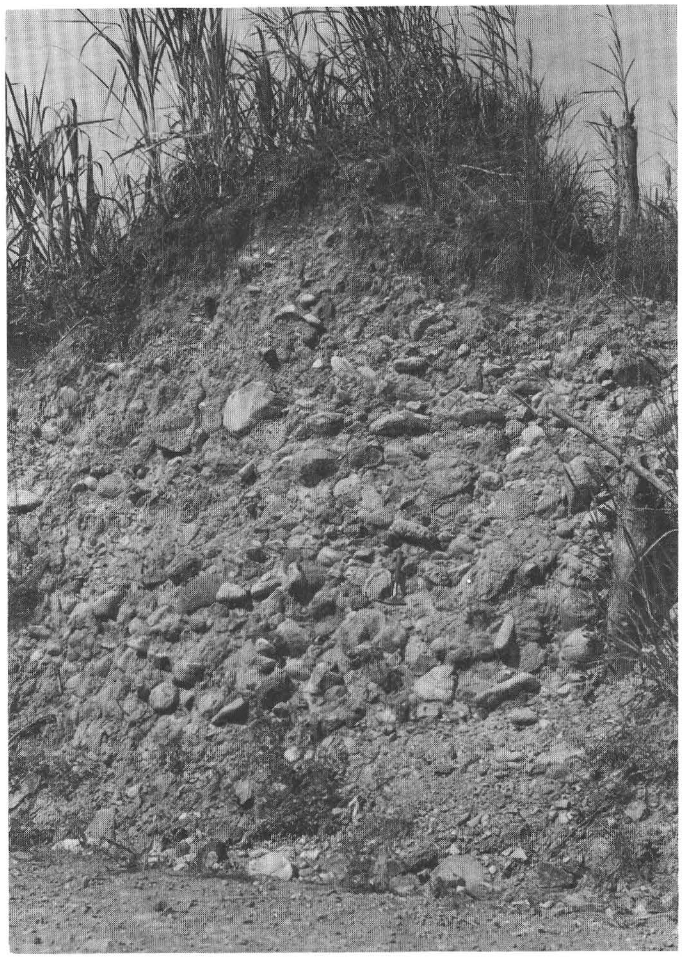

FIGURE 6.—Cobbles in sand of San Sebastián Formation about 30 m above base; roadcut at Isleta, 2.4 km south of Moca (November 1967).

A section 40 m thick in which the San Sebastián is apparently overlain directly by the Cibao Formation is exposed discontinuously in the bed of a small creek (79,610 E., 63,360 N., Moca quadrangle) about 1.3 km northwest of Moca. Bergquist, in January 1945, collected nearly 40 species of fossils (USGS Coll. 17283) from this section, and he stated (written commun., June 1945) that the material contains some of the best preserved mollusks ever obtained from Puerto Rico.

Near Lares, the upper middle part of the formation contains several thin beds of lignite. In the section exposed along Highway 111 in the northern part of Lares (105,150 E., 51,860 N., San Sebastián quadrangle), 5 beds of lignite (fig. 7), each about 10 cm thick, are exposed in a sequence of silty

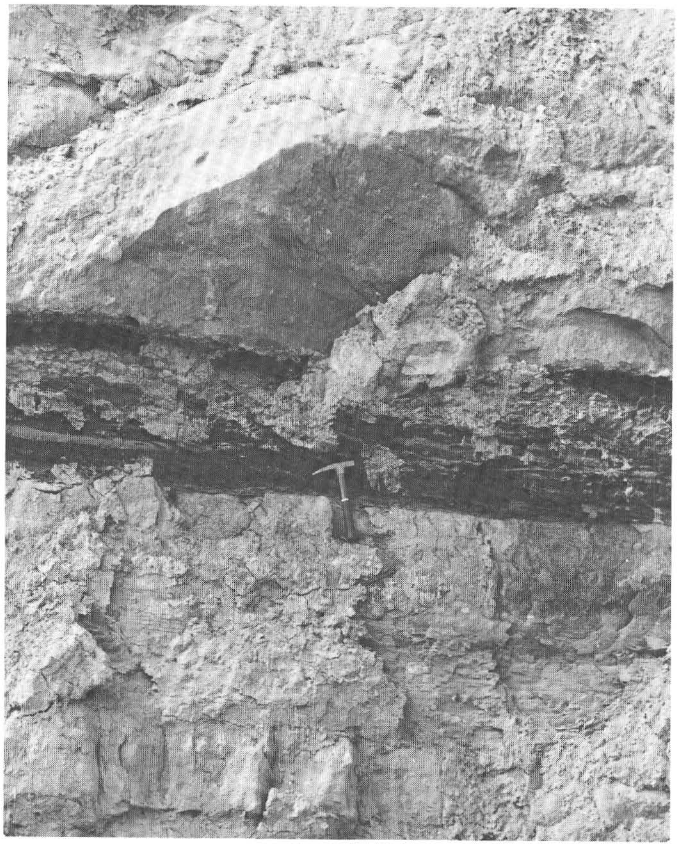

FIGURE 7.—Lignite beds in San Sebastián Formation in cut on bypass of Highway 111 at Lares (105, 150 E. 51, 860 N., San Sebastián quadrangle) (January 1967).

carbonaceous clay and fine sand, whose top is 21 m below the base of the Lares Limestone.

At this locality, Graham and Jarzen (1969) obtained 50 samples, and from 27 samples they extracted plant microfossils. They reported that pollen from the mangrove *Rhizopora* makes up 61–77 percent of the samples from the lignite beds along Highway 111 at Lares.

Lignite has also been reported near San Sebastián (M. D. Turner, oral commun., 1958), but I have not seen the deposits in that area. C. W. Cooke (unpub. data, 1957) reported soft carbonaceous shale and lignite overlain by brown sand at Km-28, Hm-7 on Highway 111, 3 km east of Lares. Briggs (1961) recorded a bed of coal in the San Sebastián in an oil test well drilled on the Atlantic coast east of Arecibo.

Nelson and Tobisch (1968) reported that between Lares and the Río Grande de Arecibo the San Sebastián consists of brown-to-red to yellow-to-orange poorly consolidated sandstone, siltstone, shale, clay, and conglomerate, and some calcareous layers near top of the formation. The sandstone ranges from fine to coarse grained and commonly contains clay between well-rounded grains.

On Highway 146 about 8.5 km west-southwest of Ciales, a cut on the north side (140,900 E., 51,540 N., Florida quadrangle) shows one of the few visible contacts of the San Sebastián on the older rocks, which here are tuff breccias of the Pozas Formation. The contact is nearly flat. The San Sebastián consists of reddish clay containing highly weathered boulders of volcanic rock, as much as 30 cm in diameter. Above the basal conglomeratic beds, the San Sebastián in this area consists mostly of pale-red clay containing black stains of manganese oxide.

In the Ciales quadrangle, Berryhill (1965) divided the San Sebastián Formation into two members. His upper sandy limestone member is now considered a part of the Mucarabones Sand and will not be discussed here. His lower sand and gravel member is the eastward continuation of the San Sebastián Formation. He (p. 75) described the lower part as "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." He pointed out that the thick conglomeratic lenses at the base contain detritus from almost every Upper Cretaceous and lower Tertiary rock unit in the area. In the upper part of the San Sebastián, as here restricted, he reported interbedded fine-grained partly calcareous friable sandstone and subordinate thin beds of gravel and of olive-gray and pale-red silty clay. The clay beds are particularly noticeable in cuts on Highway 159 2–3 km east of Morovis. When wet, the clay is very unctuous, and apparently it has slipped out from under the massive Lares Limestone to form the landslides along the Río Unibón and those about 5 km farther northeast in the valley of the Río Cibuco, west of Corozal (Monroe, 1964a).

In the Corozal area, the upper part of the San Sebastián is freshly exposed in many streambanks, but probably the most complete exposure is at a waterfall about 25 m high (161,300 E., 56,560 N., Corozal quadrangle), which is some 400 m southwest of Cibuco Triangulation Station and 3.2 km due west of Corozal. Here, slightly glauconitic silt is overlain by grayish-green sandy glauconitic clay, which is in turn overlain by beds of clay a meter or more thick. At the top of the waterfall are thick beds of very glauconitic slightly sandy chalky limestone, which probably is a part of the Mucarabones Sand. Elsewhere in the area, bluish-gray silt and sandy clay are common at the top of the formation.

THICKNESS

The San Sebastián Formation varies in thickness inversely with the height of the hills on the old erosion surface on which it was deposited. Between San Sebastián and San Juan, the formation ranges from 0 to about 100 m in thickness, averaging about 70 m. The formation seems to thicken toward the north, possibly because it is an onlapping unit, which includes downdipped beds that are older than any exposed on the outcrop. Briggs (1961) in his study of of the Kewanee Interamerican Oil Company's test well, 4CPR drilled near the Atlantic coast east of Arecibo, considered that the well was drilled through San Sebastián between depths of 4,505 and 5,527 ft and possibly also between depths of 5,527 and 5,580 ft. This identification indicates that the formation is some 310–328 m thick in the test well.

West of San Sebastián, in the area where rocks assigned to the San Sebastián Formation include clastic strata that are time correlative with the Lares Limestone farther east, the formation is locally as thick as 155 m. This indicates a remarkable thinning toward the west of the combined San Sebastián and Lares Formations, for near Lares the San Sebastián is about 80 m thick and the Lares is about 280 m for a combined total of about 360 m; whereas at Aguadilla, neither the San Sebastián nor the Lares is present. This thinning of the sequence suggests that most of the clastic rocks assigned to the San Sebastián near Moca are coeval with the Lares.

FOSSIL CONTENT AND AGE

The San Sebastián Formation contains a variety of fossils of animals and plants. The formation has long been known for the excellently preserved molluscan shells that have been collected from beds of sandy clay and earthy limestone exposed in the bottom and banks of Quebrada Collazo. Maury (1920) listed 18 species collected by C. A. Reeds, of which 9 are restricted to the San Sebastián Formation as presently defined. Hubbard (1920b) listed 29 species, of which 12 were found only in the San Sebastián. Most of the fossils collected by Reeds and Hubbard are from Quebrada Collazo, referred to as Collazo River. Bergquist (written commun., 1945) reported 87 species found in many outcrops of the San Sebastián Formation—included were 4 echinoids of which 2 were restricted to the San Sebastián, 1 was found in the San Sebastián and the beds transitional with the Lares, and 1 ranged from the San Sebastián into higher formations. He recorded 35 species of gastropods of which 20 were restricted to the San Sebastián, 5 were found in the San Sebastián and also in the Juana Díaz Formation in southern Puerto Rico, 3 were from the San Sebastián and the transitional beds at the base of the Lares, and 7 ranged from the San Sebastián into still higher formations. He also listed 48 species of pelecypods of which 23 were found only in the San Sebastián; 5, in the San Sebastián and Juana Díaz; 3, in the San Sebastián and basal Lares; and 17 ranged upward into much younger formations, even to the top of the middle Tertiary.

These studies show that more than 62 of the species of fauna found in the San Sebastián are restricted to the formation and the overlying transitional beds. Only 10 species are common to the San Sebastián and the Juana Díaz in southern Puerto Rico. Most of the species are types that prefer a muddy or sandy bottom.

All the plant fossils collected from the middle-Tertiary rocks of Puerto Rico are from the San Sebastián Formation mostly from the Lares–San Sebastián area. In 1915–16, Hubbard made a small collection of leaves from carbonaceous shale on Quebrada Collazo near the base of the second falls below the bridge on Highway 111. In 1926, N. L. Britton and Arthur Hollick made a much more complete collection from the entire sequence exposed in the gorge, although most of their specimens came from the first and second falls below the bridge. They collected a large number of specimens, including 91 species and 50 genera, of which the majority are dicotyledons. Hollick (1928) considered that the entire flora is typical of a tropical environment mostly near lagoons or estuaries in which brackish water was present. Although the flora is Tertiary in age, it is almost identical generically with the existing flora of Puerto Rico and adjacent regions.

Graham and Jarzen (1969) have studied the plant microflora of the San Sebastián from three localities, two near Lares and one in Quebrada Collazo. The beds of lignite in the section on the bypass of Highway 111 near Lares (105,150 E., 51,860 N., San Sebastián quadrangle) are composed largely of pollen from the mangrove *Rhizophora*. Graham and Jarzen stated (1969, p. 346) that about 75 percent of the genera identified grow in the West Indies today, but seven genera no longer do. Three genera, *Fagus*, *Liquidambar*, and *Nyssa* are known today only from temperate to cool-temperate climates. On this basis Graham and Jarzen postulated that during the Oligocene there must have been mountains nearby that were higher than 3,175 m above sea level; the pollen of these three species could then have been blown by the wind or washed in streams to the site where the pollen was embedded in the clay of the San Sebastián Formation. D. H. McIntyre (oral commun., 1970) found pieces of silicified wood in the bed of the Río Culebrinas. He believed that it came from outcrops of the San Sebastián, but he did not find any petrified wood in place in the formation.

The age of the San Sebastián Formation has been generally considered as Oligocene. On the basis of the mollusks and echinoids, Hubbard (1923) and Zapp, Bergquist, and Thomas (1948) assigned the formation to the middle Oligocene. Sachs (1959), on the basis of two collections from the middle and upper part of the formation between Lares and San Sebastián, definitely placed the formation in the upper Oligocene because the collections contain the species *Lepidocyclina* (*Eulepidina*) *undosa,* which is restricted to the middle and upper Oligocene, and the genus *Miogypsina,* which ranges from the upper Eocene to the middle Miocene. There seems little doubt, then, that the San Sebastián Formation is at least as young as middle Oligocene and is probably late Oligocene.

ORIGIN

Just before deposition of the San Sebastián Formation, the landmass that is now Puerto Rico was considerably larger than it is today, and it stood higher above sea level. Graham and Jarzen (1969) postulated that some of the spores they have recovered from the San Sebastián came from plants that live only in a temperate climatic zone, which in the latitude of Puerto Rico would be found only above 3,000 m. The upland was drained by several large rivers some of which persisted during deposition of the upper Oligocene and lower Miocene formations.

At some time during the early Oligocene, the Puerto Rico Trench north of Puerto Rico began to subside (Monroe, 1968d), dragging the northern coast down with it and thus permitting the ocean to flood inland over the land surface. The soil that had accumulated on the upland surface throughout the early Oligocene and perhaps during a part of the Eocene was eroded and then deposited in the transgressing sea as the silty clay that contains pebbles and cobbles in the lower part of the San Sebastián Formation. The presence of marine shells and prints and molds of mollusks fairly low in the formation shows that the clastic materials were deposited in the sea or in estuaries near the sea. The lignite near Lares and San Sebastián consists largely of material derived from mangrove swamps (Graham and Jarzen, 1969) almost certainly similar to the coastal swamps of present-day Puerto Rico.

The supply of clastic material gradually diminished, and deposition of calcareous mud gradually predominated, so that the upper part of the formation contains beds of calcareous clay and earthy limestone some of which contain such lime-secreting organisms as corals and algae. At the end of San Sebastián time, the supply of clastic material was exhausted, except near the rivers described below; and at most places, the generally epiclastic San Sebastián sediments graded upward into the fairly pure limestone of the Lares.

The San Sebastián Formation was deposited on a fairly rugged surface. High hills on this surface in the vicinity of what is now the Río Grande de Arecibo persisted as islands throughout San Sebastián and Lares time. Both east and west of this high area, the San Sebastián contains little coarse epiclastic sediment for several kilometers. West of San Sebastián, however, the formation contains abundant pebbles and cobbles, which probably indicate that a large river emptied into the sea close by. This was one of the major rivers of Puerto Rico during Oligocene and early Miocene time, for deposition of coarse clastic material continued in the area throughout Lares and most of Cibao time. The San Sebastián contains considerable gravel in the vicinity of Corozal, suggesting that another large river entered the sea in that area.

Apparently deposition of the San Sebastián was restricted to a basin on the shelf that did not extend west of Aguadilla or east of San Juan, although deep wells drilled in the sea northwest of Aguadilla or on land in the Carolina-Loíza area may find some San Sebastián downdip in areas where it does not now crop out.

PHYSIOGRAPHIC EXPRESSION

Throughout most of its belt of outcrop, the San Sebastián Formation is on a steep escarpment (Blume, 1968), which ranges in slope from about 20° to nearly vertical. Weathered volcanic rocks crop out at the foot of the scarp; and at most places, a cliff of the overlying Lares Limestone forms the crest. At most such places, the San Sebastián is covered by masses of limestone and clay that slid down the slope when the clay of the San Sebastián became wet (Monroe, 1964a).

At a few places, the San Sebastián extends updip for 1 or 2 km from the Lares scarp. The most notable places are in the vicinity of San Sebastián—the Caguana area, 4 to 6 km west-northwest of Utuado, and a small area in barrio Frontón of Ciales about midway between the Río Grande de Arecibo and the Río Grande de Manatí. At all these places, the San Sebastián crops out in gently rolling hills having a hill-to-swale relief of 20–40 m, sloping generally parallel to the dip and having a total relief of about 60 m. Most of these areas are densely forested, for they are especially favored for raising coffee.

At both ends of the belt of outcrop of the San Sebastián where the Lares Limestone grades laterally into clastic facies, the San Sebastián crops out in low rolling hills. In the Bayamón area, these hills are commonly less than 20 m high, but in the area between San Sebastián and Moca where the San Sebastián includes the clastic facies of the Lares Limestone, the hills are as high as 50 m above the valleys.

LARES LIMESTONE

NAME

The Lares Limestone was first adequately described by Hubbard (1923) as the Lares formation, although the name had previously been used by Berkey (1915) as Lares shales. Hubbard (1923, p. 42) defined the formation as "the massive limestone overlying the San Sebastián shale, and most conspicuous north of the town of Lares." Zapp, Bergquist, and Thomas (1948, sheet 2) used the term Lares Limestone for "relatively pure limestone made up principally of the remains of marine organisms" and included in the formation two great bioherms of Oligocene and Miocene(?) age, the upper parts of which are assigned in this report to the Cibao Formation. Nelson and Monroe (1966) restricted the Lares Limestone to limestone beds below rocks that can be traced laterally to the west and to the east into the clay and chalk that previous writers (Hubbard, 1923; Zapp and others, 1948) had designated Cibao. The upper part of the western bioherm of the Lares of Zapp, Bergquist, and Thomas (1948) is now called the Montebello Limestone Member of the Cibao Formation, and the upper part of their eastern bioherm is now considered the Río Indio and Quebrada Arenas Limestone members of the Cibao. Although Hubbard designated no type locality, he referred many times to the limestone at the top of the escarpment north of Río Guajataca at Lares.

AREAL DISTRIBUTION

The Lares Limestone crops out in a continuous belt of limestone from the vicinity of San Sebastián eastward to the vicinity of Corozal. West of San Sebastián, the limestone intertongues with clastic beds of sand, clay, and cobbles that are assigned to the San Sebastián Formation (Monroe, 1969b).

The basal few meters of the Lares grades laterally into calcareous sandstone near Ciales. This sandstone is a westward-extending tongue of the Mucarabones Sand, which is thicker east of Corozal. Between Corozal and the Río de La Plata, the entire sequence of limestone of the Lares grades laterally into crossbedded sand and rather friable calcareous sandstone of the Mucarabones Sand. At the type locality of the Mucarabones, about 2 km due southeast of Toa Alta on Highway 861, about 1.5 m of limestone in a sequence of sand is apparently the easternmost outcrop of material that resembles the Lares farther west.

STRATIGRAPHIC RELATIONS

The Lares Limestone is gradational into the underlying San Sebastián Formation, and in the western part of Puerto Rico, Lares intertongues with sand and gravel beds that are indistinguishable from the San Sebastián (fig. 8). At places where the San Sebastián is missing, the Lares rests directly on the basement. The Lares is overlain sharply, but probably conformably, by the Cibao Formation. At most places, the uppermost beds of the Lares are relatively pure limestone, whereas the basal beds of the Cibao are either calcareous clay or earthy limestone. Furthermore, the lower Cibao strata are generally a darker orange than the underlying Lares, except in the area where the lower part of the Cibao is the Montebello Limestone Member. Commonly, the base of the Montebello is marked by a bed, 1–5 m thick, of oyster shells, as much as 12 cm in diameter.

LITHOLOGIC CHARACTER

The Lares Limestone consists mainly of indurated very pale orange fine- to medium-grained calcarenite stratified in beds from 10 cm to about a meter thick. Characteristically, the limestone is fossiliferous, containing abundant calcareous algae, large foraminifers such as *Lepidocyclina,* and, more locally, coral heads. The limestone forms the crest of a scarp between San Sebastián and Corozal. In this area, it consists mainly of very pure calcium carbonate except in the basal few meters, which com-

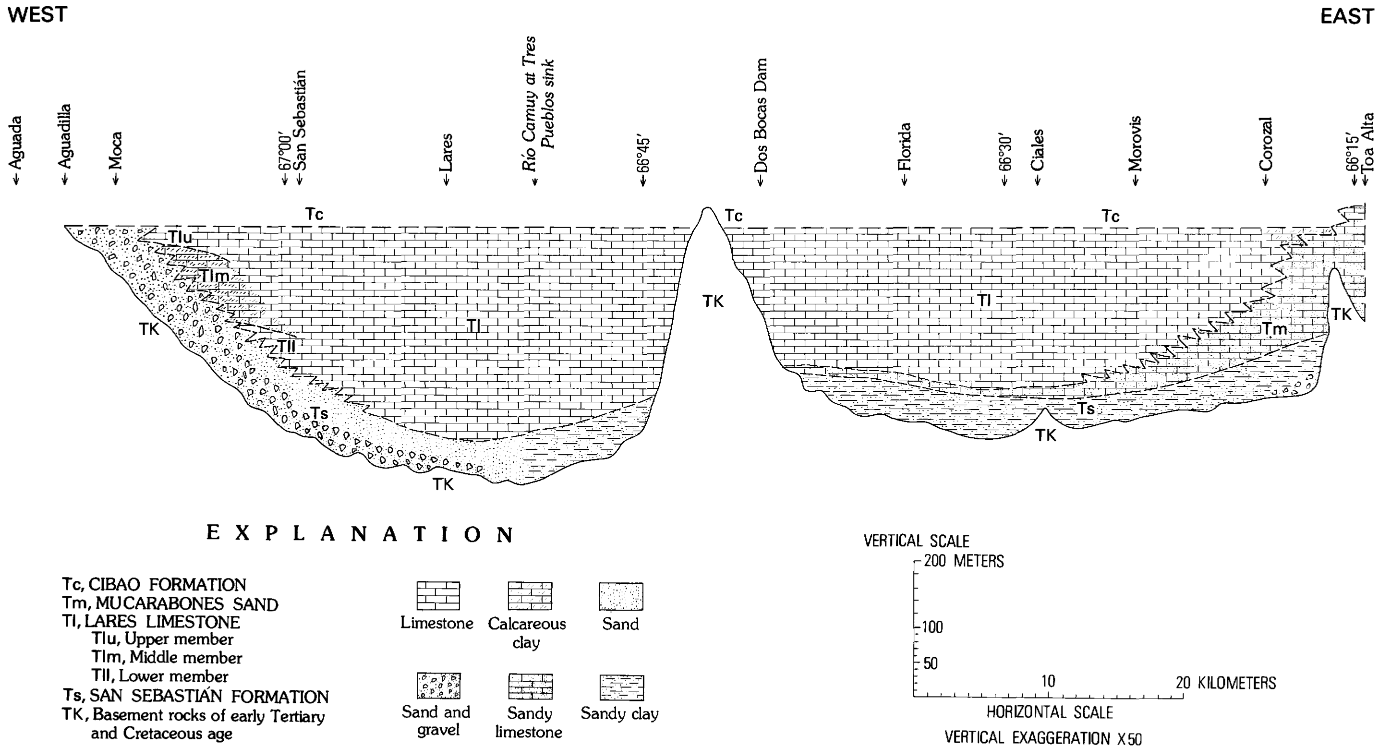

FIGURE 8.—Stratigraphic diagram showing intertonguing lithology of the Lares Limestone with the San Sebastián Formation and the Mucarabones Sand.

monly is somewhat sandy; the sand is mostly fine to medium grains derived from weathered volcanic rock and, in a few places, quartz. As can be seen in the chemical analyses[3] in table 1, the amount of noncarbonate material is very small, except in samples Field No. SS138 from the basal bed and Field No. MO184 from the area where the Lares is grading laterally into clastic beds assigned to the San Sebastián Formation.

Thin sections of six samples of Lares show that it is rich in foraminifers, algae, and other fossils and that most samples consist of fossiliferous intrasparite and packed biomicrite, according to the classification of Folk (1959, 1962) (see figs. 9, 10, and 12).

EXPOSURES IN THE TYPE AREA

Hubbard (1923) did not designate an exact type locality, but he referred (1923, p. 42) to outcrops on the cuesta north of the town of Lares. He showed this outcrop in cross section in his plate 1 and graphically in a vertical section in his plate 2. In

[3] In most of the chemical analyses included in this report, the percentage of carbon dioxide shown is excessive when compared with the percentage of lime, magnesia, and iron. I suspect that this represents organic matter that probably was present in the samples, all of which were collected from places subject to contamination by lichen and other plants.

TABLE 1.—*Chemical analysis of Lares Limestone*

[Analyzed by rapid method (Shapiro, 1975); analysts: Paul Elmore, L. Artis, S. D. Botts, G. Chloe, J. Glenn, J. Kelsey, H. Smith]

Lab. No.	W170035	W170036	W170038	W170033	W172–798
Field No.	SS133 [1]	SS138 [2]	MO184 [3]	BL95 [4]	F193 [5]
SiO_2	6.4	1.2	16.9	0.29	0.56
Al_2O_3	2.7	.51	5.1	.14	.18
Fe_2O_3	2.3	.00	2.2	.00	.09
FeO	.12	.12	.12	.00	.00
MgO	1.2	.91	1.6	.42	.34
CaO	46.8	52.7	38.4	54.2	53.3
Na_2O	.11	.00	.19	.00	.03
K_2O	.23	.05	.43	.02	.10
H_2O-	.94	.13	2.2	.05	.10
H_2O+	.96	.51	1.6	.28	.60
TiO_2	.07	.02	.24	.00	.02
P_2O_5	.09	.03	.09	.04	.04
MnO	.05	.00	.02	.00	.00
CO_2	38.0	43.7	30.8	44.5	44.5
Total	100	100	100	100	100
Acid Insoluble	-----	-----	-----	-----	0.52

[1] Hard sandy limestone just above San Sebastián Formation in cut on Highway 438, 60 m south of Highway 111, 5.8 km east-southeast of San Sebastián (98,950 E., 53,950 N., San Sebastián quadrangle).

[2] Hard limestone about 75 m above San Sebastián Formation in cut on Highway 451, 700 m east of Highway 111, 5.8 km east of San Sebastián (99,210 E., 54,760 N., San Sebastián quadrangle).

[3] Fossiliferous marly limestone in middle member of Lares in cut on west side secondary road, 1.4 km north of Highway 111, 6 km northwest of San Sebastián (88,850 E., 60,140 N., Moca quadrangle).

[4] White chalk in upper part of Lares in cut on southwest side of paved secondary road, 200 m west of Highway 129 (110,960 E., 55,560 N., Bayaney quadrangle).

[5] Limestone about 50 m below top of Lares at floor of quarry southeast of Highway 140, 3 km southwest of Florida. (136,120 E., 56,500 N., Florida quadrangle).

the latter he showed "lime sand" at the top of the San Sebastián overlain by fossiliferous massive limestone. Presumably this section was drawn from notes made on the trail that climbs the cuesta from Río Guajataca 1.2 km north by west of Lares. There he showed 220 ft (67 m) of San Sebastián overlain on the scarp by about an equal thickness of limestone of the Lares.

A series of excellent exposures of the lower 100 m of the Lares is exposed along Highway 451, which extends almost due east from Highway 111 to the sharp northward bend of Río Guajataca. Low cuts on the north side of the road about 750 m east of Highway 111 expose very pale orange, very fine grained hard calcarenite that contains impressions of fossils; the rock contains cavities that were probably formed by solution of fossils; some of these cavities are lined with calcite crystals and others with limonite. An analysis of this rock, SS138, is included in table 1; it is very pure calcium carbonate, containing less than 2 percent impurities. Similar rock, about 25 m higher stratigraphically, was collected about 200 m farther east (99,350 E., 54,830 N., San Sebastián quadrangle) on the south side of the low hill north of the road. A thin section of this rock (fig. 9) is apparently packed micrite consisting of abundant fossil fragments, mainly of foraminifers and algae; secondary sparry cement is present only in vugs and veins. The foraminifers include both benthonic and planktonic forms. Sachs (written commun., 1971) recognized *Lepidocyclina yurnagunensis* and *Heterostegina* sp., probably *H. antillea*. Highway 451 ends in a trail that leads down to a bridge across Río Guajataca; at the bridge is an exposure of about a meter of calcareous fine sand that looks like San Sebastián Formation but may be a tongue of sand in the Lares. Limestone is exposed upstream from the sand, but more sand is exposed at a few places in the valley of Quebrada Las Varas, which enters Río Guajataca at the sharp bend in the river. The stratigraphic position of these sand beds is uncertain. Perhaps they are San Sebastián raised by a small anticline or by minor faulting, or they may be lenses or tongues of sand in the Lares, which a few kilometers farther west in the valley of Río Guatemala become part of the main body of the San Sebastián Formation.

The probability that these beds are a part of the Lares, rather than of the San Sebastián, is strengthened by the presence of beds of clay and sand elsewhere in the Lares. At the west end of the large hairpin bend on Highway 119, 1.7 km northeast of San Sebastián, several meters of waxy medium-gray clay containing abundant small foraminifers overlies at least 25 m of very pale orange to grayish-orange chalk that probably is best assigned to the basal Lares. A similar bed of very fossiliferous tough medium-gray clay is present a few meters below the top of the Lares in a cut at the crest of a low ridge on Highway 147, 1.2 km north of the intersection with Highway 119.

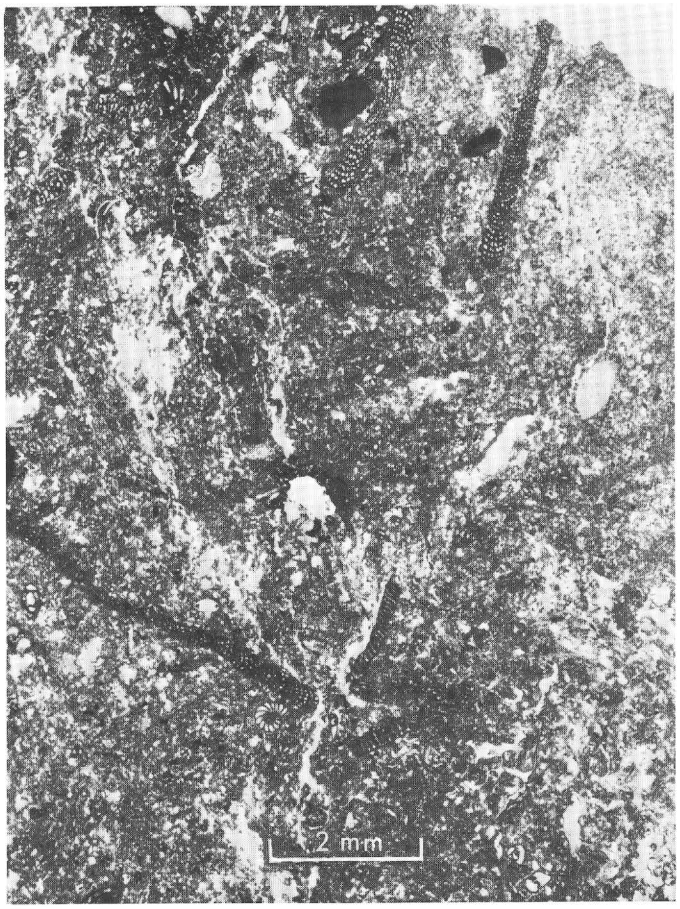

FIGURE 9.—Photomicrograph of Lares Limestone, lower part, a few meters above Highway 451, 5.9 km east of San Sebastián. Micrite contains abundant fossil fragments, mainly of foraminifers and calcareous algae. Sparry cement present in vugs and veins.

The upper part of the Lares Limestone in the type area contains abundant coral heads in soft, unconsolidated-to-hard recrystallized limestone. The top of the formation consists of dense, tightly cemented, very fine grained calcarenite, which is overlain sharply by soft limestone, the base of which is a bed 5 m or more thick consisting mainly of large oysters, probably *"Ostrea" haitensis*; this is the basal unit of the Montebello Limestone Member of the Cibao Formation.

Exposures East of the Type Area

Between the type area and the Río Grande de Arecibo, the Lares consists largely of pale-orange to white fine calcarenite, which is commonly rich in coral heads, algae, foraminifers, and other fossils. In the upper part of the formation is a lens of nearly pure, white chalk in the area just west of Highway 129. An analysis of this chalk (table 1, Field No. BL95) shows that it contains less than half a percent of impurities.

Farther east in the Florida quadrangle, Nelson and Monroe (1966, p. C15) described the Lares:

> The basal 30–50 meters of the Lares consists of thin-bedded to flaky limestone that contains fine to medium grains (Wentworth scale) of limonitic rock that may represent weathered fragments of volcanic debris. The ferruginous grains are abundant in the basal 10 meters, but are sparse in higher beds. The flaky limestone is overlain by finely crystalline, pink to yellowish-gray limestone that is massive to thin-bedded. In the eastern part of the quadrangle, very pure, white, crystalline chalk is present from about 90 to 110 meters above the base of the formation. From about 140 to 150 meters above the base, the formation consists of rather coarse-grained fragmental limestone; above 150 meters, it consists of very fine grained crystalline limestone.

At the southeast side of Highway 140, about 3 km southwest of Florida, P.R., a large quarry in the Lares is operated for production of agricultural limestone. An analysis of this limestone (table 1, Field No. F193), shows less than 1 percent of noncarbonate rock. Thin-section study shows that the rock is packed micrite containing many fragments of fossils, mainly foraminifers, including *Lepidocyclina* sp., and a few algal laths. The thin section also contains a few opaque grains, probably limonite or limonitic clay, a few widely scattered grains of quartz, and a few small grains of epidote(?).

Thin sections were studied of two other samples of Lares Limestone collected from cuts along Highway 140 southwest of the quarry. One of these (fig. 10) from a bed at the side of the highway, 4.2 km southwest of Florida, P.R., estimated to be about 190 m above the base of the formation (135,190 E., 55,870 N., Florida quadrangle), consists mainly of algal remains, many of which are nearly opaque, a few foraminifers, abundant intraclasts of micrite, and a little sparry cement, probably classifiable as a biomicrite. Some of the algal fragments have a rim of spar calcite. Sachs (written commun., 1971) recognized *Heterostegina* sp., and *Lepidocyclina* sp. in thin section.

In the eastern part of the Florida quadrangle and in the western part of the adjacent Ciales quadrangle, the lower 30 m of the Lares consists of thin-bedded, rather slabby limestone that contains many ferruginous grains and locally a few quartz grains. This lithology is transitional near the Río Grande de Manatí into calcareous sandstone, which was mapped by Berryhill (1965) as a sandy limestone member of the San Sebastián Formation but which is now considered a westward-extending tongue of the Mucarabones Sand.

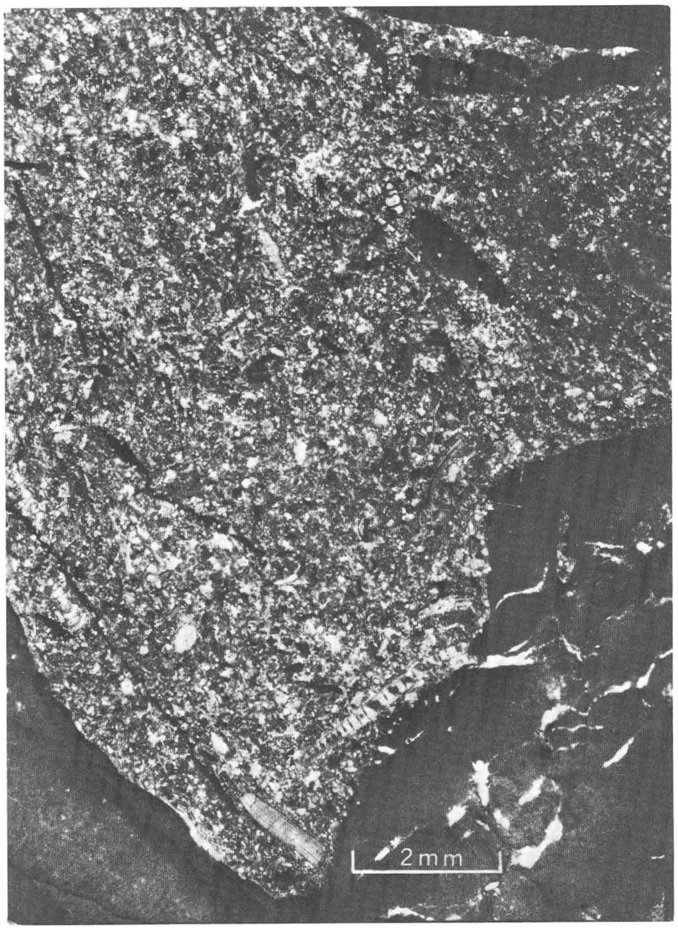

Figure 10.—Photomicrograph of Lares Limestone, middle part, from cut on west side of Highway 140, 4.2 km southwest of Florida, P.R. Biomicrite containing very large algal fragments, some having rims of calcite spar. An exceptionally large algal fragment covers bottom edge of the photograph.

In the valley of the Río Grande de Manatí, the lowest part of the Lares Limestone, resting on ferruginous sandy limestone of the Mucarabones, is about 20–30 m of crosslaminated limestone, which seems to have been deposited in an area of strong currents. This limestone grades up into very massive limestone, so massive that the single bedding plane can be recognized at a distance of 200 m. The great bend of the Río Grande de Manatí, just northwest of the bridge on Highway 149, is an incised meander in this massive limestone, and the single bedding plane is visible from Highway 149. Massive limestone of this kind (fig. 11) continues eastward for about 3 km, giving rise to the classic cone-karst topography on the upland 1.3–2.7 km east-northeast of Ciales. About 2.3 km east of Ciales, the limestone changes within a distance of a hundred meters from massive to thin-bedded, and the topographic expression changes suddenly from cone karst to the well-known zanjón karst of Morovis (Monroe, 1964b). This thin-bedded limestone extends about 3 km farther east to about the longitude of Morovis where there is an equally abrupt change from thin-bedded limestone to thick-bedded and massive limestone.

A thin section (fig. 12) of the thin-bedded limestone from the lower part of the Lares Limestone, collected from the side of a zanjón near the foot of a hill 3.2 km east-northeast of Ciales (151,820 E., 56,690 N., Ciales quadrangle), shows a closely packed mass of foraminifers and intraclasts of micrite and a little ferruginous clay. Sparry cement is present only in the centers of fossils. The rock is essentially a coquina of very small shells.

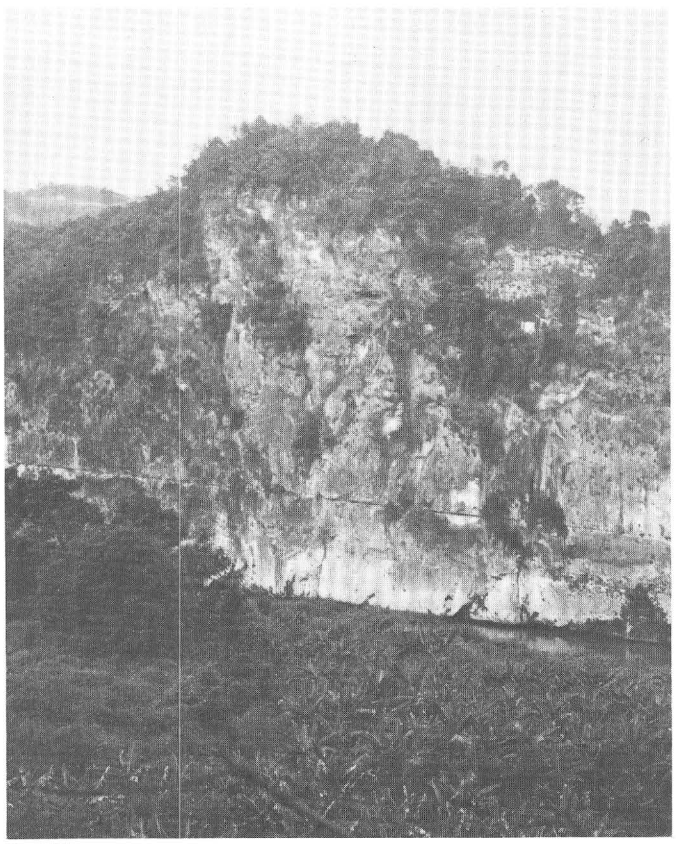

FIGURE 11.—Massive limestone in middle part of the Lares Limestone in wall on left (northwest) bank of the Río Grande de Manatí, 3 km north-northwest of Ciales. Note prominent bedding plane mentioned in text (February 1971).

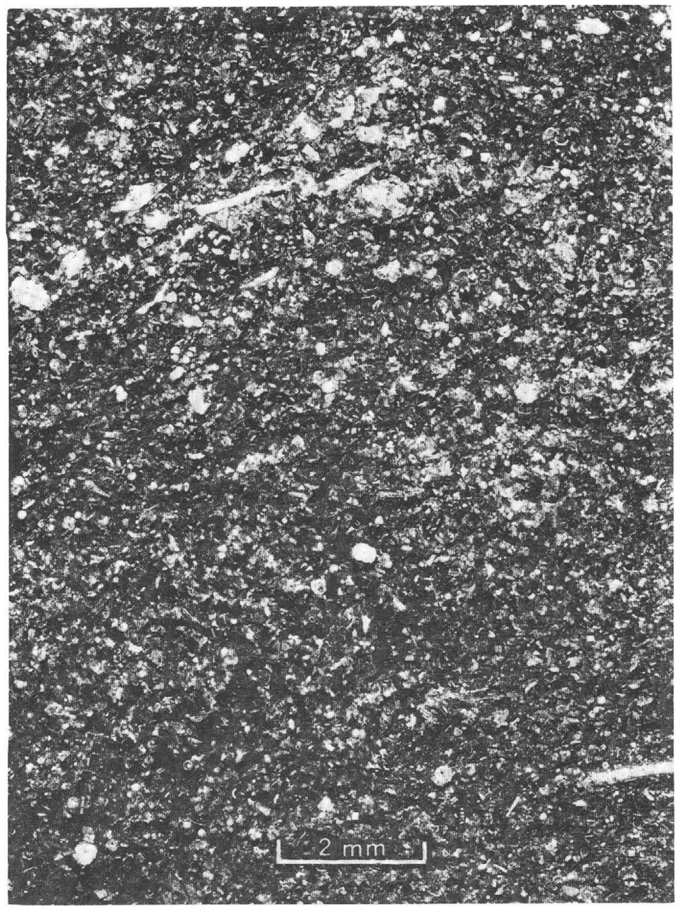

FIGURE 12.—Photomicrograph of Lares Limestone, lower part, from side of a zanjón at foot of hill, 3.2 km east-northeast of Ciales. Calcarenite containing closely packed mass of foraminifers and intraclasts.

At several places in the valleys of the Río Unibón and the Río Mavilla, the lower middle part of the Lares Limestone is thin bedded and partly cross-bedded (fig. 13). At places, the limestone is ripple-marked, showing that it was deposited in relatively shallow water affected by strong currents. East of the Río Unibón, successively higher parts of the Lares Limestone grade into the Mucarabones Sand, but the limestone remains fairly typical as far east as the longitude of Corozal. Still farther east, most of the formation is calcareous clay, and the Lares is not recognized east of Río de La Plata.

Two km northwest of Corozal, near the top of the escarpment, a bed of soft limestone contains abundant *Lepidocyclina undosa* at a stratigraphic position 30–40 m below the contact with the overlying Cibao

FIGURE 13.—Crossbedding in lower part of Lares Limestone in cliff on west side of Río Unibón above landslide (157,030 E., 57,190 N., Ciales quadrangle), 3.1 km northeast of Morovis. The upper beds dip 4½° N. and the beds below dip 13° N. The upper bed shows cross sections of ripple marks (October 1960).

Formation. This bed appears to be continuous at about the same stratigraphic position for 6 km to the north-northeast; but to the east of the Río Mavilla, it is at the base of the calcareous clay mapped as Lares. The bed rests on a highly glauconitic bed in the Mucarabones Sand. At its easternmost extremity, however, the overlying calcareous clay mapped as Lares is only 20 m thick.

EXPOSURES WEST OF THE TYPE AREA

In extreme northwestern Puerto Rico between San Sebastián and Moca, the Lares Limestone grades laterally into epiclastic beds indistinguishable from the San Sebastián Formation. In this area, the Lares is divided into three informal members—lower, middle, and upper (Monroe, 1969b).

The lower member, gradational into the underlying San Sebastián Formation, consists of sandy marl interbedded with soft, locally very fossiliferous limestone. Excellent exposures of the unit are found on Highway 445 above the landslide debris 1–1.5 km north of Highway 111. There, 5 m of alternating hard blue-gray marlstone that weathers yellow and beds of hard light-gray limestone, made up largely of coral heads, rest on 20 m of blue-gray marl containing abundant large oysters, echinoids, and other fossils. The marl bed is transitional into the San Sebastián Formation, which is exposed at a few outcrops below the landslide.

The middle member consists of 40–80 m of white to yellow and pale-orange chalk and calcareous clay containing many oysters and other mollusks and a few corals. Locally, it contains lenses of sand and gravel. Toward the west, it grades into and intertongues with sandy clay, sand, and gravel of the San Sebastián.

The upper member consists of 30 m or more of hard fossiliferous limestone interbedded with chalk and calcareous clay. Colors range from white to yellowish gray and very pale orange. Coral heads are common, and many beds are rich in molds of mollusks. The beds of limestone are resistant to erosion and form a line of peaks, easily recognized from the south, to a point about 3 km east of Moca. The member is overlain sharply by calcareous clay of the Cibao Formation.

Hubbard assigned to the Lares the limestone and marl beds exposed between Aguada and Ríncon in western Puerto Rico, but these beds contain Miocene fossils that are now considered upper Cibao.

SAMPLES FROM WELLS

Cuttings of rocks assigned to the Lares have been examined from three wells in Puerto Rico. Briggs (1961) assigned to the Lares 505 m of the limestone, calcarenite, and claystone encountered in the Kewanee Interamerican Oil Company Test Well 4CPR, between depths of 2,852 and 4,505 ft, but he suggested the possibility that the lower part of the Lares in the well "is made up of strata older than any beds assigned to the Lares in the outcrop," because they represent "earlier deposits of the encroaching middle Tertiary sea" (Briggs, 1961, p. 9). This well was drilled near the coast (130,830 E., 72,780 N., Arecibo quadrangle) about midway between Arecibo and Barceloneta.

A core of the Lares Limestone was cut in the Kewanee well between depths of 3,704 and 3,726 ft. A thin section of the core shows that the limestone is micrite, containing *Lepidocyclina* sp. and other foraminifers. The section includes cracks and voids, which have been partly filled with coarse-grained calcite spar. Briggs (1961, p. 7) reported that porosity of the limestone ranges from 9.5 to 18.2 percent, averaging about 13 percent, and that the permeability ranges from 0.6 to 34.6 millidarcies.

Samples were examined from a well drilled for water at the Arecibo Ionospheric Observatory (118,520 E., 57,100 N., Bayaney quadrangle). The contact with the overlying Montebello Limestone Member of the Cibao Formation is not certain but is probably about 25 ft below the well head. Below this point, the well penetrated about 265 m (875 ft) of limestone, all of which probably is Lares. At the bottom, at about 275 m (900 ft), the well was probably near or at the base of the Lares, as the last sample included some chips of pale yellow-brown silty clay that may be San Sebastián. This thickness of Lares is rather surprising, because only a kilometer to the south-southwest, volcanic breccia of the Jobos Formation (Nelson and Tobisch, 1968) is exposed in the valley of Río Tanamá, and at a place in the hills east of the river, a buried ridge of the basement has been exhumed. The altitude of the bottom of the well is about 15 m above sea level, and the altitude of the top of the Jobos Formation on the ridge is about 275 m.

Disposal well 1 of the Abbott Company, drilled at the northwest corner of the intersection of Highways 2 and 140, started in the Aymamón Limestone and was completed in the Lares. The bottom 236 m of this well (depths of 1,621 to 2,395 ft) is in a monotonous sequence of very pale orange limestone and fine- to medium-grained limestone sand of the Lares.

THICKNESS

The maximum thickness of the Lares Limestone along its outcrop belt is 310 m in the Bayaney quadrangle in the eastern part of the type area. Westward, it thins to a featheredge northeast of Moca where the lower part of the Lares grades laterally into stratigraphically equivalent epiclastic beds of the San Sebastián. East of the Bayaney quadrangle as far east as Ciales, the Lares is fairly constant in thickness, about 270 m, except in the Utuado and Florida quadrangles, where the lower part and locally the entire formation is missing on the buried hills of the basement described earlier. Between Ciales and Corozal, the formation thins from 260 m to about 40 m, and at the extreme northeastern part of the Corozal quadrangle near the Río de La Plata, the calcareous clay assigned to the Lares is only about 20 m thick.

Briggs (1961) assigned to the Lares about 505 m of the strata drilled in the Kewanee Interamerican Oil Company's Test Well 4CPR. This is thicker than any sequence of Lares Limestone exposed in Puerto Rico and may indicate some thickening downdip or a change in lithologic character of the San Sebastián from shale to limestone away from shore, or perhaps both.

FOSSIL CONTENT AND AGE

The Lares Limestone is rich in marine fossils similar to those living in a reef environment today, such as corals, algae, mollusks, and foraminifers. In addition, locally echinoids are common and at a few places, crab remains have been found.

The first interest in fossils in the Lares came from corals collected by R. T. Hill, probably in January 1899, and later studied by Vaughan (1919), who described 12 species, of which 4 were new. These corals and others collected by Reeds, Hubbard, and others were described by Coryell and Ohlsen (1929), who listed 33 species of corals from the Lares, of which 27 are not recorded from other formations. Apparently the collections accessible to these geologists were mainly from the Lares and Juana Díaz because only scattered specimens are listed from other formations, although abundant corals are also present in the Cibao, Aguada, Aymamón, and Ponce. Thus, the small stratigraphic range of their Lares species is probably not reliable. Large coral heads are prominent in the Lares in many outcrops of hard limestone, and in the softer beds, the finger corals *Porites* are notable.

Most useful in field correlations are two foraminifers that are abundant from the bottom to the top of the Lares and are found throughout most of the areal extent of the formation. These are *Lepidocyclina undosa* and its correlative *L. gigas* and the smaller *Heterostegina antillea*, which is especially notable in well cuttings and which first appears in wells at or just above the top of the Lares.

The most complete published study of mollusks from the Lares is that of Hubbard (1920b), who recorded 29 species. Most of these species are recorded only from the San Sebastián and Lares, but seven are also found in the Cibao, and four range as high as the Aymamón; only five mollusks are restricted to the Lares. Hubbard's stratigraphic assignments must be used with caution, however, as he included in the Lares a part of the limestone now consdered the Montebello Limestone Member of the Cibao Formation.

Bergquist (written commun., 1945) also studied the fossils of the Lares, but as he included the Montebello Limestone Member in the Lares, it is difficult to evaluate his findings. Bergquist called attention to the bulbose echinoid *Echinolampus lycopersicus* Jackson as having stratigraphic value because it ranges in Puerto Rico only from the San Sebastián Formation up through the Lares into the lower part of the Cibao Formation; most specimens have been found in the San Sebastián and the lowest 10 m of the Lares. Bergquist mentioned also that *Ostrea collazica* Maury is known only in the San Sebastián and Lares Formations; other oysters are locally common. Various species of *Pecten* are conspicuous in some beds.

Most of the fossils of the Lares have only fair stratigraphic value for determining the age of the formation. Many of the corals are also found in the Antigua Formation in the Lesser Antilles of late Oligocene or early Miocene age. On the basis of the abundance of the foraminifer *Lepidocyclina* (*Eulepidina*) *undosa*, the formation must be considered Oligocene, and on the basis of some faunal elements of Miocene aspect, it probably should be considered late Oligocene.

ORIGIN

The Lares Limestone was deposited in clear water, for throughout most of its outcrop it consists of nearly pure limestone that contains abundant coral heads. The Lares can be called a reef limestone because it contains abundant reef-forming organisms such as corals and algae and because thin sections (figs. 9 and 10) show that it is a skeletal limestone (Nelson and others, 1962). The limestone does not fit the classification of bioherm, however, for stratigraphic relations with clastic deposits both to the east and to the west indicate that the main mass of limestone never formed a lenslike mass projecting above the clastic sediments. Instead, tongues of the limestone project laterally into the clastic beds, showing that, while limestone was being deposited in one part of the basin, sand and clay were being deposited in about the same depth of water elsewhere.

During Lares time, the hills near the Río Grande de Arecibo at Dos Bocas projected above the sea forming islands; thus, very little sediment was supplied by rivers to that area. Farther west, the great river that apparently drained most of northwestern Puerto Rico was bringing large quantities of coarse clastic material into the sea. At times, the amount of clastic material was greater than at others, and then tongues of sand and clay were deposited on top of limestone. At other times, when the supply of clastic material was less, limestone accumulated in the same area, resulting in a westward-projecting tongue of limestone. As time continued, the amount of sediment being dumped into the sea in the San Sebastián-Moca area became less, and calcareous deposition extended farther west.

As mentioned in the description of the origin of the San Sebastián Formation, another large river emptied into the sea near Corozal, bringing large quantities of sand and mud. The sand was carried westward by longshore currents, diluting the carbonate of the lower part of the Lares for a distance of a few kilometers to the west of Ciales and resulting in deposition of the predominantly clastic Mucarabones Sand in the Corozal-Bayamón area.

Within the area of predominantly carbonate deposition, conditions of deposition varied from place to place. At some places, organic reefs, made up largely of corals and algae, formed traps for the accumulation of a wide variety of organisms, including mollusks and foraminifers. At other places, possibly in back-reef quiet waters, thick masses of lime mud accumulated, and in some areas, nearshore currents were strong enough to sort the calcareous mud and calcareous sand into thin beds, some of which are crosslaminated.

Basically, however, the Lares Limestone is predominantly a skeletal limestone that near the eastern and western ends of its depositional area competed with clastic deposits being carried into the sea by large rivers heading in the still-mountainous upland of ancestral Puerto Rico.

PHYSIOGRAPHIC EXPRESSION

The Lares Limestone is notable for the large variety of karst features that have formed on it. These vary from place to place, depending, apparently, on minor variations in the lithology.

The most prominent feature of the entire belt of middle Tertiary rocks in northern Puerto Rico and one of the notable features of the geography of Puerto Rico is the south-facing escarpment (Blume, 1968) of limestone that can be traced from the region of Corozal to a point a few kilometers northwest of San Sebastián. The caprock on the escarpment is the Lares Limestone; the lower slopes are commonly clay, silt, and sand and gravel of the San Sebastián and at the bottom are volcanic and intrusive rocks of the Cretaceous-Eocene basement.

Although the Lares Limestone is not commonly indurated below the surface, the top few meters has been recrystallized at most places into hard solid rock (Monroe, 1966a), very resistant to erosion, and

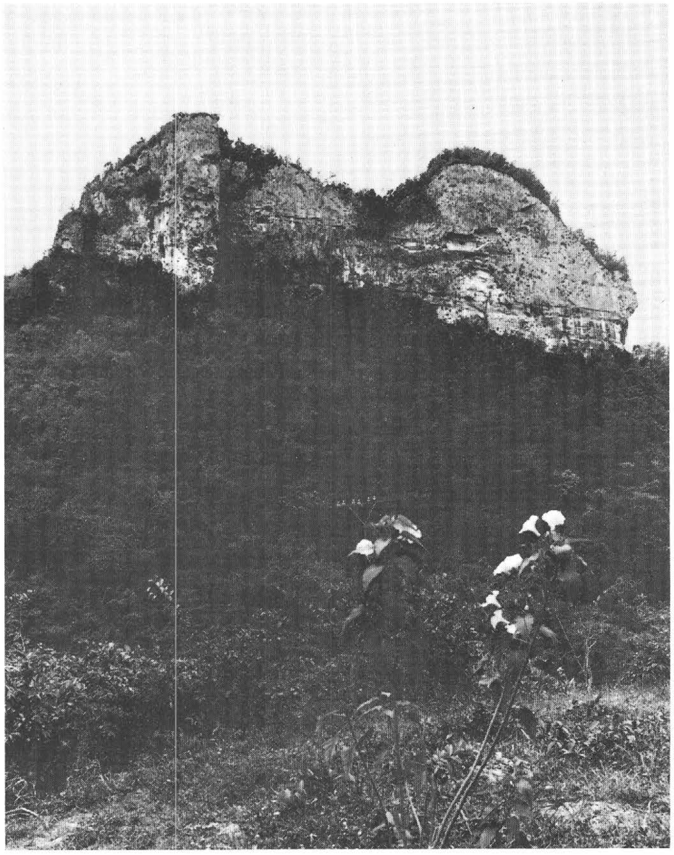

FIGURE 14.—Tower of lower part of Lares Limestone on west side of valley of Río Grande de Manatí, 1.5 km north-northwest of Ciales (April 1963).

presenting such an unbroken surface to torrential rain that most of the water flows off without further solution. Thus, the limestone forms an effective caprock along the escarpment (fig. 14), in marked contrast to the much more easily weathered and eroded San Sebastián Formation and the volcanic and intrusive rocks of the basement complex. The escarpment has a nearly vertical crest throughout its length because of a nearly continuous belt of landslides; in this belt, masses of Lares Limestone have broken away and slid downslope as the clays of the San Sebastián have been eroded and have become wet and plastic, thus reducing support of the limestone (Monroe, 1964a).

On the upland north of the escarpment, the Lares has been weathered into a wide variety of karst features [4] including cone karst, zanjones, collapse and solution sinks, karst valleys, and caves (Monroe, 1976). The most common solution form is cone karst characterized by closely spaced conical hills separated by star-shaped valleys, many of which are closed depressions. Cone karst is being developed at places where the limestone is massive, as in the Ciales area, but it is also well developed where the beds are thicker than 30 cm. In areas where the limestone is thin bedded, commonly in beds averaging about 10 cm in thickness, the Lares has been dissolved into zanjones (Monroe, 1964b), which are long parallel or subparallel trenches a few centimeters to many meters in depth.

Solution sinks many meters deep are common in most of the outcrop belt of the Lares, except in those places where zanjones have formed, and even there, small closed depressions are common in the bottoms of the zanjones. Collapse sinks have formed at many places, particularly near the Río Camuy and the Río Tanamá.

Where the Lares is relatively pure high-carbonate limestone, hundreds of caves are found, ranging in size from mere rock shelters to present and ancient underground water courses several kilometers long. The largest known cave of this kind is the underground course of the Río Camuy, which within the belt of outcrop of the Lares is more than 3 km long and which extends at least 4 km farther north within the belt of outcrop of the Cibao Formation.

Long karst valleys, most of which seem to have formed by collapse of long caves, are well developed at several places. The most persistent valley is along the Río Tanamá; it consists of a long cave now largely unroofed. Probably the Río Camuy valley, south of the entrance of the river into the cave system, had the same origin. In summary, the Lares Limestone has been dissolved into an intricate karst topography dominated by the steep south-facing escarpment at its updip edge.

MUCARABONES SAND

NAME

The Mucarabones Sand is a part of the deposits of the Eastern Clastic Basin of Zapp, Bergquist, and Thomas (1948) and was included in the San Sebastián Formation in early reports of the present mapping project (Monroe, 1963a; Monroe and Pease, 1962). However, when Ted Arnow of the Geological Survey pointed out (oral commun., 1962) that these beds constitute a good aquifer in contrast to most of the San Sebastián Formation, these strata were given a new name; they are believed to be younger than any part of the San Sebastián, except that in the Moca–Aguadilla area.

[4] The karst features named here and in descriptions of the other middle Tertiary formations have been defined in the Glossary of Karst Terminology (Monroe, 1970).

Accordingly, Nelson (1966) assigned the name Mucarabones Sand to the sand in the northeastern part of the Corozal quadrangle that is equivalent to the Lares Limestone in the northwestern part. The type locality is in barrio Mucarabones in the northwest corner of the Naranjito quadrangle, where the formation is well exposed along Quebrada Piña. The type locality is on Highway 861, 700–2,000 m northwest of its intersection with Highway 827.

AREAL DISTRIBUTION

The Mucarabones Sand has its greatest thickness in the area west and southwest of Bayamón where it is the lateral equivalent of the Lares Limestone and the lower two-thirds of the Cibao Formation. Farther west, successively lower parts grade laterally into the Cibao Formation and the Lares Limestone until the Mucarabones is reduced to a few meters beneath the Lares. This tongue of the Mucarabones extends westward to the vicinity of Ciales where it is strongly calcareous and is considered a basal sandy limestone of the Lares.

East of Bayamón, the Mucarabones is recognizable as far as the Río Piedras, but still farther east in the town of Río Piedras, outcrops of recognizable middle Tertiary material beneath definite calcareous Cibao Formation are very scarce. It was almost impossible to distinguish outcrops of the eastern equivalents of the San Sebastián and the Mucarabones from a mantle of similar material that apparently is of Tertiary and Quaternary alluvial origin.

STRATIGRAPHIC RELATIONS

The Mucarabones Sand rests conformably, but sharply, on the San Sebastián Formation; it is gradational through an interval of less than 5 m into the overlying Lares Limestone in the western part of its belt of outcrop and into the Cibao east of the Río de La Plata. It grades laterally westward into and intertongues with the Lares and Cibao. Within the city of San Juan, it becomes indistinguishable from the underlying San Sebastián and an overlying surficial clay deposit of late Tertiary or Quaternary age.

LITHOLOGIC CHARACTER

The Mucarabones Sand consists primarily of crossbedded grayish-orange and a characteristically yellow fine to medium sand, but near the base, the sand is coarser and contains lenses of subangular to subrounded gravel and lenses of greenish-gray sandy clay. Scattered through the middle and upper parts of the formation are lenses of sandy limestone and very pale orange to grayish-brown sandy clay, both richly fossiliferous.

The type locality of the formation is on Highway 861, 2.8 km southeast of Toa Alta (173,740 E., 59,580 N., Naranjito quadrangle) where 10 m of grayish-orange to dark-yellowish-orange ferruginous calcareous quartz sandstone contains a 1-m bed of very fossiliferous recrystallized very pale orange to light-brown limestone. Bergquist (written commun., 1945) collected more than 12 species of mollusks here—including oysters, pectens, corbulas, and gastropods.

West-northwest of the type locality along Highway 861 are nearly continuous exposures of highly crossbedded, fine to very fine, ferruginous, compact, slightly calcareous sand. The sand contains a few prints of marine fossils and apparently was deposited near the mouth of a large river. Similar sand, probably exactly equivalent, is exposed in a sand pit (170,125 E., 59,190 N., Corozal quadrangle) on Highway 823, about 500 m west of Highway 165. The sand in the pit varies from slightly glauconitic, nearly pure quartz sand to very calcareous sand. Within the pit, the sand is strongly crossbedded; it strikes N. 60° E. to N. 30° W. and dips 15° SE. to 15° SW. The southerly dip of cross-stratification in this part of the Mucarabones was also noted in exposures on a low hill just east of Highway 165, about 300 m south of the intersection with Highway 823. In both of these areas, the base of the formation strikes N. 80° E. to due east and dips 5°–7° N.; therefore, the steep opposite dips described above are a form of current bedding.

The upper part of the Mucarabones Sand in barrio Quebrada Arenas, particularly between Highways 159 and 823, contains a persistent bed of very glauconitic sandy clay that is rich in tests of the foraminifer *Lepidocyclina undosa*. This bed is an excellent stratigraphic marker that can be traced continuously for several kilometers.

A cut on Highway 160 northeast of the Río Unibón (158,570 E., 56,800 N., Corozal quadrangle) and about 600 m north of the intersection with Highway 159 exposes about 10 m of light-olive-gray slightly clayey, very sandy compact limestone containing abundant medium sand grains of dark-green to black glauconite. The sandy limestone, assigned to the Mucarabones, is overlain sharply but conformably by light-yellow to very pale orange platy nonsandy, nonglauconitic limestone of the Lares. Cooke (unpub. data, 1956) collected from the sandy limestone the echinoid *Agassizia clevei,* the foraminifer *Lepidocyclina gigas,* and the mollusks *Ostrea antiguensis, Pecten laresensis, Pecten vaun, Chlamys (Lyropecten) marionensis,* and *Spondylus tampaensis.* This glauconitic limestone is, of course, much lower stratigraphically than the glauconitic clay at the top of the Mucarabones farther east.

Outcrops in the hills about 2 km southwest of the roadside outcrop described above and about 2.5 km east of Morovis show a lentil within the Mucarabones of very fragmental light-brown limestone that contains very little quartz but some glauconite. The limestone contains many fossils, including foraminifers and crab remains. This lentil of limestone has been dissolved into a typical karst topography in contrast to most of the Mucarabones, and it is characterized by several sinkholes, some small caves, and a small natural arch between two of the sinkholes.

East of the Río Bayamón, most of the Mucarabones Sand is coarse sand interbedded with sandy limestone, coarsely sandy clay, and lenses of gravel. In 1960, there was a sand and gravel pit on the site of the present Urbanización Villa España (183,900 E., 63,020 N., Bayamón quadrangle), 800 m due west of Bayamón District Hospital. Although the face shown in figure 15 and described below no longer exists, a similar face is still present in the side of the hill at the east side of Villa España. The face exposed strongly stratified thick-bedded coarse sand, sandy clay, calcareous sandstone, and a little sandy limestone containing a few fossils. Near the center of the east wall was a small normal fault striking N. 70° E. and dipping 50° N. The maximum displacement was about a meter down to the north. The lower part of the quarry exposed beds of cross-bedded gravel containing many subangular to subrounded pebbles averaging about a centimeter in length, which alternate with beds of greenish-gray sandy clay. In one part of the quarry, the gravel was overlain by a bed of very sandy fossiliferous limestone containing *Kuphus* tubes and other fossils.

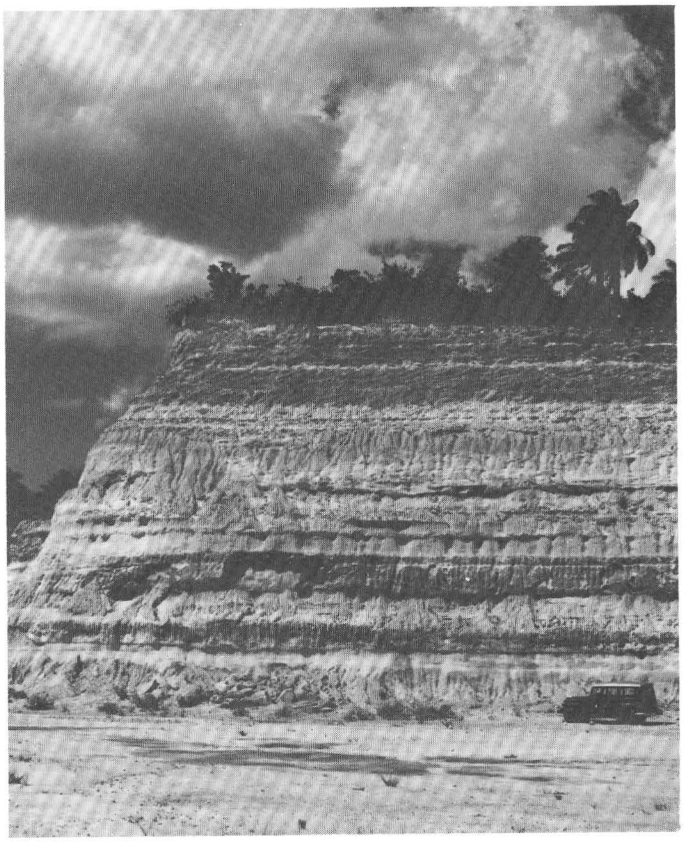

FIGURE 15.—Stratified coarse sand, sandy clay, calcareous sandstone, and sandy limestone of Mucarabones Sand in old quarry, 800 m due west of Bayamón District Hospital. Face later removed in building Urbanización Villa España (May 1960).

THICKNESS

The Mucarabones Sand thickens from a highly calcareous facies about 10 m thick near Ciales to a maximum of about 120 m, mostly sand, south of Hato Tejas near Bayamón. Farther east, the Mucarabones Sand appears to thin to less than 90 m in the western part of the city of San Juan. Farther east, it is indistinguishable from the underlying San Sebastián Formation and overlying surficial material, but its stratigraphic equivalent probably does not extend as far east as Carolina at the eastern end of the middle Tertiary basin of deposition.

FOSSIL CONTENT AND AGE

The Mucarabones contains many sand-facies fossils and locally contains abundant oysters, echinoid remains, internal molds of pelecypods, and foraminifers. The presence of the foraminifer *Lepidocyclina undosa* throughout most of the formation indicates an Oligocene age. *Lepidocyclina* has not been seen in the uppermost beds of the formation near Bayamón, and this part of the formation may be of Miocene age.

ORIGIN

The Mucarabones Sand is the sediment deposited in the sea by several large rivers, especially the ancestral Río de La Plata, Río Bayamón, and Río

Piedras. All these rivers had courses in the uplands different from the courses they have today, and all were actively eroding during Lares and Cibao time.

Throughout deposition of the formation, the sea was encroaching farther and farther onto the eastern side of the basin of deposition, and in the present area of the town of Río Piedras, strata equivalent to the Mucarabones probably rest directly on the Río Piedras Siltstone of Eocene age.

The part of the Mucarabones beneath the Lares Limestone between Corozal and the Río Grande de Manatí may very well be sand that was being carried into that area of predominantly limestone deposition by longshore currents. The tongue is thin, and deposition of the sand did not continue very long, possibly because of deflection of the river mouths to a site farther east or perhaps because of capture of some of the headwaters of the more western rivers by the eastern ones. The sand was probably deposited in rather shallow water, and on the bottom, shellfish were abundant.

PHYSIOGRAPHIC EXPRESSION

In the area west of Corozal, the landforms on the Mucarabones Sand are transitional between the rolling hills of the San Sebastián Formation and the cone karst or zanjón karst of the Lares Limestone. Near Torrecillas, west of Morovis, the zanjones that are well developed in the Lares Limestone extend south-southwest into the outcrop belt of the Mucarabones, but they are somewhat subdued.

East of Corozal, where the Mucarabones becomes thicker, the formation gives rise to rolling sand hills, except near the overlying limestone, where it forms a cliff face beneath the limestone ledges. In the area of its greatest thickness, southwest of the city of Bayamón, the Mucarabones underlies low rolling hills that are more deeply dissected than the hills underlain by the San Sebastián farther south. Quebrada Santa Catalina and its tributaries have cut a steep-sided valley about 25 m deep in the sand and sandy clay of the formation. Unconsolidated quartz sand interbedded with sandy clay makes the formation especially subject to gullying. The surface expression of the Mucarabones contrasts with the more gently rolling hills of the adjacent San Sebastián because the latter, in this area, consists mainly of clay; gullying is therefore not so common in the San Sebastián.

In the San Juan area, almost the entire surface of the formation has been built over by the city. Topographic maps made in 1940 before the city extended over the outcrop area show that the original topography consisted of low rolling hills drained by shallow valleys less than 10 m deep, which contained perennial streams.

CIBAO FORMATION

NAME

The Cibao Formation was first adequately described by Hubbard (1923) as the Cibao limestone. Hubbard (1923, p. 44) designated as a type locality barrio Cibao, north of Lares, where the formation "is essentially a soft, white, chalky limestone" interbedded with "beds of marl with abundant oyster shells" and "beds of hard pink or white limestone."

Zapp, Bergquist, and Thomas (1948) used the name Cibao marl for deposits of clastic material between the Lares Limestone and the Aguada Limestone. The rocks they included in the Cibao marl are present only in their western clastic basin, in their interbioherm area between the Río Grande de Manatí and the Río Morovis, as a thin unit above their eastern bioherm between the Río Morovis and Corozal and as a thicker unit in an eastern clastic basin east of Corozal.

Monroe (Monroe, 1962; Nelson and Monroe, 1966) found an apparently continuous bed at the base of the Cibao near the Río Grande de Manatí and traced this bed to the east and to the west. The limestone above the base of this bed was therefore separated from the Lares Limestone and considered a part of the Cibao, which was redefined (Monroe, 1962) as the Cibao Formation, consisting of several members of calcareous clay, limestone, sand, and gravel. East of the Río Grande de Manatí, the Cibao Formation includes unnamed members of typical calcareous clay or earthy limestone similar to those in the type area ,and also the Río Indio Limestone Member, the Almirante Sur Sand Lentil, the Quebrada Arenas Limestone Member, and the Miranda Sand Member. In the western bioherm of Zapp, Bergquist, and Thomas (1948), the upper part of the limestone formerly included in the Lares Limestone is now known as the Montebello Limestone Member of the Cibao Formation. In northwestern Puerto Rico, a sequence of sand and gravel in the upper middle part of the Cibao is called the Guajataca Member, as proposed by Zapp, Bergquist, and Thomas (1948).

AREAL DISTRIBUTION

The Cibao Formation is exposed from the hills in Pueblo Viejo in the southwestern part of San Juan to the western tip of Puerto Rico near Rincón, except for local cover by alluvium in the valleys of the larger rivers of the northern coastal belt. The outcrop belt of the formation reaches its greatest width of about 6 km on the upland near the valley of the Río Grande de Arecibo but its more usual width is about 3 km, as exposed in the area northeast of Ciales.

East of Pueblo Viejo, the formation is concealed by alluvial deposits throughout the most of the San Juan area, but it reappears in the hills between Carolina and Canóvanas at the extreme eastern edge of the basin of deposition of the middle Tertiary formations of northern Puerto Rico.

STRATIGRAPHIC RELATIONS

The Cibao Formation rests on the Lares Limestone; a marked change in lithologic character is evident at most places. In the Ciales-Morovis area, the basal beds of the Cibao contain scattered grains of glauconite, whereas the upper beds of the Lares do not. Furthermore, the upper Lares is commonly stratified in beds of 10 to 30 cm, whereas the basal Cibao is commonly thicker bedded, and the Lares is white to very pale orange, whereas the basal Cibao is a considerably deeper grayish orange.

Farther west, between the Río Grande de Manatí and the Río Guajataca, the Lares is commonly very fine grained calcarenite, whereas basal beds of the Cibao are a much coarser calcarenite, commonly crossbedded and at most places having an easily recognized basal bed of oysters (more than 10 cm in diameter)—*"Ostrea" haitensis*. On the upland west of the Río Grande de Arecibo, the Cibao rests directly on volcanic rock of the basement complex at a few points. Between the Río Guajataca and Moca, the contact is marked by a change in lithology from limestone in the Lares to yellowish calcareous clay in the basal Cibao. West of Moca, the Cibao overlaps all older units and from Aguadilla to Rincón rests on the basement complex.

East of the Río de La Plata, the lower two-thirds of the Cibao intertongues and grades laterally eastward into the Mucarabones Sand as far as the western part of the city of Bayamón where only the upper part of the Cibao remains as a sandy calcareous clay (Monroe, 1973b). About a kilometer east of the Río de La Plata, the bottom 35 m of the Aguada Limestone intertongues with chalky beds that are indistinguishable from the underlying Cibao. The basal thick bed of calcarenite at the base of the Aguada can be traced about a kilometer farther east but then is lost in sandy calcareous clay that resembles the upper part of the Cibao. Hence, farther east, the chalky beds of the Cibao include about 35 m of material that stratigraphically is equivalent to the Aguada farther west. In short, so far as can be determined by lithologic criteria, the Cibao is conformable and nearly gradational with the overlying Aguada Limestone.

LITHOLOGIC CHARACTER

The Cibao Formation is by far the most heterogeneous and lenticular (fig. 16) of all the middle Tertiary formations of northern Puerto Rico. It contains intergradational and interlensing beds of calcareous clay, limestone, sandy clay, sand, and gravel that seem to reflect varying amounts of sediment carried into the Atlantic Ocean by the Tertiary rivers of Puerto Rico from an upland that was generally rising spasmodically.

Hubbard (1923, p. 44) designated barrio Cibao as the type area of the Cibao Formation. There are two barrios called Cibao in the area Hubbard studied, but apparently he was referring to the barrio that is a part of the municipio de Camuy, the area north and northeast of Central Soller. Within this barrio is exposed almost the entire thickness of the Cibao Formation, except for the Montebello Limestone Member, most of which Hubbard included in his Lares formation. Hubbard (1923, p. 44) described the formation in the type area as "essentially a soft, white, chalky limestone with an abundant but poorly preserved molluscan fauna. Interbedded with this white chalky limestone are: 1. Beds of marl with abundant oyster shells (*O. sellaeformis portoricoensis*). 2. Beds of hard pink or white limestone with *Lepidocyclina* and *Orbitolites*." The material in the type area is, of course, the standard lithologic type to which the name Cibao is applied without qualification.

Because of the variation in lithologic character, the formation has been divided into six members, which are shown on the geologic map (pl. 1). Chemical analyses of samples of the more calcareous units of the Cibao Formation are given in table 2.

Typical Exposures

The exposures along the road leading northeast from Central Soller, which is at the southeast corner of Lago de Guajataca, may well be considered typical of the Cibao Formation; they consist of soft yellowish-gray, very pale orange, and grayish-orange limestone interbedded with calcareous clay.

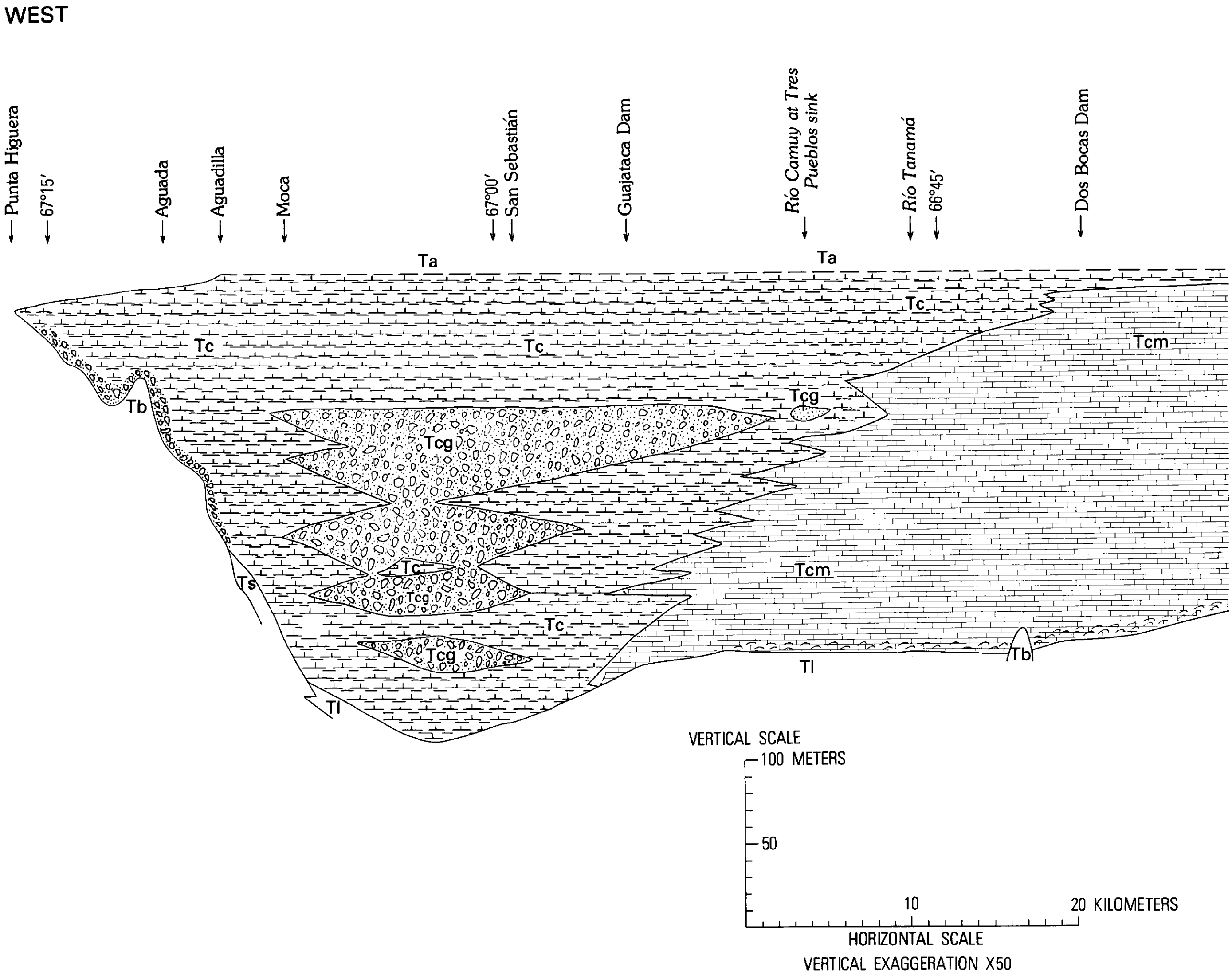

FIGURE 16.—Stratigraphic diagram showing intertonguing lithology of members of the Cibao Formation.

The Montebello Limestone Member is present a few meters below the surface at the bottom of these exposures and on the hills to the south; the eastern extension of the Guajataca Member is present at the top.

Between the Río Tanamá and the village of Montebello, the stratigraphic interval of the typical beds is occupied by the Montebello Limestone Member, but near Montebello, a wedge of chalky limestone interbedded with calcareous clay is again present. This limestone thickens toward the east at the expense of the Montebello Limestone with which it intertongues. Just east of the Río Grande de Manatí, all the Cibao below the Quebrada Arenas Limestone Member (see fig. 16) resembles closely the exposures in the type area, and material like that in the type area is exposed to the east nearly to the Río Morovis. This is the area designated by Zapp, Bergquist, and Thomas (1948) as the interbioherm area. The lower part of the typical beds of the Cibao to the east of the Río Grande de Manatí, especially in cuts on Highway 643 immediately northeast of Highway 149, include scattered grains of glauconite.

Sand and sandstone on Highway 643 about 300 m northeast of Highway 149 may be the stratigraphic equivalent of the Almirante Sur Sand Lentil, which is well developed several kilometers farther east, but the two bodies are not connected on the surface.

In the area between Highway 155 and Río Indio and Río Morovis, the entire typical chalky sequence

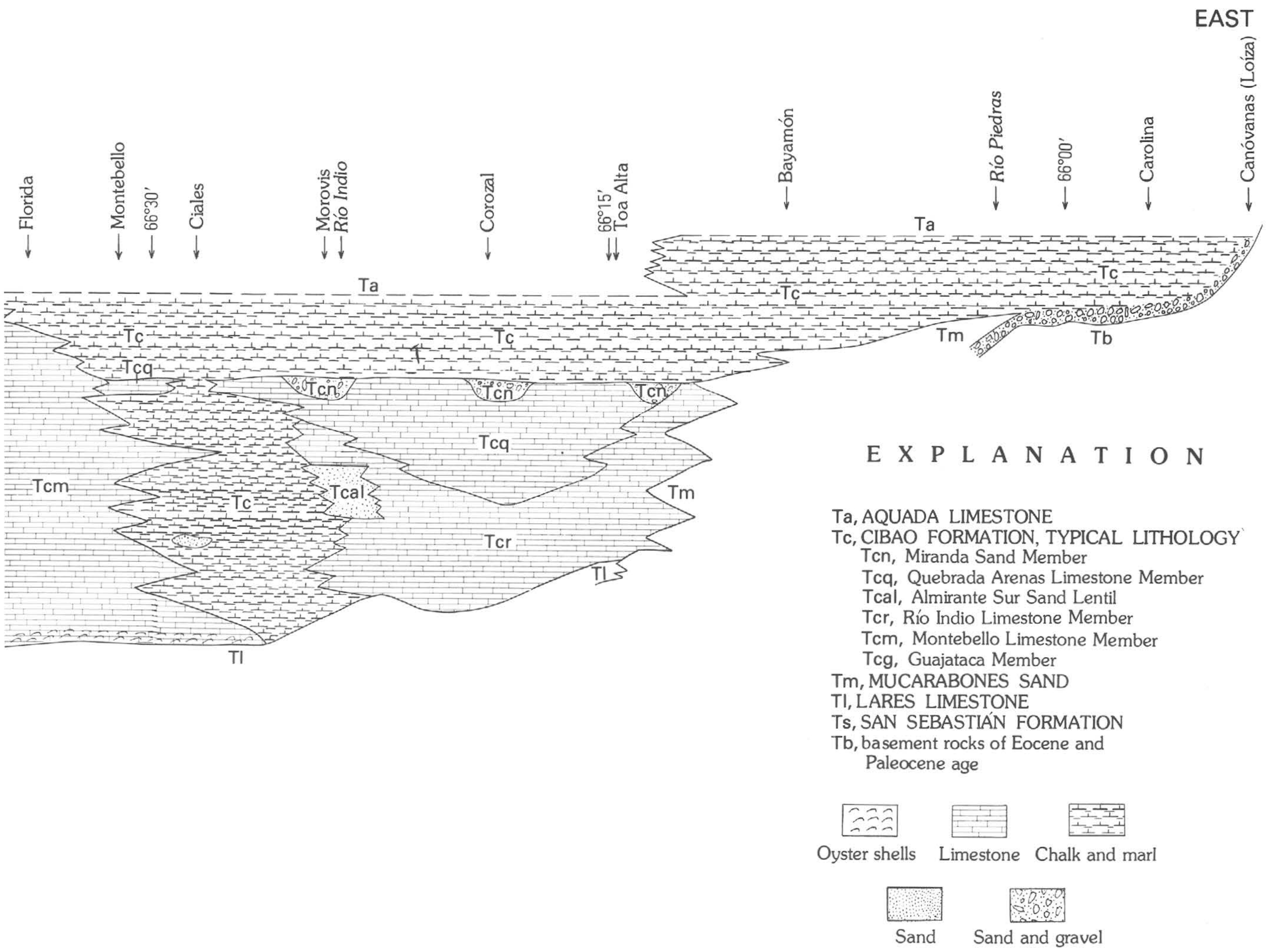

FIGURE 16.—Continued.

grades laterally eastward into a sequence of limestone and sand within which separate members are recognized, which are described below. (See fig. 16.)

Guajataca Member

Within the typical strata of the Cibao Formation are a series of lenses of sand and gravel, largely composed of silicified volcanic rocks interbedded with calcareous clay and chalky limestone (fig. 17), to which Zapp, Bergquist, and Thomas (1948) gave the name Guajataca Member from exposures on the escarpment to the east and to the west of Lago de Guajataca. As they described it: "The Guajataca Member consists of interbedded gravels, fine to coarse sands, shales and impure limestones. The gravel beds reach several meters in thickness and cobbles up to 10 cm in diameter were observed" (Zapp and others, 1948, sheet 2).

The Guajataca Member is recognizable continuously from outcrops in the secondary road up the escarpment 2 km east-northeast of the southeastern tip of Lago de Guajataca westward to the vicinity of Moca. Beds of clayey sand and sandy clay at about the same stratigraphic position have been seen in roadcuts to the east and to the west of the Río Camuy valley; these are probably lenses of sandy material related in origin to the Guajataca Member but not physically continuous with it.

The Guajataca Member reaches its maximum thickness in the eastern part of the Moca quadrangle, about midway between the towns of San Sebastián and Moca, where lenses of sand, gravel, and cobbles interbedded with calcareous clay and limestone total about 160 m in thickness. Many of the cobbles in the lenses there are more than 10 cm long and reach a maximum length of 25 cm. The sand beds and the intervening calcareous beds in

TABLE 2.—*Chemical analyses of Cibao Formation*

[Analyzed by rapid method (Shapiro, 1975); analysts: Paul Elmore, L. Artis, I. Barlow, S. D. Botts, G. Chloe, J. Glenn, J. Kesley, H. Smith]

Lab. No.	W170034	158746	158741	158751	W175022	W170032	W170024	158750
Field No.	WM146[1]	BBA227[2]	BBA175[3]	BBA387A[4]	QA[5]	BL1[6]	QR4[7]	BBA386A[8]
SiO_2	4.0	0.11	0.25	0.44	0.90	3.4	12.3	8.6
Al_2O_3	1.2	.08	.14	.30	.25	1.0	4.5	2.8
Fe_2O_3	1.0	.04	.06	.23	.21	.44	1.6	1.1
FeO	.08	.04	.07	.06	.04	.04	.16	.13
MgO	.76	.38	.36	.31	.16	.94	1.0	.45
CaO	49.6	54.3	54.6	54.0	53.6	51.1	41.8	46.9
Na_2O	.00	.05	.03	.04	.03	.00	.00	.06
K_2O	.14	.01	.01	.02	.00	.12	.35	.13
H_2O-	.64	.02	.24	.14	.07	.58	2.1	1.2
H_2O+	.76	.35	.34	.53	1.3	.52	1.5	.16
TiO_2	.06	.02	.02	.02	.00	.05	.07	.12
P_2O_5	.12	.05	.01	.02	.05	.02	.04	.03
MnO	.00	.00	.01	.00	.00	.00	.02	.01
CO_2	41.6	43.2	43.4	43.0	42.5	41.7	33.9	37.5
Total	100	99	100	99	99	100	99	100
Acid insoluble		0.51	0.66	0.84	1.4	-------	-----	10

[1] Río Indio Limestone Member at type locality from cliff at side of Highway 645 at west end of bridge over Río Indio (156,340 E., 60,280 N., Manatí quadrangle).

[2] Montebello Limestone Member, trailside sample on upland west of Río Grande de Arecibo, 4.5 km northwest of Dos Bocas dam (124,400 E., 58,980 N., Utuado quadrangle). Collected by R. P. Briggs.

[3] Montebello Limestone Member, trailside sample from exposures 2.9 km west of Río Grande de Arecibo, 4.2 km south-southwest of San Pedro (122,640 E., 59,990 N., Arecibo quadrangle). Collected by R. P. Briggs.

[4] Quebrada Arenas Limestone Member from hillside outcrop 900 m northeast of Montebello (143,460 E., 60,070 N., Barceloneta quadrangle). Collected by R. P. Briggs.

[5] Quebrada Arenas Limestone Member from type locality, side of Highway 645, 1.7 km due west of bridge over Río Indio (154,670 E., 60,360 N., Manatí quadrangle).

[6] Chalky limestone between Montebello Limestone Member and Guajataca Member from small quarry north of Highway 455, 7.6 km west of Bayaney (106,630 E., 58,640 N., Bayaney quadrangle).

[7] Compact calcareous clay from cut on Highway 453 just north of T-road east, 2.2 km southeast of Guajataca dam (102,040 E., 60,840 N., Quebradillas quadrangle). Rock contains 0.0026 percent elemental uranium.

[8] Upper member from cut at side of Highway 642, 1.6 km northeast of Montebello (144,360 E., 60,030 N., Barceloneta quadrangle). Collected by R. P. Briggs.

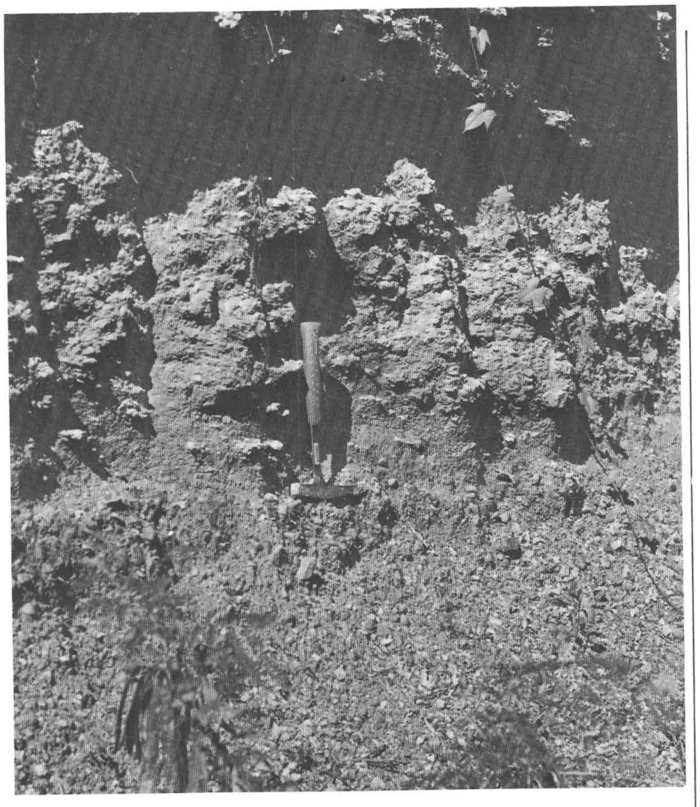

FIGURE 17.—Sand and gravel of the Guajataca Member of the Cibao Formation exposed on secondary paved road (99,950 E., 60,840 N., Quebradillas quadrangle), 2 km south of Guajataca dam (November 1967).

the area are even more fossiliferous than most of the rest of the Cibao, containing abundant oysters and other mollusks and rare echinoids. Cooke (unpub. data., 1956) collected *Ostrea rugifera*, *Turritella* sp., *Pecten* sp., and a fragment of *Echinolampus semiorbis* from gray and yellow marl from a cut in Highway 445, 1.4 km east of the intersection with Highway 112; 400 m west of the junction, he collected *Globularia anguillana*, *Orthaulax pugnax*, *Ostrea pauciplicata*?, *Pecten vaun*, *Pecten crocus*, *Metis chipolana*, and *Kuphus incrassatus* from similar material that rests on gray gravel and sand. The westernmost outcrops in which the member has been recognized are in cuts on the secondary road that goes north from Highway 444, about 1.5 km northeast of Moca.

MONTEBELLO LIMESTONE MEMBER

Zapp, Bergquist, and Thomas (1948) placed all thick masses of reef-type limestone within the Río Guatemala Group in the Lares Limestone and recognized two areas in which the Lares is exceptionally thick—an eastern and a western bioherm. The western bioherm was defined as the thick limestone sequence between the Río Manatí and the Río Guajataca. Detailed study of the eastern part of this bioherm in the Florida quadrangle (Nelson and Monroe, 1966) show that the boundary between the Lares Limestone and the Cibao Formation, as exposed northeast of Ciales, can be recognized in the Florida quadrangle by a marked change in the lithologic character of the limestone. The Lares Limestone is fine-grained calcarenite, commonly stratified in beds some 30 cm thick, whereas the overlying material is a weakly indurated medium to coarse calcarenite composed largely of foraminifers and fragments of molluscan shells. Also, at most places, beds of large oysters are present above the typical Lares material. This change in lithology seems to reflect a change in conditions of sedimentation from nearly quiet water to higher energy waves and currents. As the change is readily detectable at least as far west as the Río Grande de Arecibo, the material above the contact was designated the Montebello Limestone Member and was placed in the Cibao Formation, with which it intertongues toward the east. Later studies (Nelson, 1967b; Nelson and Tobisch, 1968; and work by Monroe in the San Sebastián quadrangle) traced the Montebello as far west as Quebrada Chicharrones, 4.7 km northeast of San Sebastián.

The type locality of the member is at the base of the cliff on the east side and about 5 m above a jeep trail (143,550 E., 58,330 N., Florida quadrangle 1.2 km south-southeast of Montebello. The bottom of the exposure is about 10 m above the Lares Limestone, which is exposed about 100 m farther south on the trail. On the cliff face, about 20 m of massive, slightly chalky limestone rests on 10 m of thin-bedded and crossbedded, medium- to coarse-grained calcarenite (fig. 18) which is composed in part of shell fragments. The crossbedded layers are separated from each other by nearly horizontal layers, the angle between crossed beds being 15°. The rock contains *Lepidocyclina* sp., algal fragments, echinoid spines, and fragments of molluscan shells. A thin section of the rock shows a network of foraminifers, especially *Lepidocyclina* sp., a few algal fragments, intraclasts, a few grains of limonite, and scattered grains of sparry calcite (fig. 19). K. N. Sachs (written commun., 1971) has identified *Lepidocyclina asterodisca* and *Heterostegina* sp. in the thin section.

In the area between Montebello and Florida, which may be considered typical, the upper part of the member consists of very pure calcium carbonate, some of it originally a pure chalk, which has been recrystallized into a hard white limestone that resembles fine porcelain.

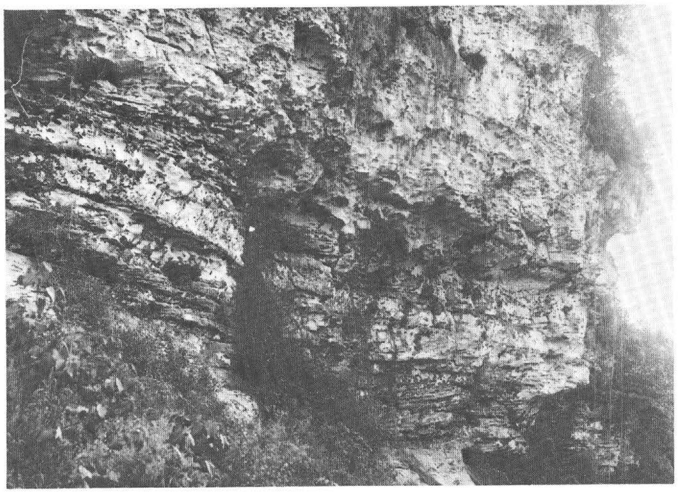

FIGURE 18.—Crossbedded and thin-bedded, medium to coarse calcarenite near base of the Montebello Limestone Member of the Cibao Formation at the type locality of the member at side of a trail, 1.2 km south-southeast of Montebello (February 1963).

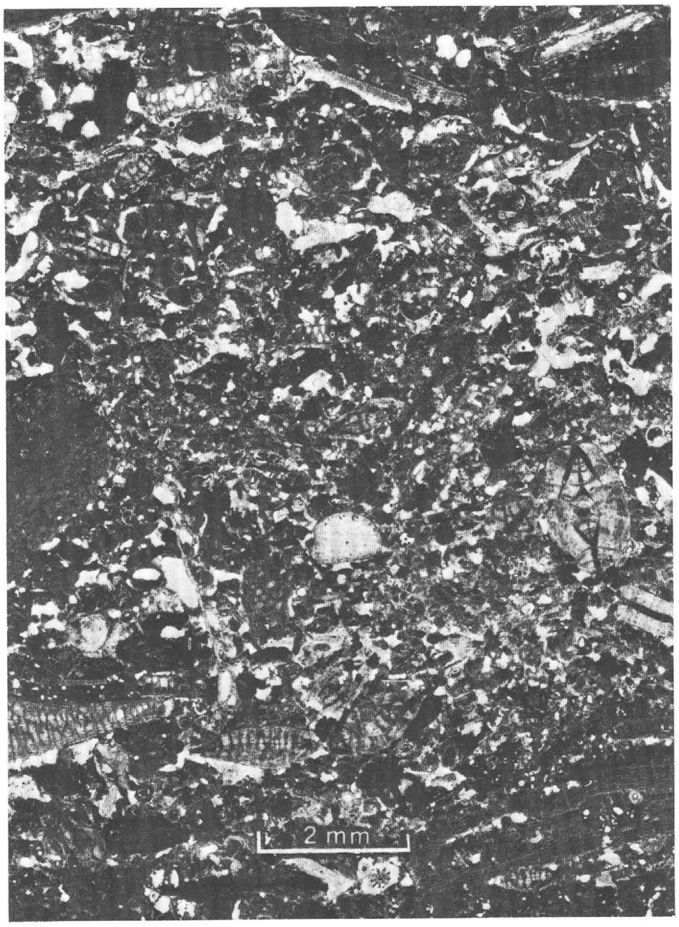

FIGURE 19.—Photomicrograph of calcarenite from type locality of Montebello Limestone Member, 1.2 km south-southeast of Montebello. Abundant foraminifers, algal fragments, and intraclasts in a dispersed sparry matrix.

East of Montebello, the member thins rapidly by intertonguing and lateral gradation into soft chalky limestone and calcareous clay typical of the Cibao.

The fullest development of the Montebello Limestone Member is near the Río Grande de Arecibo where the member is about 200 m thick and is overlain by only about 10 m of typical chalk. As mentioned in the discussion of the basement, the volcanic rocks of the Jobos Formation form several ridges that project up into the middle Tertiary rocks. A ridge that trends west by north from the mouth of Quebrada Jobos was so high during the Oligocene that the Lares sea did not cover it; and on the higher parts, granular chalk of the Montebello rested directly on highly weathered volcanic breccia.

The bed of large oysters (*"Ostrea" haitensis*?) commonly found at the base of the Montebello is especially conspicuous in the area west of the Río Tanamá. It forms a convenient marker (fig. 20) for reconnaissance mapping of the contact between the Lares Limestone and the Montebello Limestone Member. Most commonly the oysters occur in yellowish-orange soft limestone, and at some places, the oyster reef is as much as 3 m thick. Oysters are also fairly common above the basal bed.

FIGURE 20.—Oysters in basal bed of the Montebello Limestone Member of the Cibao Formation at side of Highway 451 (102,840 E., 56,920 N., San Sebastián quadrangle), 6 km north-northwest of Lares (January 1967).

At many places in the area between the Río Tanamá and the Río Guajataca, the rock directly above the basal oyster bed is rather soft chalky crumbly yellow limestone, which at many places contains abundant *Lepidocyclina undosa* and *L. gigas*. In a cut on Highway 454, about 1.5 km south by west of the intersection with Highway 455 and about 1.5 m above the base of the Montebello (109,300 E., 56,710 N., Bayaney quadrangle), some of the *Lepidocyclina* tests are as large as 10 cm in diameter.

Two thin sections of the lower part of the Montebello Limestone were obtained from outcrops near Highway 453, east of Río Guajataca, from localities 5.3 and 6 km north of Lares. Both sections show abundant *Lepidocyclina* and other foraminifers and some algal fragments in a matrix primarily of micrite (fig. 21). Sparry cement is present, principally filling cavities in foraminifers. Scattered through the rock are many intraclasts and a few small opaque grains of limonite. K. N. Sachs (written commun., 1971) identified *Lepidocyclina undosa, L. canellei*?, and *Heterostegina* sp. from one of these sections and *L. undosa, L. yurnagunensis, Nummulites dia,* and *Heterostegina* sp. from the other.

In the area west of the Río Tanamá, the upper part of the Montebello intertongues with typical more marly beds of the Cibao, and the member becomes thinner as the overlying softer beds become thicker.

Rio Indio Limestone Member

Near Highway 155, the typical deposits of Cibao of the interbioherm area of Zapp, Bergquist, and Thomas (1948) grade laterally eastward and intertongue with a predominantly limestone sequence that is equivalent to the upper part of their eastern bioherm, which is thinner than the western bioherm. This limestone sequence was divided by Monroe (1962) into two new members of the Cibao Formation—the Río Indio Limestone Member below and the Quebrada Arenas Limestone Member above. The latter is overlain by the clayey deposits of the upper member.

The type locality of the Río Indio Limestone Member (fig. 22) is a cut on the west side of Highway 645 just west of the bridge over the Río Indio

FIGURE 21.—Photomicrograph of Montebello Limestone Member of the Cibao Formation from side of a zanjón north of a secondary road (104,020 E., 56,530 N., San Sebastián quadrangle), 5.3 km north of Lares. Biomicrite containing many algal remains and foraminifers; a little sparry cement.

(156,340 E., 60,280 N., Manatí quadrangle), 7.6 km south of Vega Baja where about 20 m of pale-yellowish-orange, compact but not recrystallized calcarenite contains medium grains of dark-yellowish-orange limestone. A chemical analysis of this rock (table 2, Field No. WM146) shows that it consists of about 90 percent calcium carbonate and that the orange color is dependent on only about 1 percent ferric oxide. A thin section of the Río Indio Limestone from the type locality shows that the limestone is an intramicrite, which contains scattered opaque grains, probably limonite, a few very small angular grains of quartz, and many fossils, including *Lepidocyclina* sp. and other foraminifers, many fragments of algae, and scattered molluscan fragments.

In the type area, the Río Indio is split into a lower part about 40 m thick and an upper part about 20 m thick by the Almirante Sur Sand Lentil, which is described below. The basal beds of the lower part in the type area commonly contain scattered grains of glauconite, but farther east, glauconite is not present at the contact. In nearly all basal outcrops of the Río Indio, the limestone is very fragmental, resembling a breccia, and at many places, layers of large oysters are common, much like those at the base of the Montebello Limestone Member. The Río Indio is not as consistently pure indurated limestone as the Montebello because in most sections it is interbedded with thin units of unindurated rather chalky limestone, much like the typical beds of the Cibao Formation; and at the same longitudes as the occurrences of the Almirante Sur Sand Lentil and the Miranda Sand Member, the limestone is likely to contain quartz sand grains and locally thin beds of calcareous sandstone.

The upper part of the Río Indio in the type area commonly contains many quartz sand grains, probably a continuation of the sedimentation that produced the underlying sand lentil, and on Highway 645, about 600 m due west of the Río Indio, it consists of a coquinoid limestone.

The Río Indio Limestone Member can be traced eastward to a featheredge about 4 km west of Bayamón, but east of the Río de La Plata, the member contains increasing amounts of sand and clay as it grades laterally into the Mucarabones Sand.

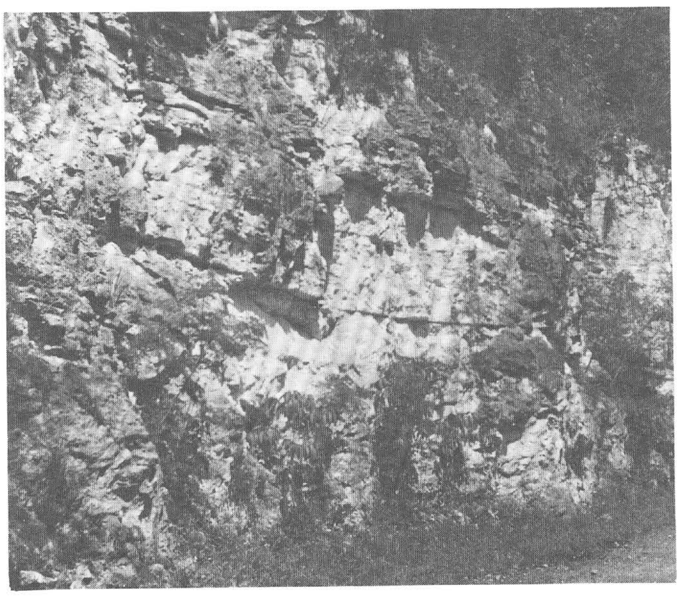

FIGURE 22.—Crossbedded pale-yellowish-orange limestone exposed at type locality of the Río Indio Limestone Member of the Cibao Formation on west side of Highway 645, just west of bridge over the Río Indio, 7.6 km south of Vega Baja (October 1959).

Almirante Sur Sand Member

Within the Río Indio Limestone Member is a large lentil of sand and sandstone, which was originally named Almirante Sur Sand Member by Monroe (1962) after the barrio that contains the type locality. The best exposures are along Highway 645 on both sides of Río Indio and especially near the type locality, which is at the southernmost bend of the highway to the east of the river (159,000 E., 59,420 N., Ciales quadrangle). At the type locality, 4 m of crossbedded coarsely glauconitic and pebbly fossiliferous calcareous sand and sandstone grades upward into about 2 m of glauconitic slightly sandy calcarenite. The upper bed makes a prominent line of boulders on hillsides to the east. The pebbles are well rounded and as much as 3.5 mm long. Near the top, the sand bed contains scattered very thin shells of oysters. Coarsely glauconitic chalk, approximately 2 m below the sand, rests directly on limestone of the Río Indio. At the type locality, 40 m of Río Indio is exposed between the sand and the top of the Lares Limestone. On the ridge east of Highway 645 about 250 m northeast of the type locality, the sand contains abundant very large specimens of *Pecten*, which appear to be confined to a bed somewhat higher than that exposed at the type section.

From the type locality, the sand is nearly continuously exposed in cuts of Highway 645 for about 500 m to the north-northeast where at a bend to the northeast (at the boundary of the Manatí and Ciales quadrangles) about 5 m of very calcareous glauconitic fossiliferous fine sand is exposed. Within 200 m toward the northeast, the sand grades laterally by intertonguing into nearly sand-free crystalline limestone of the Río Indio, whose beds average 30 cm in thickness. A cut on the southeast side of the road halfway between these two outcrops shows interbedded crystalline limestone and very sandy limestone. The Almirante Sur has not been seen farther east, although the Río Indio contains a little quartz sand at about the same stratigraphic position on Highway 155.

The Almirante Sur Sand Lentil is exposed in the valley of the Río Indio as far north as the mouth of Quebrada El Toro where it is overlain by the upper part of the Río Indio Limestone Member and dips below the river level. So far as is known, it has not been found in wells farther north, and it probably merges downdip into the Río Indio within a very short distance north of its northernmost outcrop.

Quebrada Arenas Limestone Member

Resting conformably on the Río Indio Limestone Member to the east of Highway 155 and extending to the west into the typical beds of the Cibao in the interbioherm area of Zapp, Bergquist, and Thomas (1948) is a section of varying thickness of hard very pale orange fossiliferous crystalline limestone and hard very pale orange to grayish-orange calcarenite that resembles the Lares Limestone in some places and the much younger Aymamón Limestone in others. It was probably the presence of this limestone that caused Zapp to postulate his eastern bioherm. As it is readily traceable within the Cibao Formation, however, Monroe (1962) considered it a member of that formation selecting as a type locality outcrops on Highway 645, 1.7 km due west of the bridge over the Río Indio, immediately east of Escuela Quebrada Arenas. An analysis of the Quebrada Arenas Member (QA) from this locality is given in table 2. A thin section cut from a sample taken at the type locality shows that the rock is an intramicrite containing angular quartz grains and many shell fragments, small foraminifers, and algal remains. Calcite spar fills cavities in the rock.

The Member was traced westward to a point about 4 km east of Florida, P.R., where it is lost in the Montebello Limestone Member, and it is now obvious that the Quebrada Arenas Limestone Member is merely an eastward-extending tongue of the Montebello. It becomes so thick farther east, however, that it seems desirable to retain the name as a separate member.

The Quebrada Arenas Member reaches its greatest thickness of about 60 m in the area south of Vega Alta where it is characterized by deep sinks, in contrast to most of the Cibao Formation. The member is especially well exposed in the cuts on Highway 647 to the west of the Río Cibuco from 4.5 to 5 km south-southwest of Vega Alta. The base of the member is a ledge of very hard limestone containing many coral heads (160,820 E., 60,900 N., Vega Alta quadrangle), which is well exposed about 450 m southwest of the bridge over the river; the ledge rests on much softer chalky limestone that contains abundant *Lepidocyclina undosa*. On the steep hill slope about 250 m farther southwest, the roadcuts expose about 60 m of alternating beds of very pale orange to grayish-orange indurated limestone in strata about 50 cm thick and grayish-orange chalky limestone in strata about 50 cm thick. At the crest of the hill (160,025 E., 60,500 N., Vega Alta quadrangle), the hard limestone of the member is overlain by yellow calcareous clay.

The Quebrada Arenas Member contains an anomalous bed of chalky sandstone 6 m thick in cuts of Highway 823 (166,000 E., 59,740 N., Corozal quadrangle). The sandstone is very pale orange to grayish-orange and is composed of subangular to subrounded medium to very coarse quartz and calcite grains in a matrix of pale-yellowish-orange chalky clay. This is the only place that a bed of sand or sandstone has been seen in the member, although scattered quartz grains are present at a few other places. The member has been traced east to a point about 5 km to the west of Bayamón (Monroe, 1973a), where it grades into the Mucarabones Sand.

Miranda Sand Member

Perhaps the most interesting part of the Cibao Formation is the discontinuous Miranda Sand Member, which is found in channels eroded in the top of the Quebrada Arenas Limestone Member. The member apparently is the alluvium deposited near the seacoast by rivers. The member was named for relatively widespread outcrops of pink and white clayey sand near the village Comunidad Rural de Miranda near the intersection of Highways 160, 645, and 646 near the southeastern corner of the Manatí quadrangle. The type locality (fig. 23) is a shallow roadcut (157,660 E., 60,760 N., Manatí quadrangle) on the east side of Highway 645, about 300 m south of the intersection with Highway 646, where about 10 m of coarse sand in a silty and clayey noncalcareous matrix, mottled grayish red and yellowish gray, rests sharply on hard limestone of the Quebrada Arenas Limestone Member. This sand does not appear to be marine, for it does not contain any fossils and is consistently noncalcareous. In fact, many geologists have assumed that the sand is a surficial deposit of Quaternary age, but this cannot be because it passes under chalky limestone and calcareous clay of the upper member of the Cibao on the low hill to the west of the intersection of Highways 645 and 646 and also, although less clearly, in cuts on Highway 160 north of the intersection with Highway 645.

Farther north, downdip in the valley of the Río Indio, sand of the Miranda Sand Member can be traced continuously for only a few hundred meters, but very sandy limestone interbedded with loose sand, probably a downdip equivalent of the Miranda, was noted on a trail about 20 m below Highway 646 (156,700 E., 61,670 N., Manatí quadrangle) and about 1.3 km northwest of the intersection with

Figure 23.—Mottled grayish-red and yellowish-gray clayey silty coarse sand exposed in a cut on east side of Highway 645 at the type locality of the Miranda Sand Member of the Cibao Formation (August 1962).

Highway 160. The Miranda Sand Member is not present at the type locality of the Quebrada Arenas Limestone on the west side of Quebrada El Toro, but similar sand is present again in the valley of Quebrada Hicotea, about 800 m south of the intersection of Highways 155 and 645.

East of the type area, the Miranda is present again in a well-defined channel eroded in the top of the Quebrada Arenas Limestone Member exposed along Highways 677 and 820, 3.5 to 3.8 km due north of Corozal. The trend of the channel is well marked by gravel float on the tops and sides of hills and by gravel in roadcuts, especially on Highway 677 across the road from Gallera Maricao. The member contains siliceous pebbles and cobbles of all sizes up to 10 cm long. Many of the pebble are subangular to subrounded fragments of jasper.

The Miranda is not present on the slope up from the valley 200 m farther west, so the outcrop described above is near the southwestern side of the ancient river channel in which the Miranda was deposited. Gravel of the member was observed on trails 450 m north-northwest on the south slope of the Río Lajas, but no sign of the member could be found in the cane fields on the north side of the Río Lajas valley. The northeasterly trend of the channel is plainly visible in the outcrop pattern of the member as shown on the geologic maps of the Vega Alta (Monroe, 1963a) and Corozal (Nelson, 1967a) quadrangles. A bed of oysters (fig. 24) rests on clean white sand at the top of the Miranda Sand Member (164,630 E., 60,050 N., Vega Alta quadrangle) along Highway 820, 250 m east-southeast of the intersection with Highways 677 and 678. The marly limestone above the oyster bed, which probably represents the base of the upper member, contains scattered rib bones, probably of a Sirenian (manatee or seacow).

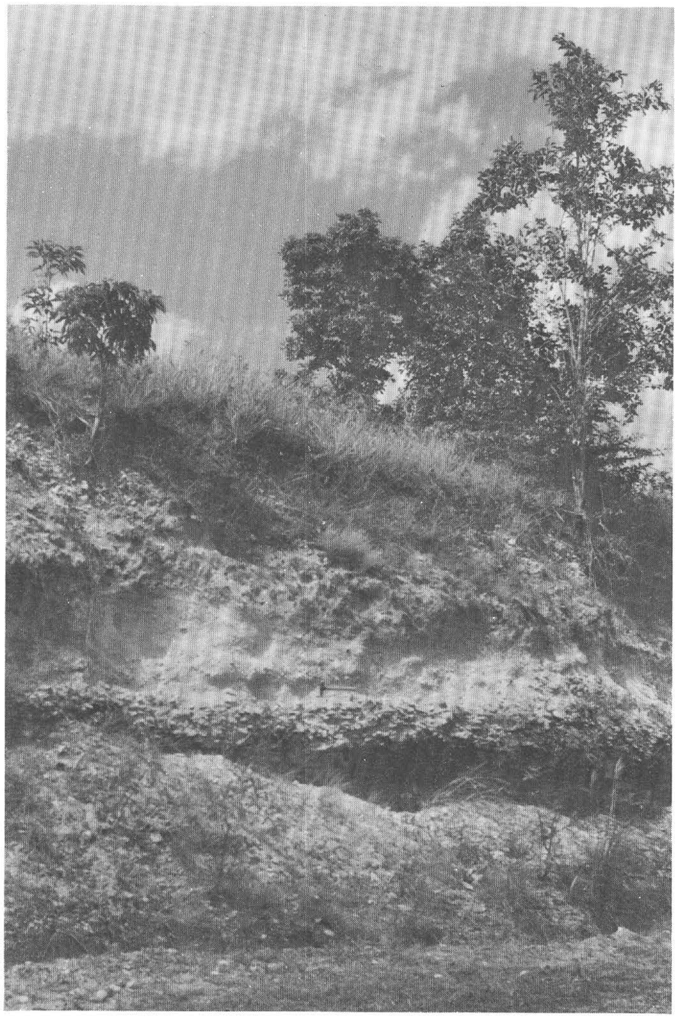

FIGURE 24.—Bed of oysters resting on clean quartz sand at the top of the Miranda Sand Member of the Cibao Formation in cut on south side of Highway 820, 3.6 km north of Corozal. Above the oyster reef is semi-indurated clayey limestone of the upper member of the Cibao (October 1959).

The easternmost area of outcrop of the Miranda Sand Member is in a channel cut in the Quebrada Arenas Limestone Member cropping out 2–2.8 km east of Toa Alta on the north slope of Río Bucarabones where about 10 m of clayey coarse quartz sand contains well-rounded pebbles and cobbles of quartz and volcanic rock. Farther east, the Quebrada Arenas is missing, and any channel-filling sand and gravel is lost in the clastic beds of the Mucarabones Sand.

Upper Member

Lithologically very similar to the typical beds of the Cibao are the strata at the top of the formation designated informally as the upper member (Monroe, 1962). The upper member is mostly chalk or chalky limestone, which contains enough clay to give it an unctuous or soapy feel. Sample analysis, Field No. QR4 in table 2, shows that the earthy limestone consists of about 76 percent calcium carbonate. This sample was collected from a cut on Highway 453 near the crest of the hill to the east of Lago de Guajataca. It is from a section that is 5 m thick and that is sufficiently radioactive to be noted in an airborne radiometric survey (MacKallor, 1965). This bed of earthy limestone is apparently continuous and can be recognized on the ground by the radioactivity shown by a scintillometer, ranging from 2 to 6 times background. The sample QR4 (table 2) contains 0.0026 percent uranium. In Geological Survey practice, uranium is reported as percentage of element, not as an oxide. The westernmost radioactive outcrop is 5.7 km to the north of San Sebastián on a secondary road just northwest of Highway 446 (95,260 E., 61,460 N., Quebradillas quadrangle); this outcrop yielded limestone containing 0.0013 percent uranium. The easternmost sample collected was on a secondary road 3 km east of Lago de Guajataca (105,130 E., 60,540 N., Quebradillas quadrangle); this sample contained only 0.0004 percent uranium. The scintillometer survey was carried still farther east, and although the same bed could be recognized radiometrically, the anomaly was much lower. This bed of earthy limestone is only of scientific interest, as the amount of radioactive material that it contains is of no foreseeable economic importance. Much of the upper part of the Cibao Formation is similar lithologically except that it is not radioactive at most places.

At many places in the type area, the upper part of the Cibao contains beds of calcilutite as much as half a meter thick which are extremely fossiliferous; the fossils are mostly molds, but include in places oysters and the foraminifer *Marginopora*.

A sequence of upper Cibao is well exposed on the upper part of an escarpment (83,850 E., 63,510 N., Moca quadrangle) in cuts on the northeast side of a secondary road. At a level about 15 m below the top of the Cibao is a bed of carbonaceous silt containing stringers of lignite; this bed is overlain and underlain by fossiliferous calcareous clay, which contains a bed of crystalline white to grayish-orange limestone from which Bergquist (written commun., 1945) collected a few fossils, including *Spondylus bostrychites*, *Phacoides smithwoodwardi* (not saved), and *Chione woodwardi*. This lignitic zone is the only one I have seen in the upper part of the Cibao Formation.

The lower part of the upper member is exceptionally well exposed, but somewhat inaccessible, in the nearly vertical cut just north of Highway 111 on Highway 2. This cut exposes about 25 m of chalk and chalky limestone, which contains at the base a bed of calcilutite 1.5 m thick overlain by about 1.2 m of broken limestone; a similar bed of calcilutite crops out about halfway to the top of the cut. The base of this sequence is about 60 m below the top of the Cibao Formation.

Beds of limestone, chalk, and at the base sand and gravel (apparently a western extension of the upper member of the Cibao Formation) crop out in the hills on the south side of the Bahía de Aguadilla from Highway 2 west to Punta Higuera, the western tip of Puerto Rico. These strata were called Lares by Hubbard (1923), probably because they rest directly on the basement rocks. Zapp, Bergquist, and Thomas (1948) considered them typical Aguada. Lithologically, however, they most resemble the upper member of the Cibao Formation and were so designated by Monroe (1968a).

The top of the Cibao Formation is well exposed (fig. 25) at the north end of Guajataca dam (100,590 E., 62,860 N., Quebradillas quadrangle). Here 9 m of compact very chalky limestone containing scattered fossils is overlain sharply by solution-riddled concretionary medium- to coarse-grained fossiliferous calcarenite of the Aguada. The basal 40 cm of the Aguada resembles a conglomerate of limestone pebbles in a fine grained matrix; this bed contains many corals.

In the type area, the upper member of the Cibao is about 80 m thick; but near Bayaney, it thins as the underlying Montebello Limestone Member thickens. In the area between the Río Grande de Arecibo and a point of a few kilometers northeast of the town of Florida, the chalky, marly material is only 10 m thick and forms a soft zone of material between the more resistant Montebello Limestone Member below and the Aguada Limestone above. Still farther east, the typical chalky material of the upper member again thickens as far as the Río Grande de Manatí where it is about 50 m thick, a thickness that it maintains nearly as far east as the town of Bayamón. An analysis of the upper Cibao 1.6 km northeast of Montebello (table 2, Field No. BBA386A), shows about 85 percent calcium carbonate and 10 percent material insoluble in HCl.

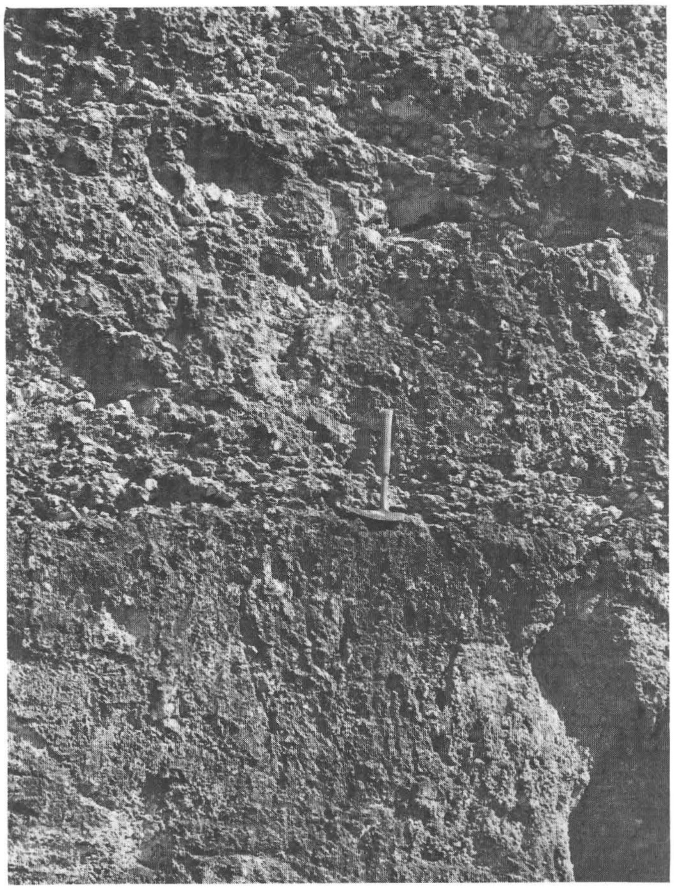

FIGURE 25.—Contact of Aguada Limestone on Cibao Formation, marked by head of hammer, exposed at north end of Guajataca dam on Highway 119 (November 1967).

At the side of a trail (143,970 E., 59,300 N., Florida quadrangle) 1.1 km east of Montebello, soft yellow limestone interbedded with yellow chalk is exposed about 15 m below the Quebrada Arenas Limestone Member and 10 m above the Montebello. The exposure includes a bed about 25 cm thick that is composed almost entirely of *Lepidocyclina undosa*.

Also present are *Lepidocyclina waylandvaughani*, *Nummulites dia*, and *Planorbulinella larvata* (Sachs, 1964).

Near Vega Alta, the uppermost Cibao contains several lenses of sand and of green sandy clay. On Highway 677, about 3.5 km due south of Vega Alta, a cut (163,100 E., 60,770 N., Vega Alta quadrangle) exposes about 30 cm of nearly clay-free yellow quartz sand that is overlain by about 15 cm of white sand; the sand is underlain by sandy calcareous clay. The contact of the Aguada Limestone on the Cibao Formation is well exposed (fig. 26) on the northeast side of Highway 677 near the top of the valley wall of the Río Cibuco (162,215 E., 62,170 N., Vega Alta quadrangle), 2.5 km south-southwest of Vega Alta; the top of the Cibao is represented by a bed a few centimeters thick of clayey quartz sand that rests on 6 m of soft yellowish-gray chalky limestone in strata 1–2 m thick. The sand is overlain by fossiliferous very pale orange, hard calcarenite in beds 25–50 cm thick and by very rubbly hard limestone of the Aguada.

The top of the Cibao Formation is exposed at several places in the south-central part of San Juan. One of the best exposures is in an abandoned quarry (fig. 27) just north of the main entrance to Fort Buchanan, northwest of the Caparra Intersection of Highways 2, 23, and 24 (168,870 E., 64,440 N., San Juan quadrangle). Although the quarry is no longer active, the exposures of Cibao and Aguada can be seen west of the warehouses now built on the site of the photograph. The contact is about 23 m above the base of the quarry face.

FIGURE 27.—Contact of Aguada Limestone (Ta) on Cibao Formation (Tc) north of entrance to Fort Buchanan, northwest of the Caparra Intersection of Highways 2, 23, and 24 in the southwest part of San Juan (June 1960).

FIGURE 26.—Contact of Aguada Limestone on Cibao Formation exposed in cut on northeast side of Highway 677, 2.5 km south-southwest of Vega Alta. The contact is at the top of a bed of clayey quartz sand directly beneath the overhanging ledge (May 1964).

About 10 m of fossiliferous upper Cibao is exposed under Aguada Limestone on the north side of a hill (197,930 E., 63,100 N., San Juan quadrangle) just north of Highway 3 in Country Club urbanization, about 5.5 km east of Highway 1 at Río Piedras. This is probably the hill visited in 1919 by Vaughan (1923, p. 313), from which he collected foraminifers, corals, a bryozoan, and *Kuphus* sp.

The easternmost outcrops of Cibao that have been recognized are in roadcuts about 2 km northeast of Canóvanas (Loíza) on Highway 188, the new road to Loíza Aldea about a kilometer north of Highway 3. There, sandy calcareous clay assigned to the Cibao underlies calcarenite of the Aguada Limestone.

SAMPLES FROM WELLS

The Cibao Formation has been identified in samples of three wells drilled in northern Puerto Rico. The most northerly well is the Kewanee Interamerican Oil Company's Test Well 4CPR, drilled near the coast between Arecibo and Barceloneta (pl. 1). Briggs (1961) assigned to the Cibao Formation 306 m consisting mainly of calcarenite and calcareous claystone but also including sandstone, marl, and dense limestone obtained from depths of 1,850–2,852 ft (564–870 m). This thickness is somewhat greater than found in the outcrop belt, but all the middle Tertiary formations are thicker in this well than in outcrop.

The first sample of rock taken from the well of the Arecibo Ionospheric Observatory from a depth of 25 ft (7.6 m) consists of white to very pale-orange fine- to medium-grained calcarenite containing fragments of corals, oysters, and other mollusks. On the basis of the abundant fragments of oysters in the sample and of the prominent oyster reef that has been seen at the observatory at the base of the Montebello Limestone Member of the Cibao Formation, this sample from a depth of 25 ft (7.6 m) has been placed in the Cibao and all samples below, in the Lares.

Disposal well 1 of Abbott Laboratories, near the northwest corner of the intersection of Highways 2 and 140, entered the Cibao Formation at some depth between 610 and 690 ft (186–210 m) and probably entered the Lares Limestone at a depth between 1,550 ft (473 m) and 1,621 ft (494 m), most probably the latter. The section of the well assigned to the Cibao consists mainly of white to very pale orange nongranular limestone, calcarenite, and chalk, but between depths of 870–880 ft (265–268 m) and 1,000–1,010 ft (305–308 m), the well penetrated beds of bentonitic clay, which is light grayish olive, mottled with grayish blue green. Quartz sand was penetrated at several depths, and the samples from depths of 900–910 ft (274–277 m) and 970–980 ft (296–299 m) are almost entirely quartz sand. The clay beds, particularly the lower one, apparently act as confining beds because the water encountered below is under strong artesian pressure and because the section of the well between depths of 1,180 and 1,550 ft (360 and 473 m) was completed as an artesian well; the confined pressure of the water in various beds in this interval ranges from 80 to 90 pounds per square inch at the surface of the well. During the drilling, the pressure of the water was so strong that cuttings could not be collected, but large pieces of the formation were blown from the well.

THICKNESS

In the outcrop belt, the Cibao Formation seems to vary in thickness along the strike depending on the lithologic character. The thickest sequence (260 m or perhaps slightly more) is apparently in the area between the longitudes of San Sebastián and Moca, where the Guajataca Member is thickest. In the area between the Río Camuy and Florida, P.R., the formation is 210–220 m thick, but it appears to thin to about 200 m between Florida and Ciales. Still farther east, the formation thins more rapidly until near Corozal where it is only about 170 m thick. East of the Río de La Plata, the lower part of the formation intertongues with the Mucarabones Sand, and farther east, successively higher parts merge eastward into the Mucarabones until in the area of Bayamón only the upper 50 m of the formation remain.

In Kewanee Interamerican Oil Company's test well 4CPR, Briggs (1961) assigned a thickness of 306 m to the Cibao. The disposal well 1 of Abbott Laboratories near the intersection of Highways 2 and 140 reached the top of the Cibao at a depth between 186 and 210 m (610 and 690 ft) and entered the underlying Lares Limestone at a depth between 472 and 494 m (1,550 and 1,621 ft), which indicates a thickness somewhere between 262 and 308 m.

All members of the Cibao Formation are lenticular. The Montebello Limestone Member ranges in thickness from a featheredge to a maximum of about 200 m, which is nearly the entire thickness of the formation in the area near Florida, P.R. The Guajataca Member is only 10 m thick east of Lago de Guajataca, but in the area northwest of San Sebastián, it apparently is more than 160 m thick. The Río Indio Limestone Member ranges in thickness from 70 m to somewhat more than 100 m in the vicinity of the Río Indio and Corozal but thins to a featheredge east of the Río de La Plata. The Almirante Sur Sand Lentil reaches its maximum thickness of 30 m just east of the Río Indio and thins by intertonguing both east and west. The Quebrada Arenas Limestone Member reaches a maximum thickness of 60 m near Vega Alta but thins to about 10 m west of the Río Indio and near its eastern extremity west of Bayamón. The Miranda Sand Member is a narrow, channel-filling unit that may reach a thickness of about 20 m to the east of the Río Indio, but at most other places, it is only about 10 m thick.

At most places, typical chalky limestone of the Cibao Formation is present as an upper member. In western Puerto Rico, this member is about 80 m thick above the Guajataca Member; in the region just east of the Río Grande de Arecibo, the member is only about 10 m thick above the Montebello Limestone Member, and farther east, it seems to be consistently about 50 m thick above the Quebrada Arenas Limestone Member and above the Mucarabones Sand.

FOSSIL CONTENT AND AGE

The Cibao Formation yields large numbers of fossils, but as is common in the formations of northern Puerto Rico, most of them are interior or exterior molds. Hubbard (1920b) listed about 21 mollusks from the beds that he considered Cibao and from those between Aguadilla and Rincón that he considered Lares but that are now included in the Cibao. Of the 21 species, only 3, however, are confined to the Cibao; 14 range down into the Lares and San Sebastián, and the rest range up as high as the Camuy.

Bergquist (written commun., 1945) listed 3 species of echinoids from the Cibao and 21 species of mollusks from the typical marl beds and the Guajataca Member. He also listed about 39 species from massive beds of the Lares Limestone, but his unit included the Lares Limestone as defined in the present report and also the Montebello, the Río Indio, and the Quebrada Arenas Limestone Members of the Cibao. It is difficult, therefore, to determine which of these species were collected only from rocks now restricted to the Lares and which from overlying limestone of Cibao age.

Cooke (unpub. data, 1956) also made extensive collections from the Cibao Formation, and he called especial attention to the echinoids, of which *Echinolampas aldrichi* and *Schizobrissus antillarum* are important as having stratigraphic value, being restricted to the upper Oligocene. Another echinoid that is common in the Cibao is the large high-domed *Echinolampas semiorbis.*

Among the mollusks common in the Cibao are several species of oysters (which have some stratigraphic value, as oysters are rare in the overlying Aguada Limestone) a large *Strombus,* large corpulent Lucinas, *Spondylus bostrychites,* and several species of *Pecten.*

Foraminifers are common in all parts of the Cibao except in the Miranda Sand Member, and in the field, the larger forms are useful stratigraphically. These include in the lower part of the formation, *Lepidocyclina undosa* and *L. gigas,* and at the base, *Heterostegina antillea.* In the upper part of the formation and in the part between Aguadilla and Rincón, the Miocene genus *Marginopora* is present but is not common.

Fossils believed to be restricted to the Oligocene, including *Lepidocyclina undosa, Echinolampas aldrichi,* and *Schizobrissus antillarum,* are found in the Cibao in the Quebrada Arenas Limestone Member and lower units, in the lower part of the Guajataca Member, and in the lower part of the Montebello Limestone Member. *Marginopora* sp. has been found in the upper member in the area east of the Montebello and in western Puerto Rico above the Guajataca Member; the presence of this foraminifer suggests a Miocene age. On the basis of this rather scanty evidence, it seems that roughly the lower two-thirds of the Cibao Formation is upper Oligocene and that the uppermost part is lower Miocene, the Oligocene-Miocene contact being somewhere in between.

ORIGIN

The Cibao Formation has by far the most heterogeneous lithology of the middle Tertiary formations of Puerto Rico; this reflects diverse conditions of sedimentation for the various parts of the formation.

The drainage of the mainland of Puerto Rico during deposition of the formation on the northern coastal shelf was quite different from the drainage of the upland sections of Puerto Rico today. The lithology of the formation indicates that during Cibao time the larger rivers of Puerto Rico entered the sea only west of the present Río Guajataca and east of the Río Grande de Manatí. Little, if any, drainage entered the sea in the intervening area. The large ridges of volcanic rock that persisted as islands in the sea throughout Lares time appear to have acted as barriers to streams draining the central part of the island, and throughout Cibao time the sea in the area between the Río Grande de Manatí and the Río Guajataca was very clear, so that corals and coralline algae flourished and formed large reefs, probably barrier and fringing reefs. This limestone sequence constitutes the Montebello Limestone Member.

The large river entering the sea west of San Sebastián in Lares time persisted through Cibao time, but its mouth may have migrated farther east. During the early part of deposition of the Cibao in this area, the river was bringing into the sea mostly clay and sand that was deposited as a mud. Apparently the upland was slightly raised at the beginning of Cibao time, for commonly deposition of clay succeeded the deposition of the pure limestone of the Lares, except in the area of clear seas represented by the Montebello Limestone Member. The amount of sedimentation was not great enough to smother mollusks, for they flourished in the relatively shallow sea. Some kinds of corals were able to live in the somewhat muddy water of the early Cibao, but they did not build the large reefs so common farther east in the central area where the Montebello Limestone Member was being deposited at the same time.

Shortly after middle Cibao time, the central part of Puerto Rico was again uplifted, and the great western river began to erode the soils that had accumulated during late Lares and early Cibao time and to bring into the sea large quantities of clay, sand, and gravel. The sand and gravel were deposited as lenses, perhaps sand bars, to form the Guajataca Member.

Toward the end of Cibao time, the area near Aguada and farther west was covered by the sea for the first time since the Eocene, and chalky limestone and calcareous clay were deposited on a thin basal conglomerate made up largely of reworked gravelly soil. During this period, erosion was less active in central Puerto Rico so that the deposits farther east contain no gravel and little sand but contain a considerable amount of clay and earthy limestone which form the part of the Cibao Formation above the Guajataca Member.

East of the region of clear water represented by the Montebello Limestone Member, in general east of th Río Grande de Manatí, the sedimentation during Cibao time was more complex (Monroe, 1966b). At least three large rivers debouched into the sea, as represented by lentils of sand and gravel in the formation.

In the eastern part of the depositional basin, the slight uplift of the present upland region of Puerto Rico at the beginning of Cibao time changed the depositional pattern from limestone to calcareous clay and chalky limestone as the streams brought in more mud. This was particularly so in the area between the Río Grande de Manatí and the Río Indio; farther east, the water remained somewhat clearer, although not so clear as during Lares time, and the Río Indio Limestone Member was deposited. One large river, probably related to the Río Bauta, the Río Matrullas, and the Río Orocovis, entered the sea near the present Río Indio and deposited the sand represented by the Almirante Sur Sand Lentil. This sand was deposited in an estuary in which some tidal scour and some current action produced oscillatory-type and current-type crossbedding. The water was probably brackish, for oysters formed thin reefs on the sandy bottom. After a short time, this river ceased to carry sand into the sea, and the deposition of the slightly ferruginous limestone of the Río Indio Member resumed. As the upland was eroded to a more gentle plain, the rivers ceased to carry so much sediment, and deposition of reef limestone of the Quebrada Arenas Limestone Member began.

At about the end of the Oligocene, the center of the landmass was arched upward, so that the streams began to erode more rapidly and to carry considerable sand and gravel to the sea. This arching raised the newly deposited Quebrada Arenas Limestone Member slightly above sea level, and streams cut trenches into it at several places near the present Río Indio, north of Corozal, and in barrio Mucarabones, east of Toa Alta. The streams deposited alluvium in these trenches and formed flood plains that ranged in width from a few hundred meters to about a kilometer. The alluvium consists of clayey sand in the area near Río Indio, of sand and gravel in the area north of Corozal, and of clayey sand in the area of barrio Mucarabones. Even while the rivers were depositing the alluvium, the entire landmass was subsiding, slowly, so that the sea was able to encroach on the valleys, transforming them into estuaries, as shown by the well-developed oyster reef near the top of the Miranda Sand Member on Highway 820 north of Corozal (fig. 24). A short time later, the sea transgressed over the flood plains, so that the mouths of these rivers were somewhat farther inland. They were still active streams, however, carrying large quantities of debris into the sea, so that the sea water was very muddy throughout the area east of the Río Grande de Manatí and the upper member of the Cibao was deposited. Some of the mud was carried far to the west by longshore currents. This accounts for the thin bed of typical Cibao calcareous clay between the Montebello Limestone Member and the Aguada Limestone. The most active of these rivers was the one whose flood plain was north of Corozal, for in that area the upper member of the Cibao contains lenses of sand much like the Miranda Sand Member.

The locations of these rivers in the upland of Puerto Rico are difficult to determine, but the river whose floodplain was near the present Río Indio was probably the same Río Bauta-Río Matrullas-Río Orocovis system that may have had its estuary in the same general area during deposition of the Almirante Sur Sand Lentil. This river remained active well into Aguada time, as shown by quartz sand grains present in the Aguada north of the Almirante Sur Lentil. The alluvium of the flood plain north of Corozal now preserved as the Miranda

Sand Member, contains jasper, similar to that found near Barranquitas; thus, it seems reasonable that at that time the river basin included the headwaters of the present Río Grande de Manatí near Barranquitas, the present Río Mavilla, and the Río Cibuco south of Corozal. The ancient flood plain in barrio Mucarabones may be an ancestral Río Bayamón, which may have included the present headwaters of the Río de La Plata.

The thick masses of skeletal limestone represented by the Montebello and Quebrada Arenas Limestone Members have the shape of bioherms and were called the western and eastern bioherms by Zapp, Bergquist, and Thomas (1948). In view of more recent studies of carbonate reef deposits, however, as summarized by Nelson, Brown, and Brineman (1962), the term "bioherm" does not appear appropriate, for these masses of limestone never projected very far above the sand and clay that were being deposited contemporaneously to the east and west. The term "reef limestone" is appropriate, for the limestone masses are composed of a skeletal mass of corals and coralline algae that have interstices filled in by limestone, sand, foraminifers, and molluscan shells.

East of the Río de La Plata, successively higher parts of the Cibao Formation are represented by clastic deposits of the Mucarabones Sand, which are the debris carried into the sea near the eastern end of the basin of deposition by ancient rivers, such as the Río Bayamón, the Río Piedras, and probably an ancestral Río Grande de Loíza. So far as known, the area east of Loíza Aldea never contained any deposits of Cibao age and was a hilly land surface throughout Cibao time.

PHYSIOGRAPHIC EXPRESSION

The heterogeneous lithologic character of the Cibao Formation has given rise to an equally varied landscape, each member being characterized by different landforms.

The typical Cibao, including the upper member, weathers to a calcareous clay loam, typically of the Soller series (Roberts and others, 1942), which becomes eroded into a gently rolling upland surface. Locally, beds of indurated limestone within the usual chalky limestone and calcareous clay sequence act as resistant layers that form a cap rock on hills or "stair steps" on the hillsides. In a few places, these beds of limestone are thick enough to be dissolved into shallow dolines. At most places, however, the typical beds form low rolling hills that are drained by surface streams. Some of the drainage must be underground, however, for in some areas these surface streams disappear into swallow holes.

The abrupt changes in lithology from the chalky limestone and calcareous clay to sand and gravel, as in the Guajataca Member, or to limestone, as in the Quebrada Arenas Limestone Member and westward-extending tongues of limestone of the Montebello, have given rise to steep southward-facing escarpments. An escarpment of this kind, apparently held up by the Quebrada Arenas, is a prominent feature of the landscape in the valley of the Río Grande de Manatí and eastward to the Río de La Plata. This escarpment rises some 60 m above the lowland to the south. At most places, however, a surface stream in the lowland flows parallel to the escarpment and increases its relief. Quebrada Grande de Morovis, which flows east into the Río Morovis near the northern edge of the Ciales quadrangle, has cut a valley in typical rocks of the Cibao that makes the Quebrada Arenas scarp about 100 m high. East of the Río Cibuco, the valley of the Río Mavilla accentuates the escarpment even more. In western Puerto Rico from a point a few kilometers east of the Río Guajataca, the Guajataca Member of sand and gravel lenses makes a notable scarp about 100 m high in the plains northeast, north, and northwest of San Sebastián.

The Montebello Limestone Member gives rise to a kind of tower karst superimposed on the cone karst of the Lares Limestone; it produces a form appropriately named "cliffed cone karst," for the Montebello forms vertical cliffs that rise above the cone karst, especially in the area south of Florida. West of the Río Tanamá, the Montebello has been dissolved into a kind of doline or sinkhole karst, but in that area, underground drainage channels have collapsed to such an extent that one could almost characterize the area as collapse karst. In the area north of Lares and on both sides of the Río Guajataca, the Montebello has been weathered into long parallel east-trending trenches or zanjones, which are in the aggregate several tens of meters deep; this is the only place that zanjones have been seen except in the Lares Limestone.

Besides giving rise to a notable southward-facing escarpment, the Quebrada Arenas Limestone Member has been dissolved into deep solution dolines on both the east and west sides of the Río Cibuco. These sinks are only about 20 m deep below the lowest places on their rims, but they occur in the normally gently rolling upland of the upper member and thus are anomalous.

The Miranda Sand Member forms a capping of sand and gravel on hilltops along the channel-fill north of Corozal and near Cerro Santa Barbara in the Vega Alta and Corozal quadrangles; farther west in the area between the Río Cibuco and Río Indio, the unit forms rather wide sand flats, possibly accentuated by some colluvial action.

As mentioned above, the drainage on the Cibao Formation is both surface and subsurface. In places, surface streams flowing on the Cibao, as in the upland west of the Río Camuy, disappear in caverns or swallow holes dissolved in limestone in the upper part of the Cibao. One of these caves in barrio Santiago, municipio de Camuy, is essentially a natural sewer because the sides of the tube are highly polished, because mud is lacking on the floor, and because bits of twigs and leaves are found on the walls and ceiling, showing that during rainy periods the tube, which is about 4 m in diameter, is full of water.

In the area between the Río Grande de Manatí and the Río Indio, many surface streams that originate in the typical beds of the Cibao flow into karst valleys formed by walls of the Aguada Limestone and apparently have filled with alluvium a succession of sinks in the Cibao. The most notable of these streams ends in a sink that has an intermittent pond at a place known as El Salto. This pond is being filled with alluvium derived from the typical beds of the Cibao, and one can predict the sinkhole into which the stream will be diverted when the depression at El Salto has been filled.

AGUADA LIMESTONE

NAME

The Aguada Limestone was named by Zapp, Bergquist, and Thomas (1948, sheet 2) "from prominent exposures in the vicinity of the town of Aguada." It consists of the transitional beds between the underlying Río Guatemala group and the overlying Aymamón Limestone. Detailed mapping near Aguada by Monroe (1969a) showed that the rocks in the hills near Aguada more closely resemble rocks in the Cibao Formation farther east than do the rocks overlying the Cibao in areas east of San Sebastián, which had been mapped as Aguada Limestone from Bayamón westward (Monroe, 1962, 1963a, 1963b, 1967, 1969b, 1969c; Monroe and Pease, 1962; Briggs, 1965, 1968). Accordingly, a reference locality (Monroe, 1968a) was selected 10 km northeast of Aguada within the rocks mapped as Aguada Limestone farther east. In the same paper, the Aguada Limestone was defined as to stratigraphic position, and several alternate sections were described.

Apparently the base of the Los Puertos Limestone of Hubbard (1923) is nearly the same as the base at the Aguada Limestone in Hubbard's type area in barrio Puertos east of Lago de Guajataca (Hubbard, 1923, pl. 1, cross section 5, and pl. 2, columnar section 5), but he apparently included in the Los Puertos about 85 m of limestone now included in the Aymamón Limestone. Hubbard showed in his sections the thin-bedded limestones now placed near the middle and at the top of the Aguada. Zapp, Bergquist, and Thomas (1948) abandoned the name Los Puertos for Aguada probably because they were uncertain of the top of the Los Puertos and because they considered the rocks near Aguada as typical, whereas Hubbard included them in the Lares. These are now considered a part of the Cibao.

AREAL DISTRIBUTION

The Aguada Limestone crops out in a generally west-trending belt, interrupted only by the alluvial deposits of several large streams extending from a point just east of the Río Grande de Loíza northeast of Canóvanas, west to the coast at Aguadilla. The belt is commonly 2–3 km wide, and outliers are present updip to the south for as much as a kilometer farther south. In most areas, the formation is present in the bottoms of deep sinks, surrounded by Aymamón Limestone, for a kilometer or more downdip toward the north within the general belt of outcrop of the Aymamón.

STRATIGRAPHIC RELATIONS

The Aguada Limestone rests conformably on the Cibao Formation, and in many places, it is difficult to distinguish the two formations, especially in places where the upper part of the Cibao contains beds of limestone. Commonly, however, the limestone in the Cibao is porcelaneous to very finely crystalline and is filled with molds of mollusks, whereas the limestone in the Aguada is a calcarenite and somewhat less fossiliferous. At most places, the base of the Aguada Limestone is marked by a bed of fine- to medium-grained calcarenite from half a meter to a meter thick. Scattered blocks of this bed commonly cover the hillsides of calcareous clay at the top of the Cibao. In the area east and west of the Río Guajataca, especially in the Quebradillas and Moca quadrangles, the lower 60 m of the Aguada contains much soft earthy limestone and calcareous clay that resembles the underlying Cibao Formation, except for the beds of calcarenite.

The top of the Aguada is marked by a sharp contact with the overlying Aymamón Limestone at nearly all the places where it has been observed. The contact may be conformable, or it may represent a short diastem. At most places, the uppermost Aguada is a zone of thin-bedded, crosslaminated calcarenite, ranging from less than a meter to as much as 10 m thick. At some places, some of these thin beds show desiccation cracks, suggesting that the water was extremely shallow at the time of deposition. The overlying Aymamón Limestone is commonly thick bedded, and in some places, the base of the formation consists of a rubbly limestone that may be a reef breccia or possibly a basal conglomerate. The evidence suggests that a very brief interruption in sedimentation probably took place between deposition of the two formations, but certainly there is no evidence of a major unconformity.

LITHOLOGIC CHARACTER

As pointed out by Zapp, Bergquist, and Thomas (1948), the Aguada Limestone is transitional between the Cibao Formation and the Aymamón Limestone. The Aguada is almost entirely limestone, containing many chalky beds in the lower part, resembling the Cibao, and consisting predominantly of indurated limestone in the upper part, resembling the Aymamón. It resembles the Cibao, also, in containing quartz sand, but only in scattered grains, not in beds of sandstone, whereas the Aymamón contains few, if any, visible grains of quartz.

The Aguada Limestone is well exposed in the reference localities 2–3 km north of Moca along Highway 110, as described by Monroe (1968a) in redefining the formation. The excellent outcrops along the road consist mainly of relatively unfossiliferous light-reddish-brown to very pale orange calcarenite. The contact of the Aguada and the overlying Aymamón Limestone is very well exposed in cuts at Escuela Centro (80,790 E., 65,325 N., Moca quadrangle) at highway marker km 16 hm 6, which is 2.8 km north of Moca (Monroe, 1968a, p. G10) where 2 m of massive very pale orange finely porous very finely crystalline limestone of the Aymamón rests on 5 m of thin-bedded, crosslaminated, grayish-orange-pink to moderate orange pink fine- to medium-grained calcarenite (fig. 28) of the Aguada. *Marginopora* sp. is present in the Aguada here. A thin section (fig. 29) of the Aguada at this locality shows that the rock is predominantly biomicrite

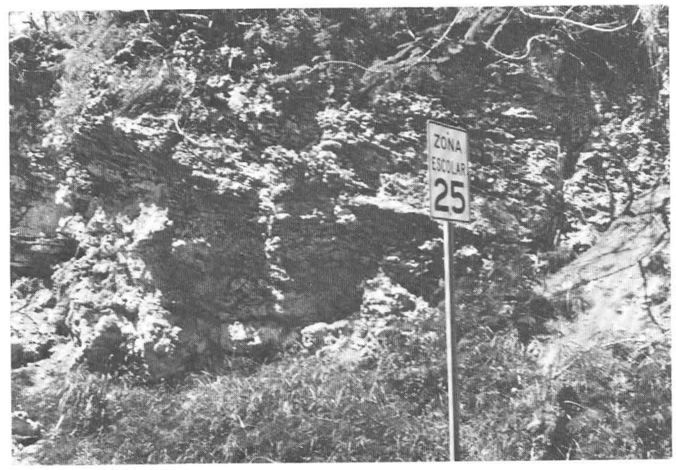

FIGURE 28.—Crosslaminated limestone at the top of the Aguada Limestone in cut on west side of Highway 110 at Escuela Centro, 2.8 km north of Moca (March 1967).

FIGURE 29.—Photomicrograph of upper beds of Aguada Limestone in cut on Highway 110 at Escuela Centro, 2.8 km north of Moca. Biomicrite contains abundant foraminifers including *Marginopora* sp., a few laths of algae, and a few angular grains of quartz. Sparry calcite cement fills many of the cavities.

containing abundant foraminifers, including *Marginopora* sp., and *Archaias angulatus*, a few laths of coralline algae, and a few angular grains of quartz. Sparry calcite cement fills many of the cavities, especially in the foraminifers. An analysis of thin-bedded limestone from this locality (MO534) is included in table 3.

The Aguada is chemically intermediate between the Cibao and the Aymamón, as can be seen readily by comparing the chemical analyses given in tables 2, 3, and 4. The analyses in table 3 show that the Aguada is mostly limestone containing somewhat more silica and alumina than the Aymamón. The material that is insoluble in acid ranges from about 1.3 to about 9 percent; interestingly, the sample that has the least insoluble residue has visible grains of quartz in thin section, as will be described later.

The thin-bedded crosslaminated limestone at the top of the Aguada has been seen at every contact of the Aguada and Aymamón Limestones—from the sea cliff 2 km north of Aguadilla, on the old railroad grade (75,640 E., 68,620 N., Aguadilla quadrangle), and along the public footpath that leads down the ravine south of the Montemar Hotel (75,970 E., 68,130 N., Aguadilla quadrangle) east to an area between the Río Grande de Arecibo and the Río Grande de Manatí. Farther east, the thin beds have been seen at many outcrops, but in some areas, they could not be found. In these areas, massive or thick-bedded very pure limestone of the Aymamón rests directly on pink or very pale orange calcarenite of the Aguada. Most of the Aguada contains grains of varicolored limestone and black grains that are probably manganese dioxide. A typical exposure between the Río Camuy and the Río Tanamá is in a cut (fig. 30) on the west side of Highway 487 (113,820 E., 64,040 N., Camuy quadrangle), 9 km south of Hatillo, just south of the community of El Saco.

The contact of the Aymamón and the Aguada is less clear than usual in cuts on Highway 446 at the sharp U-bend around a narrow ridge (96,060 E., 63,010 N., Quebradillas quadrangle), 2.1 km south of Pueblito de Ponce. There, the thin-bedded zone at the top of the Aguada is overlain by a rubble zone, which has been included in the Aguada but which may be a basal conglomerate of the Aymamón.

TABLE 3.—*Chemical analyses of Aguada Limestone*

[Analyzed by rapid method (Shapiro, 1975); analysts: Paul Elmore, L. Artis, I. Barlow, S. D. Botts, G. Chloe, J. Glenn, J. Kelsey, H. Smith]

Lab. No.	158740	W170023	W172800	W170039	158739
Field No.	BBA168[1]	CM454[2]	M166[3]	MO534[4]	BBA111[5]
SiO_2	6.6	4.0	1.2	4.4	7.2
Al_2O_3	1.2	2.7	.69	2.8	2.0
Fe_2O_3	.60	.91	.24	1.1	.26
FeO	.09	.08	.04	.24	.09
MgO	.30	.51	.24	.43	.26
CaO	49.8	49.6	52.3	48.4	49.4
Na_2O	.06	.00	.05	.02	.07
K_2O	.02	.03	.06	.12	.09
H_2O-	.19	.48	.14	.33	.14
H_2O+	.85	1.2	.28	1.6	1.1
TiO_2	.06	.11	.05	.12	.04
P_2O_5	.04	.02	.02	.02	.03
MnO	.01	.02	.00	.02	.02
CO_2	39.8	40.3	43.7	40.3	38.8
Total	100	100	99	100	99
Acid insoluble	7.5	----	1.3	----	9.0

[1] Basal limestone bed from exposure at side of Highway 626, 2.2 km south of San Pedro (124,200 E., 61,640 N., Arecibo quadrangle). Sample collected by R. P. Briggs.

[2] Chalky limestone about 20 m above base of Aguada from cut on east side Highway 129, 2.2 km northeast of Bayaney (115,665 E., 61,180 N., Camuy quadrangle).

[3] Limestone about 30 m above base of Aguada from west side Highway 160, 5.3 km south of Vega Baja (158,460 E., 62,700 N., Manatí quadrangle).

[4] Thin-bedded limestone at top of Aguada from cut on west side of Highway 110 at Escuela El Centro, 2.8 km north of Moca (80,770 E., 65,340 N., Moca quadrangle).

[5] Limestone at top of Aguada from exposure on west side of Highway 639, 3.4 km south of intersection with Highway 2 (134,130 E., 63,370 N., Barceloneta quadrangle). Sample collected by R. P. Briggs.

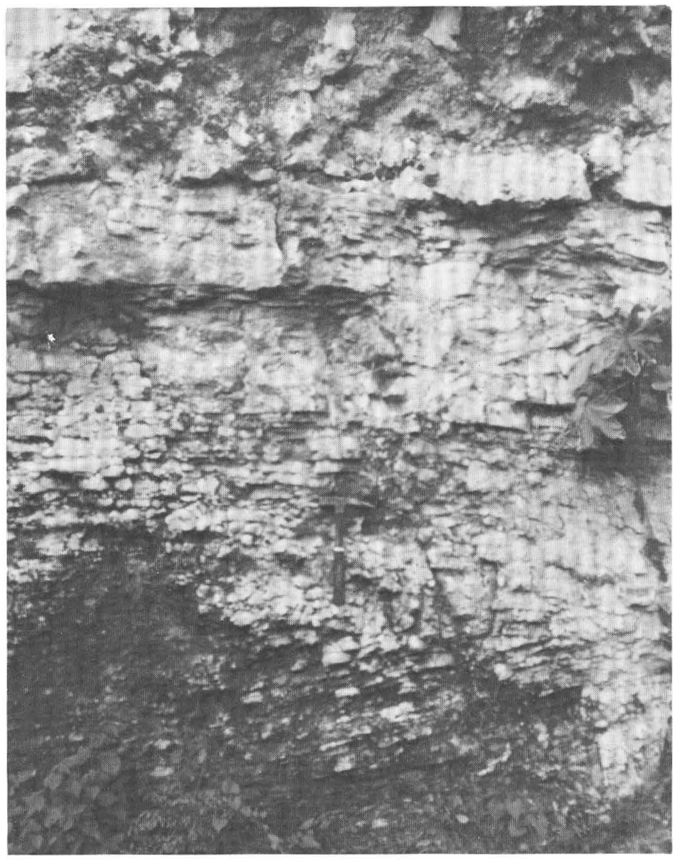

FIGURE 30.—Crosslaminated limestone at top of Aguada Limestone in cut on west side of Highway 487, just south of El Saco, 9 km south of Hatillo (January 1967).

A cut 150 m farther north exposes a bed of gray clay about 5 cm thick in Aguada-like chalk. This bed is some 6 or 7 m above the contact described above, and the chalk is overlain by typical Aymamón crystalline limestone. These outcrops suggest that the contact between the two formations in this area may have a relief of 10 m or more. Around the bend in the highway just to the north, typical Aymamón Limestone rests on thin-bedded limestone of the Aguada, some 8 m lower.

Pink limestone is very common in the upper part of the Aguada, and commonly it contains a few fossils, especially peneroplid foraminifers. A thin section cut from an unfossiliferous bed cropping out in a roadcut on the west side of Highway 112, about 15 m below the top of the Aguada (89,210 E., 66,740 N., Moca quadrangle), 3.8 km south of Highway 2 at Mora, shows the rock to be micrite containing only a few angular opaque grains, a few widely separated intraclasts, and a few grains of calcite spar. The rock is obviously an essentially undisturbed lime mud deposited in very quiet waters, presumably in a back-reef lagoon; only 15 m higher is the crosslaminated limestone that must have been deposited in a zone of high energy.

Thin-bedded limestone, like that at the top of the Aguada, is present at other stratigraphic positions and is especially conspicuous about 40 m below the top of the formation in the area east of Río Guajataca in the Quebradillas quadrangle. In this area, the presence of two similar horizon markers tends to cause confusion, but the upper beds of the Aguada are characteristically pinker, more granular, and more fossiliferous than the Aymamón, even though some beds in the Aguada are very finely crystalline and are apparently identical in appearance with the Aymamón.

The lower zone of thin-bedded limestone in the Aguada Limestone was at about the same stratigraphic position some 18 m above water level on the east side of the Río Camuy at La Cuesta. It seems to mark the base of the more indurated upper part of the Aguada, which was mapped as an upper member in the Quebradillas and Moca quadrangles (Monroe, 1967, 1969b) where the upper 30–40 m is much more indurated than the lower 60 m. At several places, desiccation cracks were seen on bedding planes in this lower thin-bedded zone.

The upper part of the Aguada Limestone is especially well exposed in cuts on Highway 112 in the eastern part of the Moca quadrangle between San Sebastián and Isabela. Much of this sequence was mapped erroneously on the map of the Moca and Isabela quadrangles (Monroe, 1969b) as Aymamón, which it closely resembles. Later studies showed a small anticlinal nose that raises the contact some 70 m; plate 1 of the present report shows the revised contact line. The thin-bedded limestone near the middle of the Aguada was unfortunately taken as the top of the formation; this exposure (88,570 E., 64,620 N., Moca quadrangle) is 5.8 km south of Mora.

A cut on the west side of Highway 112, 200 m farther northeast (88,640 E., 64,790 N.), exposed a 10-cm bed of greenish-blue montmorillonite that at one place contains a bed of lignite 1 cm thick. This place is one of the few above the San Sebastián where lignite is present.

The lower 60 m of the Aguada Limestone near the Río Camuy and between the Río Camuy and the Río Guajataca consists in general of pink to grayish-orange chalky limestone interbedded with fine- to medium-grained calcarenite. The lower part of the Aguada, just north of Guajataca dam, has been eroded into a kind of cone karst topography characterized by rounded summits (fig. 31) of the kind designated by French geomorphologists as coupoles or cupolas. Farther down the valley of the Río Guajataca, the Aguada forms a discontinuous cliff of thin- to medium-bedded limestone (fig. 32). Chemical analysis of a sample of the more chalky limestone, 20 m above the base on Highway 129, is included in table 3 (Field No. CM454).

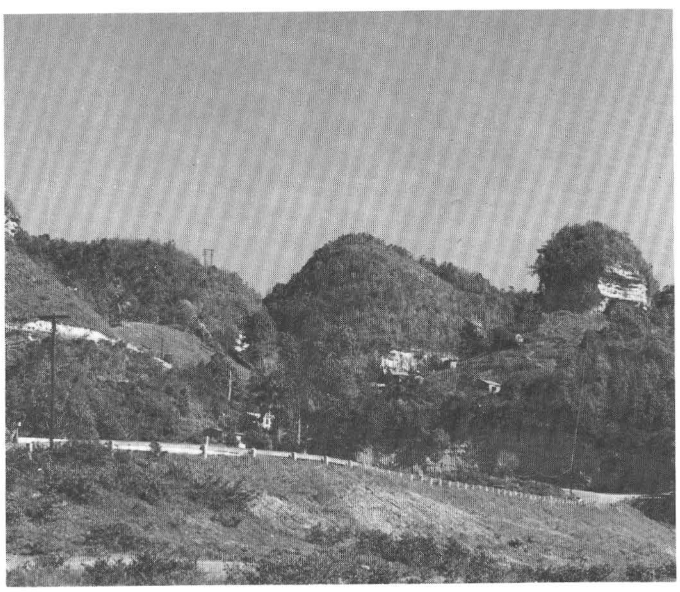

FIGURE 31.—Knobs of Aguada Limestone, lower part, at sides of Highway 119. Guajataca dam in foreground. Contact of Aguada Limestone on Cibao Formation exposed at far right at north end of dam (fig. 25) (February 1967).

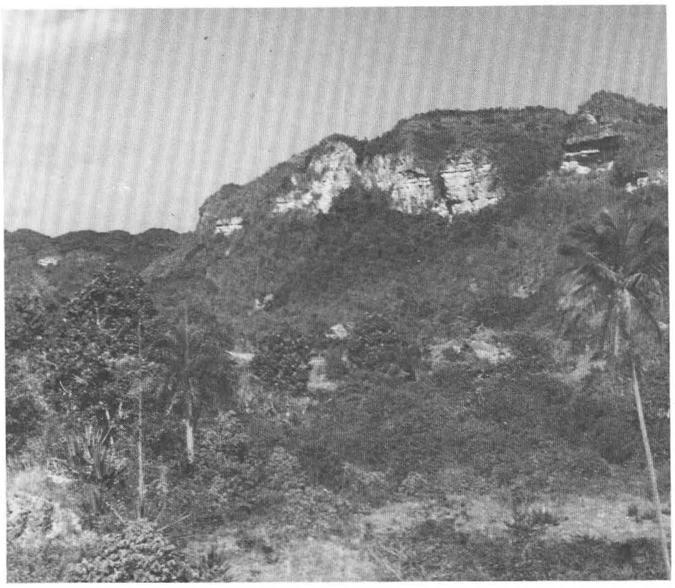

FIGURE 32.—Cliffs of Aguada Limestone on right (north) side of Río Guajataca downstream (west) from Guajataca dam (January 1967).

The cuts on Highway 119 northeast of Guajataca dam show the lower thin-bedded zone at several places, especially in cuts (101,290 E., 63,240 N., Quebradillas quadrangle) 800 m east-northeast of the north end of Guajataca dam. One of the few beds of sandy clay seen in the Aguada Limestone, stratigraphically below the thin-bedded zone, crops out in a cut on the north side of the highway (101,480 E., 63,110 N.) about 250 m southeast. Highway 119 runs through a fine example of a karst valley farther east, and many very good views of the upper part of the Aguada (fig. 33) may be obtained in the wall north of the highway (102,090 E., 63,200 N.) at the intersection with Highway 453, which goes south to Soller and Lares.

In the eastern part of the outcrop belt of the Aguada, the limestone contains many fine to medium grains of quartz, some angular, some well rounded. One of the more indurated beds in the lower part of the Aguada, about 30 m above the base, crops out at the side of Highway 160, 5.3 km south of the bridge over the Río Cibuco at Highway 2 (158,460 E., 63,700 N., Manatí quadrangle). A chemical analysis of this rock is included (Field No. M166) in table 3; the rock has the lowest percentage of material insoluble in hydrochloric acid of any samples from the Aguada. A thin section (fig. 34) shows that this rock is mostly micrite that contains intraclasts, a little sparry cement, a few angular quartz grains that have normal extinction, many algal fragments, and abundant foraminifers, especially peneroplids. This outcrop is downdip toward the north from the lenses of sand of the Almirante Sur Sand Lentil and the Miranda Sand Member of the Cibao Formation near the Río Indio, and the quartz was probably brought into the area by the same river responsible for the sand in those members.

In the western part of the Bayamón quadrangle, east of Toa Alta, the lower part of the Aguada grades laterally into chalky limestone and calcareous clay that is indistinguishable from the underlying upper member of the Cibao. The overlying parts of the Aguada continue eastward, showing little change in lithologic character except that sand and clay become increasingly common in the formation toward the eastern side of the depositional basin. The Aguada is exposed in only a few isolated hills within the city of San Juan, but northeast of Carolina, the formation is typically exposed in a range of hills north of the Río Grande de Loíza and for a short distance east of that river northeast of Canóvanas.

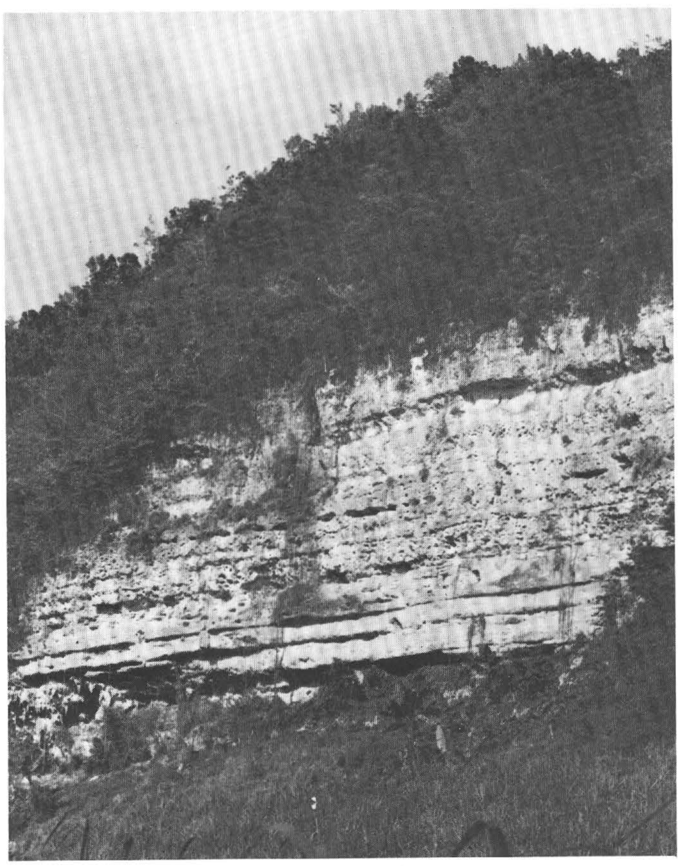

FIGURE 33.—Cliff of upper part of Aguada Limestone on north side of valley at intersection of Highways 119 and 453, 1.5 km east by north of the north end of Guajataca dam (January 1967).

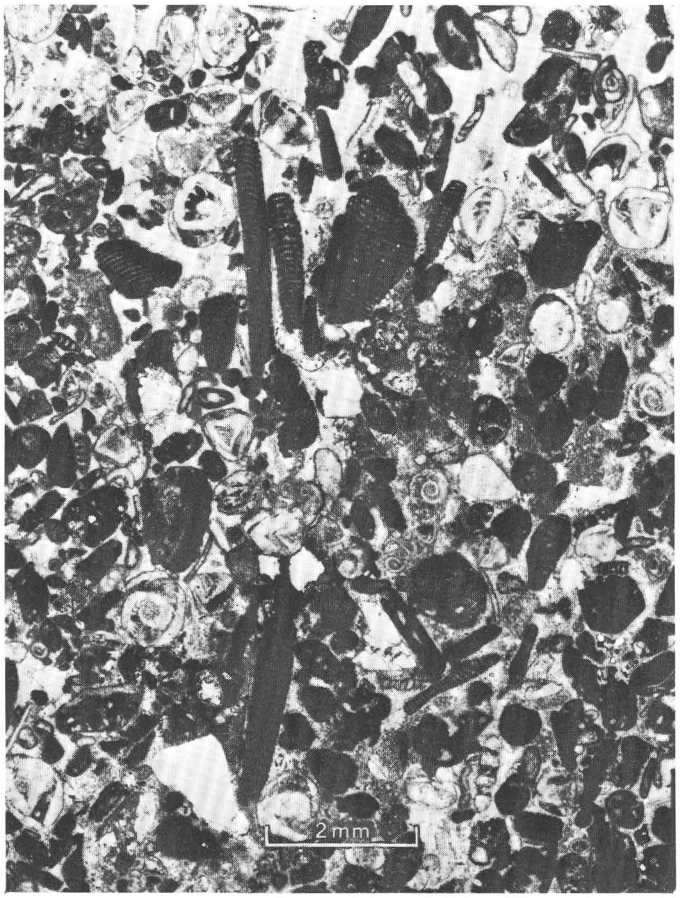

FIGURE 34.—Photomicrograph of Aguada Limestone cropping out at the side of Highway 160, 5.3 km south of the bridge over the Río Cibuco at Highway 2. Mostly micrite containing many algal fragments and abundant foraminifers, especially peneroplids, and a few angular quartz grains.

SAMPLES FROM WELLS

The Kewanee Interamerican Oil Company test well 4CPR, drilled near the coast between Arecibo and Barceloneta, penetrated dense limestone, doubtfully referred to the Aguada between depths of 1,270 and 1,420 ft (387 and 433 m) and a sequence, mostly of calcarenite, that is certainly Aguada between depths of 1,480 and 1,850 ft (451 and 564 m). No samples were saved between depths of 1,420 and 1,480 ft (433 and 451 m). Briggs (1961, p. 10, 18) described the sequence as very pale orange to yellowish-gray calcarenite, probably somewhat magnesian, commonly containing some black grains of probable manganese dioxide.

Abbott Laboratories disposal well 1 drilled near the northwest corner of the intersection of Highways 2 and 140, penetrated very pale orange to orange-white fossiliferous calcarenite between depths of 240 and 310 ft (73 and 95 m) that is doubtfully referred to the Aguada. It then penetrated a sequence of pink, white, pale yellowish-brown to very pale orange, fine- to coarse-grained fossiliferous calcarenite containing molds of mollusks and foraminifers including *Marginopora* sp. to a depth of 610 ft (186 m). Below this point, it penetrated medium-gray to very pale orange and white limestone and soft chalk, which may be either Aguada or Cibao, to a depth of 690 ft (210 m).

THICKNESS

The Aguada Limestone is more uniform in thickness than most of the other formations of middle Tertiary age in northern Puerto Rico, having a thickness of about 90 m from the Río Grande de Arecibo west to the coast at Aguadilla. Farther east, however, it is less regular. In the valley of the Río Grande de Arecibo, Briggs (1968) found that the thickness of the Aguada in the southern part of the Arecibo quadrangle is 90 m but that the formation thickens toward the north downdip to about 150 m. In the well drilled by Kewanee Interamerican Oil Company on the coast near the border of the Arecibo and Barceloneta quadrangles, Briggs (1961) assigned 113 m to the Aguada and the overlying 64 m to either the Aguada or the Aymamón Limestone, for a maximum total thickness of about 177 m. In the Abbott disposal well southwest of Barceloneta, 92 m is definitely assigned to the Aguada, 21 m to either the Aguada or Aymamón, and 24 m to either the Aguada or Cibao, for a maximum total thickness of 137 m—the probable true thickness in this well is about 115 m.

East of the Río Grande de Manatí, the Aguada appears to vary in thickness much more than it does farther west. In the Manatí quadrangle (Monroe, 1971), the thickness ranges from 90 m in the updip outcrops to about 110 m, as measured in outcrops down the dip in the valleys of the Río Grande de Manatí and the Río Indio. In the western part of the Vega Alta quadrangle (Monroe, 1963a), the thickness seems to be about 90 m in the western part of the quadrangle, but the formation thins to about 60 m in the eastern part. Recent studies in the Bayamón quadrangle (Monroe, 1973a) show that the lower 35 m of the formation intertongues with the upper part of the Cibao Formation just east of the Río de La Plata, so that farther east in the quadrangle the formation is only about 35 m thick. Because outcrops east of Bayamón are sporadic, estimates of thickness are even less reliable than those farther west, but the thickness seems to range from about 25 to 80 m in most of that area.

FOSSIL CONTENT AND AGE

The Aguada Limestone is not as rich in fossils as the Cibao Formation or the overlying Aymamón, but good collections have been made, particularly in the more chalky lower part. Most of the fossils are present as molds and impressions in the limestone.

Hubbard did not recognize the Aguada Limestone, but his Los Puertos Limestone is almost exactly the same sequence in its type area, except that he includes the lower part of the Aymamón Limestone. He listed (Hubbard, 1920b) only 10 species from beds that would be considered Aguada today, and of these 4 are found in underlying formations, 2 are also found in the Aymamón, and 4 are found in both underlying and overlying formations. He did not list any species that might be considered diagnostic of the Los Puertos Limestone alone.

Bergquist (written commun., 1945) listed 4 species of echinoids and about 40 species of mollusks from strata that today would be classified as Aguada, but few of these, if any, are restricted to the Aguada. The most conspicuous fossil is the large gastropod *Orthaulax aguadillensis*, but this is found in all the limestone formations of the late Oligocene and Miocene of northern Puerto Rico.

The foraminifers also seem to be mostly long-ranging types; most species are also present in the Aymamón, and many are present in the upper part of the Cibao. The most conspicuous and useful fossils, especially for differentiating the Aguada from the limestones in the lower Cibao and Lares, are *Marginopora* sp. and *Gypsina globula*, both of which can be recognized by means of a hand lens. The absence of *Lepidocyclina* and the presence of *Marginopora* indicate that the age of the Aguada is Miocene, and as the formation appears to be gradational into the basal Miocene beds of the Cibao, it seems reasonable to consider the formation as lower Miocene.

ORIGIN

The Aguada Limestone is composed entirely of limestone that was deposited on a slowly subsiding coastal shelf. Some of the rivers whose flood plains are preserved in the Miranda Sand Member of the Cibao Formation were still active during Aguada time, for the Aguada Limestone contains scattered quartz grains in the rocks north of the lenses of Miranda, whereas at most places, the Aguada does not contain quartz.

Throughout most of its belt of outcrop, the Aguada consists of relatively indurated limestone, but in a small area between the Río Tanamá and Moca, the lower part contains much more chalk than elsewhere. This lower member may be the consolidated part of a back-reef deposit in which the material being carried into the sea by the ancient San Sebastián-Moca River, which deposited all the gravel and sand of the upper San Sebastián Formation, diluted the relatively pure lime sand being deposited to the east and west to form the hard calcarenite characteristic of the formation.

At least a part of the Aguada was deposited in very shallow water in which currents were active, as indicated by the desiccation cracks in the top of the formation (seen in the Camuy quadrangle) and by the thin-bedded, crosslaminated limestone found at most places at the top of the formation and at many places at lower stratigraphic horizons.

The presence of *Marginopora*, according to Cloud (1952), is presumptive evidence of a reef-flat environment. Because this foraminifer is very common throughout the Aguada, because much of the limestone was deposited in very shallow water, and because fossils such as corals and algae that provide a skeletal framework are present, it seems reasonable to assume that the Aguada was deposited as a fringing reef on the Atlantic coast of the ancestral Puerto Rico.

PHYSIOGRAPHIC EXPRESSION

Throughout its belt of outcrop, the Aguada Limestone forms a dissected cuesta that has a steep south-facing escarpment rising 10–50 m above the low rolling hills formed on the upper part of the Cibao Formation. The indurated calcarenite beds of the lower part of the Aguada commonly form vertical cliffs on the escarpment that appear on the skyline as castellated crags, as shown in figures 31, 32, and 33.

The outcrop belt of the Aguada is characterized by very closely spaced sinks or dolines. In many parts of the belt, as in the Manatí quadrangle, the sinks are so closely spaced that only narrow ridges separate one sink from the next. The sinks range in depth from a few meters to as much as 70 m, but the deeper ones commonly are far down the dip where their upper walls are formed of Aymamón Limestone. Within the belt of outcrop of the Aguada itself, the sinks average about 30 m in depth. At places where a sink is entirely within the Aguada Limestone, the ridge between sinks is commonly a rounded hill, but where the upper part of a sink is dissolved in Aymamón Limestone, the dividing ridge is very steep sided. This difference is especially notable where three sinks are in juxtaposition. Within the Aguada belt, the divides are low hills at more or less uniform height, but where Aymamón is present, the divides are commonly steep-sided, cone-shaped mogotes.

Although most of the sinks observed in the Aguada Limestone appear to be solution type, in which there has been collapse only on the oversteepened walls, a few sinks are collapse type, for caves are present in many parts of the Aguada. Caves are most common, however, at the base of the formation, apparently related to the difference in solubility between the Aguada and the underlying Cibao Formation.

The deep, commonly vertical-walled sinks so closely spaced in the outcrop belt of the Aguada Limestone impede traffic across the belt except at places where the sinks have been filled with alluvium or blanket deposits, as in parts of the Manatí, Florida, and Camuy quadrangles, and at places where the few through-flowing streams have cut valleys in the formation. Thus, until recently, very few highways crossed the belt. Nowadays the advent of modern road-making machinery has made the cutting and filling needed for highway construction less of a problem, and increasingly highways are being pushed through the belt.

As may be surmised from the description above, the belt contains very little surface water, except for such large through-flowing streams as the Río Grande de Arecibo and the Río Guajataca. The top of the water table is so deep beneath most of the belt that water is present in the bottom of very few of the sinks, and most of those have water because the bottom has been sealed by alluvial clay derived from the Aguada or the Cibao Formation. A few springs have been noted in the belt, but most of these are near the bottom of sinks and form streams only to the other side of the sink where the water again passes underground.

AYMAMON LIMESTONE

NAME

The Aymamón Limestone was named by Zapp, Bergquist, and Thomas (1948, sheet 2): "from the Aymamón Mountains, an area of very rugged limestone hills just west of the Río Guajataca and about midway between the towns of San Sebastián and Quebradillas." The name replaced Quebradillas Limestone because Zapp, Bergquist, and Thomas believed that the Aymamón was the equivalent of the Quebradillas Limestone and the upper part of the Los Puertos limestone, which they considered inseparable. My more recent studies (Monroe, 1967) have indicated that the Aymamón includes the upper half of the Los Puertos, as defined by Hubbard (1923), and all but the upper most part of the Quebradillas. These studies (Monroe, 1963b, 1967) have also shown that the upper part of the Aymamón as defined by Zapp, Bergquist, and Thomas (1948) and the upper part of the Quebradillas of Hubbard constitute a separate formation, the Camuy Formation, which is separated from the Aymamón by an erosional unconformity. In effect, the Aymamón has been somewhat redefined by separation of the Camuy Formation by Monroe (1963b), and the base has been redefined in the study of the Aguada Limestone (Monroe, 1968a).

AREAL DISTRIBUTION

The Aymamón Limestone is exposed continuously, except for small areas covered by alluvial deposits, from the hills just east of Loíza Aldea, east of the Río Grande de Loíza, west to the Mona Passage and Atlantic Ocean north of Aguadilla. The limestone crops out in isolated exposures totaling only about 2 km in width on both sides of the Río Grande de Loíza. The formation is completely concealed between the longitude of Carolina and the eastern part of Santurce in San Juan where a few typical steep-sided hills used to be exposed but have been cut away in quarrying operations and city expansion. Still farther west, the formation is concealed as far as the Río de Bayamón. Between the Río de Bayamón and the Río de La Plata, the Aymamón crops out on the crests of hills in a belt about 2.5 km wide. West of the Río de La Plata, the belt is more continuous, ranging in width from about 6 to 8 km and reaching a maximum width of slightly more than 10 km in the area between Isabela and Aguadilla.

STRATIGRAPHIC RELATIONS

The Aymamón Limestone rests sharply, but apparently conformably, on the Aguada Limestone. At most localities, the upper part of the Aguada is thin-bedded limestone, which contrasts with the normally thick beds of the Aymamón. Furthermore, the Aymamón commonly is very pale orange to white, whereas the upper Aguada is reddish at many places, and the Aymamón commonly is very finely crystalline, whereas the Aguada is commonly calcarenite. Therefore, in those places where thin-bedded limestone has not been observed at the top of the Aguada, the two formations can be distinguished with little difficulty.

The Aymamón Limestone is apparently separated from the overlying Camuy Formation by an erosional unconformity (Monroe, 1963b, 1973b). The basal Camuy, moreover, is commonly very ferruginous pink to red limestone and is thin bedded and crossbedded, contrasting with the underlying massive- to thick-bedded limestone at the top of the Aymamón. Furthermore, the basal Camuy contains considerable quartz sand at most places, whereas the Aymamón is quartz free.

LITHOLOGIC CHARACTER

No specific type locality for the Aymamon Limestone was designated by Zapp, Bergquist, and Thomas (1948) when they named the formation, but they apparently had in mind the outcrops along Highway 446, which goes north from San Sebastián to Highway 2 between Quebradillas and Isabela through Montañas Aymamón. A discussion of the somewhat unusual base of the Aymamón on this road is given in the section of this report on the lithologic character of the Aguada Limestone. The Aymamón, just west of the Aymamón Mountains, is especially well exposed in the new cuts on Highway 112, which leads north from San Sebastián to Isabela. A sample collected 5 m above the top of the Aguada in a cut on this highway that is 4.6 km south of Highway 2 at Mora (89,000 E., 65,910 N., Moca quadrangle) was examined microscopically; it consists of slightly sparry micrite containing a few small foraminifers, a few algal laths, many intraclasts, and a few opaque grains. The contact of the Aymamón and Aguada limestones on Highway 112 is shown incorrectly on the geologic map of the Moca and Isabela quadrangles (Monroe, 1969b), but it has been corrected in plate 1 of the present report. On the quadrangle map, the contact is placed about 70 m too low, owing to an error in interpretation of the outcrops along the highway.

The Aymamón Limestone is remarkably uniform throughout its belt of outcrop, consisting mainly of thick-bedded to massive commonly quartz-free, very pure limestone. In northwestern Puerto Rico, the upper part of the formation consists in part of pale-grayish-orange unconsolidated chalk that alternates with thick beds of recrystallized porcelainlike pure limestone. Near the coast, dolomite has replaced some of the limestone. Except for the dolomite, however, the Aymamón is remarkably uniform in chemical composition, as is shown on table 4. Analyses of Field Nos. V35b, BBA206B, BBA224, and MO10 from table 4 of the limestones of the Aymamón range from 97.7 to 99.5 percent calcium carbonate; the other four analyses of dolomite and dolomitic limestone all contain about 98 percent carbonate and very small quantities of insoluble material.

The lower half of the Aymamón consists mainly of thick-bedded (fig. 35) very pure limestone, notably quartz free. Many of the thick beds of limestone consist of limestone breccia. Some of this breccia may be organic reef material broken by wave action shortly after formation, but much of it has formed by solution of the limestone, which left a mass of solution cobbles or blocks.

A particularly good exposure of typical Aymamón Limestone is present on the northeast side of a mogote that has been cut by Highway 2 (160,800 E., 67,330 N., Vega Alta quadrangle), 4 km northwest of Vega Alta where the cut face shows the internal features of the hill. The Aymamón is rather crudely bedded in nearly horizontal layers several meters thick. At the base is a bed of chalk

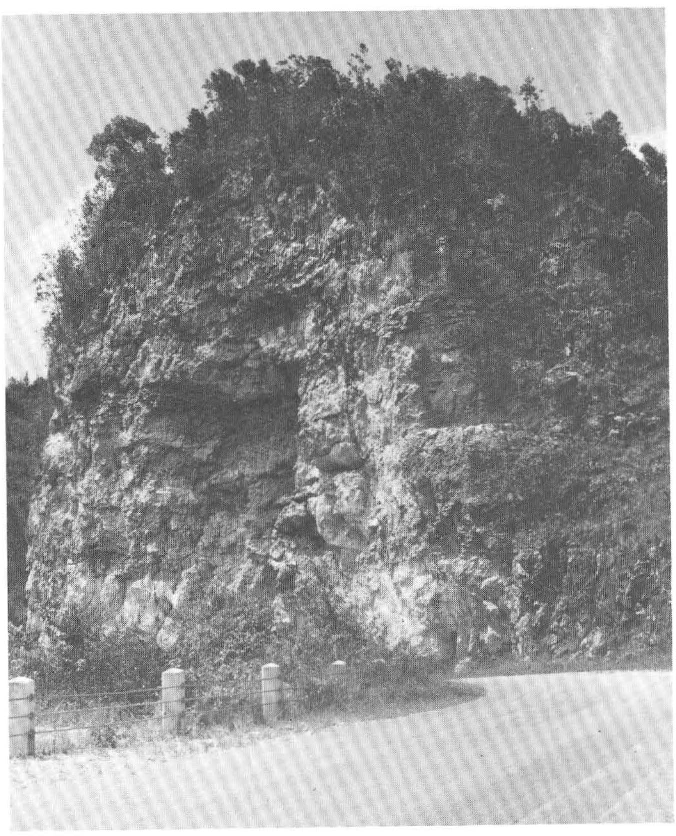

FIGURE 35.—Stratified limestone near base of Aymamón Limestone in cut on Highway 486 (107,380 E., 64,900 N., Camuy quadrangle), 7.4 km south of Camuy (August 1960).

TABLE 4.—*Chemical analyses of Aymamón Limestone*

[Analyzed by rapid method (Shapiro, 1975); analysts, Paul Elmore, L. Artis, I. Barlow, S. D. Botts, G. Chloe, J. Glenn, J. Kelsey, H. Smith]

Lab. No. / Field No.	W170031 V35b[1]	158744 BBA206B[2]	158745 BBA224[3]	W170037 MO10[4]	W170029 AG157[5]	W170025 QD3[6]	W170026 QD8[7]	W170027 QD17[8]
SiO_2	0.00	0.50	0.13	0.80	0.51	0.66	0.66	0.46
Al_2O_3	.04	.28	.14	.35	.22	.33	.55	.35
Fe_2O_3	.00	.11	.04	.00	.00	.03	.00	.00
FeO	.00	.06	.05	.29	.06	.12	.00	.00
MgO	.10	.34	.48	.33	16.5	16.4	17.0	18.6
CaO	55.3	54.5	54.7	53.4	34.2	35.1	34.2	32.7
Na_2O	.00	.04	.02	.00	.04	.00	.07	.00
K_2O	.03	.02	.01	.08	.02	.00	.00	.02
H_2O-	.00	.06	.03	.08	.05	.08	.09	.02
H_2O+	.30	.44	.32	.58	.64	.62	.68	.63
TiO_2	.00	.02	.01	.02	.11	.09	.07	.12
P_2O_5	.02	.02	.02	.03	.03	.06	.08	.02
MnO	.00	.01	.01	.00	.00	.00	.00	.00
CO_2	44.2	43.2	43.3	44.3	47.5	46.5	46.6	47.0
Total	100.	100.	99.	100.	100.	100.	100.	100.
Acid insoluble		0.82	0.31	-----	-----	-----	-----	-----

[1] Chalky limestone about 50 m above Aguada from cut in northeast side of mogote on south side Highway 2, 3.5 km east of Vega Baja (160,800 E., 67,370 N., Vega Alta quadrangle).

[2] Limestone 50 m above Aguada from cut on Highway 140, 1.5 km south-southwest of intersection with Highway 2 (137,780 E., 64,980 N., Barceloneta quadrangle). Sample collected by R. P. Briggs.

[3] Limestone about 115 m above Aguada from quarry south of road, 3 km south of Arecibo (121,130 E.. 67,920 N., Arecibo quadrangle). Sample collected by R. P. Briggs.

[4] Upper member, about 125 m above Aguada from cut on west side Highway 5, 2.1 km north-northwest of intersection with Highway 2 (81,650 E., 70,710 N., Moca quadrangle).

[5] Bed 55 m above Aguada, cut in side of trail, 320 m east of coast, 4.8 km north of Aguadilla (74,990 E., 71,090 N., Aguadilla quadrangle).

[6] Outcrop in gully 50 m above QD8 about 165 m above Aguada (93,740 E., 73,460 N., Quebradillas quadrangle).

[7] Dolomite 125 m above Aguada at foot of sea cliff, 3.1 km west of mouth of Río Guajataca (93,930 E., 73,610 N., Quebradillas quadrangle).

[8] Dolomite about 125 m above Aguada from cut on south side of Highway 2, 200 m southwest of Rio Guajataca (96,840 E., 72, 140 N., Quebradillas quadrangle).

composed of silt-sized crystals of calcite, containing abundant molds of mollusks; the chalk is honeycombed by abundant perforations 2–20 cm in diameter, which were apparently caused by solution (fig. 36). This bed is very friable in the northwest-central part of the cut, but it has been indurated to very hard marblelike limestone (Monroe, 1966a) in the southeastern half of the cut and in the northwestern 20 m. Above this bed is a rubbly layer about 4 m thick, and above that is a succession of indistinct layers of perforated and rubbly beds, some of which are chalky. The top of the mogote is composed of very hard solution-pitted limestone.

A thin section of the perforated bed at the base of the mogote shows that the bed consists of very fine grained intrasparite containing *Marginopora* sp. and other fossils, including a few algal remains. A chemical analysis of this limestone, Field No. V35b, is given in table 4. The rock consists of about 99.5 percent calcium carbonate, comparable with the other analyses of limestone from the Aymamón (table 4, Field Nos. BBA206B, BBA224, and MO10). The original marine limestone rather obviously has been recrystalized, for all the fossils are present only as cavities lined with calcite, and the rock itself is a mass of very fine crystals. Stable-carbon and oxygen-isotope studies made by Irving Friedman (written commun., 1968) show that the friable chalk and the indurated part of the same bed have both been altered from normal marine limestone by addition of light carbon, presumably derived from land plants (Friedman and others, 1968); he recorded δO^{18}SMOW$+27.0$ and δC^{13}PDB-8.3, for the friable chalk δO^{18}SMOW$+27.0$ and δC^{13}PDB-7.9 for the indurated limestone of the same bed, essentially the same. In contrast, a sample of Lares Limestone from the Kewanee Interamerican Oil Company test well 4CPR from depths of 3,704–3,726 ft (1,129–1,136 m), which apparently has never been in contact with ground water containing plant-derived carbon dioxide, shows δO^{18}SMOW$+28.3$ and δC^{13}PDB$+1.0$. Apparently, most of the Aymamón Limestone cropping out in Puerto Rico has been altered in similar fashion.

Along many of the stream valleys, especially those of the Río Guajataca, Río Grande de Arecibo, and Río Grande de Manatí, and also along some sea cliffs, the Aymamón has been indurated by recementation (Monroe, 1966a) and forms a wall or rampart that stands high above the adjacent plains, much as the mogotes stand above the surrounding plains of blanket sand. These ramparts are residual hills left by subsoil solution under the adjacent plains (Monroe, 1969a). Figure 37 shows the Aymamón

FIGURE 36.—Solution-riddled chalk in lower part of the Aymamón Limestone in cut on southwest side of Highway 2, 4 km northwest of Vega Alta. Limestone is friable in excavated part of cut, but in area shown on bottom of photograph, it has been indurated by secondary reprecipitation after partial solution (April 1963).

Limestone exposed in a sea cliff (99,500 E., 72,890 N., Quebradillas quadrangle) 1.7 km north of Quebradillas. The limestone in this cliff has been indurated after ephemeral solution by sea spray, and nearby, a window has been dissolved in a narrow wall of the limestone. The photograph shows the tidal notch so common in limestone exposed on coasts in the tropics (Kaye, 1959b) and also shows honeycomb solution of the limestone just above the notch.

In northwestern Puerto Rico, the upper part of the Aymamón Limestone contains beds of unconsolidated chalky limestone that slightly resembles the overlying Camuy. Although this chalky limestone is interbedded with hard porcelaneous limestone, it is sufficiently different from the typical recrystallized hard limestone to be mapped as an informal upper member on the geologic maps of the Aguadilla, Moca, and Isabela quadrangles (Monroe, 1969b, 1969c). The chemical analysis of the chalky limestone (Field No. MO10, table 4) shows that it is only slightly less pure than the other samples of Aymamón. The outcrop on the west side of Highway 5 (81,650 E., 70,710 N., Moca quadrangle), 2.1 km north-northwest of the intersection with Highway 2, shows nearly 5 m of pale-yellow compact fine-grained calcarenite containing scattered grains of grayish-orange to yellowish-orange limestone; this rock does not consist of the silt-size calcite crystals common in the lower Aymamón. Large specimens of *"Ostrea" haitensis* form a prominent bed in the roadcut; Cooke (unpub. data, 1956) also collected *Pecten gabbi, P. portoricoensis reticulatus,* and *Amusium* sp.

An overhanging bank at the side of the trail in Quebrada de los Cedros (82,300 E., 75,000 N., Isabela quadrangle), about 800 m south of the shore, exposes about 5 m of similar unconsolidated lime-

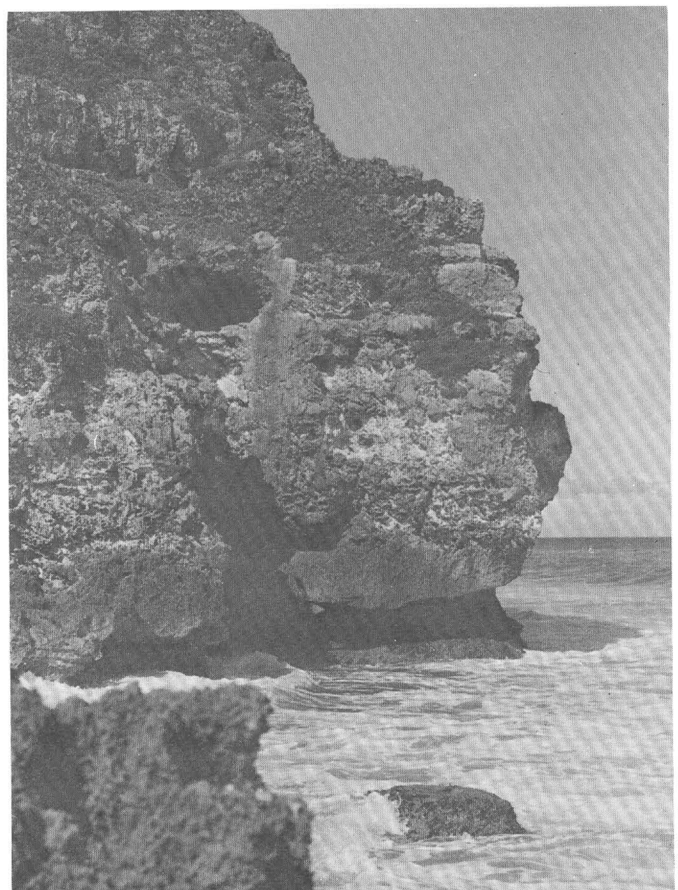

FIGURE 37.—Aymamon Limestone exposed in sea cliff 1.7 km north of Quebradillas. Note tidal notch near base of cliff and honeycomb solution of indurated bed above it (December 1965).

stone from which I collected *Clypeaster cubensis,* identified by P. M. Kier of the U.S. National Museum (written commun., Feb. 17, 1966). The unconsolidated limestone here is overlain by more typical solution-riddled hard limestone.

Near the coast, much of the Aymamón Limestone has been altered to dolomite and calcitic dolomite (Vázquez and others, 1957), in a somewhat irregular pattern. Table 4 includes several analyses (Field Nos. AG157, QD3, QD8, and QD17) of samples of the dolomite near the north coast of Puerto Rico. Although the analyses indicate only 75–85 percent MgO equivalent dolomite, which would be classed as calcitic dolomite, an X-ray determination of a sample collected close to sample QD17 (table 4), shows no measurable calcite. The best outcrops are in cuts on the south side of Highway 2 between the bridge over the Río Guajataca and the intersection of Highway 113 west of the river.

A thin section of the dolomite, collected from the roadcut on the south side of Highway 2 (97,070 E., 72,210 N., Quebradillas quadrangle) 190 m southwest of the bridge over the Río Guajataca and about 240 m east-northeast of sample QD17 (table 4) consists mainly of sparry dolomite rhombs containing a few algal remains and a few grains of an opaque mineral. The section shows a few fossil shells replaced by dolomite.

The origin of the dolomite is difficult to explain. It apparently is related in some way to the sea, for it has been found only near the sea; the same beds up the dip toward the south, away from the sea, are not dolomitic. A puzzling feature of the outcrop is that the cuts on the south side of Highway 2 consist of dolomite and calcitic dolomite, but outcrops on the hill north of the highway and along Highway 113 are not dolomite or even magnesian limestone.

Most outcrops of the Aymamón Limestone near the sea, from gullies about 4 km east of Isabela to outcrops near Camuy, are dolomitic. Dolomite has also been observed on the plateau at Punta Chivato, north of Laguna Tortuguero, and in a hill south of Loíza Aldea near the easternmost occurrence of the Aymamón Limestone. The westernmost outcrop of dolomite is on the lowland near the sea north of Aguadilla, from which sample AG157 (table 4) was collected.

SAMPLES FROM WELLS

Kewanee Interamerican Oil Company test well 4CPR, drilled near the coast between Barceloneta and Arecibo, penetrated Aymamón Limestone between depths of 560 and 1,270 ft (171 and 387 m) and penetrated rocks that may be Aymamón or Aguada between depths of 1,270 and 1,480 ft (387 and 451 m). Briggs (1961) included in the Aymamón the top 560 ft (171 m) in this well, but more recent studies (Briggs, 1968) show that these rocks belong to the Camuy Formation. The Aymamón Limestone in the well consists of white to very pale orange calcarenite containing grains of manganese dioxide and a few fossil fragments. The sequence between depths of 580 and 680 ft (177 and 207 m) is mostly calcitic dolomite containing as much as 18.5 percent MgO, equivalent to 84 percent dolomite.

Abbott Laboratories disposal well 1 (138,400 E., 66,540 N., Barceloneta quadrangle), drilled near the northwest corner of the intersection of Highways 2 and 140, penetrated 240 ft (73 m) of white, very pale orange, and pinkish-gray limestone, mostly recrystallized, that contains foraminifers and other fossils in some beds. Between 240 and 310 ft (73 and 95 m), the well penetrated very pale orange, orange-white, and grayish-orange to pink chalky calcarenite that may be Aymamón or may be Aguada.

THICKNESS

The Aymamón Limestone is the most homogeneous formation of middle Tertiary age in northern Puerto Rico, and its thickness is the most uniform throughout its belt of outcrop. The total thickness can be determined only in the area between the Río de La Plata and Isabela where the Aymamón is overlain by the Camuy Formation—elsewhere the upper part of the formation is missing.

Calculations of the thickness of the formation based on outcrop data range from about 190 to 200 m in various quadrangles, but these figures are based on projection of dips from the base of the formation to the place at which it is overlain by the Camuy. Thus, the estimates may be in error by 10 percent or more.

From study of cuttings from the Kewanee Interamerican Oil Company's test well 4CPR in the northeastern part of the Arecibo quadrangle, Briggs (1961, 1968) concluded that a sequence 216 m thick, between depths of 171 m and 387 m, represents the Aymamón, and that the sequence 64 m thick between depths of 387 m and 451 m is either Aymamón or Aguada, but probably the latter. This probable figure of 216 m is comparable with estimates based on outcrop data.

In northwestern Puerto Rico, the Aymamón has been divided (Monroe, 1969a, 1969b) into two informal members—a lower member about 110 m thick that is generally recrystallized and indurated on the surface (case-hardened) into finely crystalline nonporous limestone and an upper member about 80 m thick of very pale orange to bright-yellow chalk interbedded with hard vuggy limestone like the lower member.

FOSSIL CONTENT AND AGE

The Aymamón Limestone contains abundant fossils in some localities, but most are present only as solution molds of the exterior in commonly recrystallized limestone. Shells themselves are only present in the upper member in the northwestern part of Puerto Rico where several reefs of *"Ostrea" haitensis* have been observed.

Hubbard (1920b) listed 72 species of mollusks from the Quebradillas Limestone, which is essentially conterminous with the Aymamón Limestone and the Camuy Formation in the part of Puerto Rico in which he worked. Most of his collections are from the Aymamón, and a very high proportion are from richly fossiliferous strata near the mouth of the Río Guajataca. Of the 72 species, only 9 are found in lower stratigraphic positions, and only 2 are found the Camuy Formation, leaving 61 species restricted to Aymamón.

Bergquist (written commun., June 1945) listed 65 species found only in the Aymamón and its partial correlative in southern Puerto Rico, the Ponce Limestone, and 47 species found in the Aymamón as well as in older formations, including the San Sebastián Formation.

All the species listed by both Hubbard and Bergquist are mollusks; neither found any echinoderms in the Aymamón, although they are present in many of the formations composed of less pure limestone and in the Lares. As mentioned above, one specimen of *Clypeaster cubensis* was collected from the upper member of the Aymamón near the coast in Quebrada de los Cedros near Isabela.

Corals are present at many horizons in the Aymamón Limestone, but very few have been collected and identified. Coryell and Ohlsen (1929) recorded only two species of corals from the Aymamón, but as their collections were mostly those made by Reeds (1917) from the Lares-San Sebastián area, that is not surprising. Not only in the Aymamón but in most other Puerto Rico collections, corals have been neglected, mainly because few specialists since Vaughan (1919) have had any interest in fossil corals of the Caribbean area. Three specimens from the upper part of the Aymamón near the Vega Baja airstrip (151,900 E., 71,390 N., Manatí quadrangle) were identified by John W. Wells (written commun., 1958) as *Montastrea limbata pennyi, Psammocora gasparillensis,* and *Porites* sp. Wells reported that these shallow-water, reef-dwelling types of corals are almost certainly of Miocene age.

The Aymamón has been so thoroughly recrystallized that foraminifers are generally not easily identified in samples of the formation, but *Marginopora, Archaias,* and *Gypsina* can be recognized in hand specimens.

Although some of the early students of the fauna of the Aymamón considered that it might be late Oligocene, all recent investigators, including Galloway and Heminway (1941), Zapp, Bergquist, and Thomas (1948), and Sachs (written commun., 1968) agree that the formation is of Miocene age and probably early Miocene.

ORIGIN

Throughout its belt of outcrop, the Aymamón Limestone is consistently very pure limestone that contains almost no sand or clay. It was deposited on a reef flat in relatively shallow water, as shown by the corals it contains and by the presence of the foraminifer *Marginopora* sp. At most places, it contains abundant molds of mollusks, showing that life was abundant in the sea in which it was deposited.

The lack of clastic sediment in the Aymamón indicates that no large rivers were carrying sediment from the upland of Puerto Rico into the Atlantic Ocean at that time. Beds of alluvium in the Cibao and quartz grains in some parts of the Aguada show that large rivers had been present in ancestral Puerto Rico, and it seems reasonable to assume that these rivers still existed during Aymamón time. There is no evidence that the sea covered the island during deposition of the Aymamón. The ancient rivers still must have existed, but they were not bringing any sediment into the Atlantic Ocean. Consequently, during deposition of the Aymamón, the central part of Puerto Rico apparently was a land of very low relief that probably stood not far above sea level. This is borne out by the ancient courses of many of the large rivers of central Puerto Rico, such as the Río de La Plata, the Río Grande de Manatí, and perhaps the Río Culebrinas—all of which flow in deeply entrenched meanders.

The date of formation of the meanders cannot be determined exactly, but it seems reasonable to assume that during deposition of the Aymamón, the rivers were flowing in meanders on wide flood plains that traversed the central part of present-day Puerto Rico. This implies that the streams had eroded the landscape down nearly to base level, so that they were incapable of transporting much of a load. Since formation of these great meanders, the rivers have entrenched their courses to depths of 150 m or more below the upland surface—a surface that is gently rolling and commonly is covered by a mantle of soil, in many places more than 10 m thick (Briggs and Gelabert, 1962) derived directly from the bedrock.

During deposition of the Aymamón, no streams were flowing into the Atlantic directly north from the Utuado batholith, which is covered today and which doubtless was covered then by an easily eroded soil or saprolite of clayey sand, a material that today is easily eroded into gullies. If there had been drainage northward to the sea from the Utuado area, some ferruginous and quartz sand almost certainly would be present in the Aymamón Limestone being deposited in that area, but there is none. It can be assumed, then, that the drainage of this area was still toward the northeast and toward the northwest and that the streams draining the area had such a low grade that they were not transporting much of the sand weathered from the granodiorite and quartz diorite.

The northwest river that entered the sea between San Sebastián and Moca during deposition of the Lares may still have been somewhat active during deposition of the Aymamón Limestone, for the upper part of the Aymamón is not so crystalline as the lower part and is more of a chalk, commonly pale yellow. The analysis of this chalk (table 4, Field No. MO10) shows very little impurity, however. The presence of the oysterlike *"Ostrea" haitensis* and of the echinoid *Clypeaster cubensis* suggests that depositional conditions in the upper part of the Aymamón in northwestern Puerto Rico were different from conditions farther east where oysters and echinoids have not been found.

The very finely crystalline limestone and chalk that crop out in the Aymamón belt, however, are not the original limestone deposited in the sea, for several analyses of stable isotopes of oxygen and carbon made by Irving Friedman (written commun., 1968) show extensive alteration according to the ratio of O^{18} to O^{16} and some replacement of marine-derived carbon by carbon derived from land plants (Friedman and others, 1968). This is further borne out by the fact that nearly all the fossils of the Aymamón are either external molds or vuggy concentrates of calcite in the holes from which the fossils have been dissolved. Cuttings of Aymamón from the Abbott disposal well 1 near Barceloneta, taken from depths below sea level, consist of white porcelaneous limestone, quite different from the finely crystalline limestone that crops out. In other words, most of the outcropping Aymamón has been altered and in part replaced by bicarbonate-bearing ground water, whereas the Aymamón at depth has been little altered from the original limestone deposited under the sea, except by consolidation.

The dolomite in the upper part of the Aymamón is certainly secondary after calcite, and it probably was formed by fluxing of seawater through the pure calcium carbonate chalklike material at the top of the Aymamón. The chemistry of this change of calcium carbonate to calcium-magnesium carbonate still is not understood.

PHYSIOGRAPHIC EXPRESSION

The very pure limestone of the Aymamón lends itself both to ready solution and to reprecipitation (Monroe, 1966a), which tends to produce a very irregular topography. Deep roadcuts and quarries in the sides of hills have shown that the limestone beneath the surface is commonly either friable crystalline chalk or a rubble of solution fragments. On the other hand, most natural outcrops of the Aymamón consist of tightly cemented indurated limestone, commonly carved by solution into a maze of irregular low pinnacles and small cavities.

The landform most characteristic of the Aymamón is the mogote, also known as pepino hill or haystack hill. Mogotes are steep-sided conical hills, some having pointed crests and others being cupola shaped, that in the Aymamón terrain are separated by wide, gently rolling, nearly flat areas, covered by sand or sandy clay—the blanket deposits of Puerto Rico (Briggs, 1966). These blanket deposits are alluvial or beach deposits on top of the Aymamón Limestone, which is free of clastic materials. Mogotes range in height from a few meters to more than 50 m; most cover only a small area, but some long ridges rising out of the blanket deposits are made up of the sharp peaks of mogotes.

The mogotes are apparently limestone residual hills left after subsoil solution under the blanket deposits (Monroe, 1969a). This solution is going on at present; it commonly produces small unexpected collapses in which a part of the blanket deposit suddenly drops a few meters (Miotke, 1973). Erosion soon smooths off the slopes so that in time the entire blanket-covered plain is lowered. The hills projecting above the plain, however, are covered by a resistant surface of reprecipitated calcium carbonate that effectively delays further erosion or solution; any rain that falls on the indurated surface runs off almost immediately without carrying much calcium bicarbonate in solution or is evaporated immediately after the rainstorm by the hot tropical sunshine, leaving a new layer of secondary calcium carbonate. The net effect of the subsoil solution of the plains and the lack of solution of the limestone residual hills has been that the difference in relief of the hills and the plains has gradually increased.

Like the Aguada Limestone, the Aymamón forms a steep south-facing escarpment at its contact with the underlying Aguada, but this escarpment is hardly seen at most places because of the welter of deep sinks in the outcrop belt of the Aguada. It shows plainly, however, when one is standing on the ridge crest between Aguada sinks or when one follows one of the few roads that traverses the upland karst. At most places, the escarpment is 30–50 m high and is capped by mogotes. It shows most plainly in the Manatí and Camuy quadrangles (Monroe, 1971; 1963b).

The more chalky limestone that crops out in northwestern Puerto Rico does not weather into a mogote terrain, but rather into long east trending low ridges, much like the topography of the Camuy Formation farther east. The rather gentle topography of this area has given rise to a general belief of geomorphologists that the plateau or plain in northwestern Puerto Rico, interrupted only by the low ridges, is the remnant of a wave-cut platform. This is almost certainly true in the area of Ramey Air Force Base at the northwestern tip of the island, where Quaternary shells have been found in beach sand just below the platform (Monroe, 1968b), and it is an attractive idea for the higher levels farther south and east, north of the mogote belt that has formed on the lower part of the Aymamón. Thus far, however, no certain evidence for marine planation of most of the area has been found.

CAMUY FORMATION

NAME

The Camuy Formation was the name given by Monroe (1963b) to the youngest rocks of Miocene age in northern Puerto Rico. The type area is near the town of Camuy in northwestern Puerto Rico; a type locality was designated as cuts on the side of Highway 119 on the north-facing slope of a ridge known as La Pica, 3 km southwest of Camuy. Monroe divided the formation into three informal members: a lower member consisting of dark-orange marly chalk, a middle member of hard limestone, and an upper member varying in lithology from limestone to quartz sandstone. The type locality is in the lower part of the middle member. The three members of the formation are easily recognizable only in the Camuy quadrangle.

Meyerhoff (1975) and Moussa and Seiglie (1975) have claimed that the Camuy is synonymous with the Quebradillas limestone of Hubbard (1923), but examination of the cross sections and columnar sections in Hubbard's report (1923) and study of the localities from which he (Hubbard, 1920b) collected his Quebradillas fossils show plainly that most of his Quebradillas limestone is equivalent to the Aymamón Limestone (Monroe, 1975), although he included Camuy in his Quebradillas in 2 of the 6 sections, and he collected Camuy fossils from 3 of the 18 localities. Thus, the Quebradillas limestone of Hubbard includes much more than the Camuy Formation, and Hubbard did not recognize the unconformity at the base of the Camuy Formation.

AREAL DISTRIBUTION

The Camuy Formation forms a discontinuous belt near the northern coast of Puerto Rico from Isabela eastward to Dorado. Including outliers, the belt reaches its maximum width of 6.5 km south of Hatillo in the Camuy quadrangle and is nearly as wide between Arecibo and Barceloneta. The belt is continuous from the Río Guajataca eastward to the Río Grande de Manatí. East of the Río Grande de Manatí, the formation is present only as outliers on hills of Aymamón Limestone and as discontinuous patches near the coast near Puerto Nuevo and Dorado.

STRATIGRAPHIC RELATIONS

The Camuy Formation rests sharply on the Aymamón Limestone apparently disconformably. At all outcrops of the contact, the uppermost Aymamón is thick bedded to massive and is characterized by many small solution cavities, mostly only a few millimeters in diameter; at many places, the top meter of the Aymamón is stained pink to red, presumably by ferric oxide derived from the overlying reddish Camuy, possibly at time of deposition of the Camuy. The basal part of the Camuy is markedly stratified in beds a few centimeters thick, and at many places, these thin beds are crosslaminated. At places where the basal beds of the Camuy consist of slightly ferruginous chalk, as in the type area, the change in lithology from Aymamón to Camuy is sharp, although differences in bedding may not be noticeable. The appearance of the contact of the two formations suggests that the sea withdrew after deposition of the Aymamón, and almost immediately readvanced, at which time the Camuy was deposited. The Camuy is overlain unconformably by sand, gravel, and crossbedded limestone, which contains few fossils and is probably of Quaternary age but which may include some beds of late Tertiary age.

LITHOLOGIC CHARACTER

Although the Camuy Formation is predominantly calcareous, most of it contains appreciable quantities of quartz sand, and the lower part is so ferruginous that it weathers to pink or red chalk and limestone. Table 5 shows that the formation contains 2.2–31.7 percent silica, most of which is present as quartz. Although most of the outcrops of the formation are reddish, the highest amount of ferric oxide is 3.7 percent in a sample taken from the basal beds of the formation, only about a meter above the contact with the Aymamón Limestone.

LOWER MEMBER

In the type area, the lower member of the Camuy Formation consists of about 40 m of friable pale-yellowish-orange chalky limestone stratified in beds 5–70 cm thick and containing many dark-yellowish-orange grains. Interbedded with the friable limestone are scattered layers of hard pinkish-brown calcarenite and a breccia of grayish-orange limestone. Quartz grains are scattered through some beds. Oyster shells are common near the base of the member. A chemical analysis of the basal bed (Field No. CM35) is given in table 5.

Between Camuy and Quebradillas, the lower member is more indurated than farther east and indistinguishable from the middle member, but north of Quebradillas on Highway 2, parts of the member include considerable secondary dolomite, as shown in analysis of Field No. QD21 in table 5.

About 2 m of light-reddish-brown crossbedded limestone of the lower part of the Camuy (fig. 38) is exposed in a cut on the north side of Highway 2 (99,760 E., 70,500 N., Quebradillas quadrangle), approximately 1 km southeast of the plaza in Quebradillas. A thin section of the limestone shows that it is a mass of fossil material (fig. 39) in a matrix of limonite-stained micrite. Scattered through the

TABLE 5.—*Chemical analyses of Camuy Formation*

[Analyzed by rapid method (Shapiro, 1975); analysts, Paul Elmore, L. Artis, I. Barlow, S. D. Botts, G. Chloe, J. Glenn, J. Kelsey, H. Smith]

Lab. No. / Field No.	W170021 CM35[1]	W170028 QD21[2]	W170022 CM251[3]	W175021 AC[4]	158752 BBA393[5]	158748 BBA262A[6]	158747 BBA249A[7]	158749 BBA264[8]
SiO_2	8.3	3.4	2.2	10.6	31.7	9.2	7.0	2.4
Al_2O_3	3.0	.84	.64	1.7	4.2	2.0	1.2	.56
Fe_2O_3	3.7	.32	.32	1.3	1.9	.90	.58	.31
FeO	.08	.06	.06	.04	.09	.09	.05	.07
MgO	.71	17.2	.36	.42	.46	.52	.49	.71
CaO	44.5	31.0	52.4	46.0	31.9	47.4	49.7	53.0
Na_2O	.00	.43	.00	.09	.56	.06	.11	.09
K_2O	.13	.11	.04	.19	1.0	.27	.15	.06
H_2O-	1.4	1.2	.11	.38	.67	.14	.57	.16
H_2O+	1.5	.20	.43	.51	1.4	1.2	.73	.67
TiO_2	.09	.06	.17	.08	.20	.10	.04	.02
P_2O_5	.07	.05	.04	.02	.04	.06	.04	.04
MnO	.00	.00	.00	.00	.03	.02	.02	.02
CO_2	36.4	44.9	42.8	37.8	24.5	37.6	39.3	41.9
Total	100.	100.	100.	99.	99.	100.	100.	100.
Acid insoluble	-----	-----	-----	12.7	39.5	11.3	7.7	2.9

[1] Basal beds from cut in Highway 130 just south of Lechuga, 4.5 km south-southeast of Hatillo (113,235 E., 68,735 N., Camuy quadrangle).

[2] Outcrop of lower member 25 m above Aymamón from cut on southwest side of Highway 2, about 1.6 km north-northwest of Quebradillas (98,450 E., 72,600 N., Quebradillas quadrangle).

[3] Middle member, 65 m above Aymamón from cut on Highway 130, 2 km south-southeast of Hatillo (112,225 E., 71,030 N., Camuy quadrangle).

[4] Sandy limestone in upper member, 75 m above Aymamón from deep cut on south side of Highway 2, 1 km west of intersection with Highway 129 (120,370 E., 70,910 N., Arecibo quadrangle).

[5] Sandy limestone in upper member, about 100 m above Aymamón, from quarry south of Highway 2, 1.5 km west of intersection with Highway 129 (119,830 E., 70,910 N., Arecibo quadrangle). Sample collected by R. P. Briggs.

[6] Sandy limestone about 110 m above Aymamón from east end of quarry on north side of Ciénaga Tiburones, 9 km east of Arecibo (131,560 E., 71,500 N., Arecibo quadrangle). Sample collected by R. P. Briggs.

[7] Sandy limestone about 125 m above Aymamón from crest of hill south of Highway 2, 1.8 km west of intersection with Highway 129 (119,460 E., 70,870 N., Arecibo quadrangle). Sample collected by R. P. Briggs.

[8] About 170 m above Aymamón from outcrop on hill 200 m south of Highway 681, 8.5 km east of Arecibo (130,860 E., 72,850 N., Arecibo quadrangle). Sample collected by R. P. Briggs.

FIGURE 38.—Crossbedded ferruginous light-reddish-brown limestone of the lower part of the Camuy Formation exposed on the north side of Highway 2, approximately 1 km southeast of Quebradillas (February 1967).

matrix are many opaque grains, probably of limonite. Cross sections of single cells of many of the foraminifers have the curious appearance of gear wheels; many of these circular sections have rims of sparry calcite. J. A. Aaron (oral commun., 1974) identified these foraminifers as globigerinids.

Between Quebradillas and the western limits of the Camuy Formation near Isabela, the formation consists of about 30 m of thin-bedded and cross-laminated to massive ferruginous chalk and calcarenite varying in color from very pale orange to pale reddish brown. Many beds contain black grains of manganese dioxide and magnetite and blebs of dark-yellowish-orange limonitic clay.

East of Arecibo, the lower member is exposed only sporadically. At most places, it consists of slightly ferruginous reddish chalk, locally containing beds of oyster shells.

MIDDLE MEMBER

The middle member is best exposed in the area southwest and southeast of Camuy. At most places, it consists of about 25–30 m of hard very pale orange to light-brown ferruginous calcarenite commonly containing blebs of limonitic clay and scattered grains of quartz and magnetite. At many places, the limestone is perforated by horizontal solution holes as much as 20 cm in diameter. The type locality of the Camuy Formation is in the middle member at La Pica on Highway 119, 3 km due southwest of the plaza at Camuy where 20 m of limestone is exposed on the north-facing slope of a ridge. Interbedded with the limestone are beds of rubbly pale-yellow chalky breccia, much like the lower member. The limestone is quarried and crushed for use as concrete aggregate in a pit 3 m

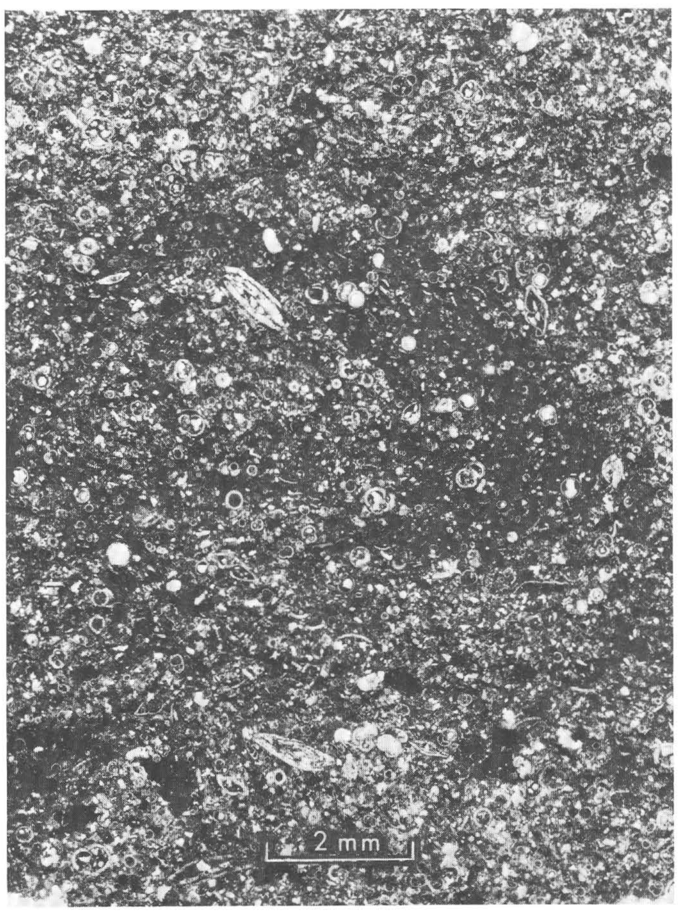

FIGURE 39.—Photomicrograph of thin section of lower part of the Camuy Formation from a cut on the north side of Highway 2, approximately 1 km southeast of Quebradillas. Biomicrite containing a mass of foraminiferal fragments and cross sections, especially of globigerinids. Many opaque grains of limonite.

FIGURE 40.—Hard sandy very pale orange limestone of the middle member of the Camuy Formation, perforated by abundant solution cavities. Cut on south side of Highway 2, 5.7 km east of Quebradillas (October 1968).

deep, 1.7 km due south of the plaza at Camuy; the limestone here contains abundant blebs of limonitic clay and a few calcite veins. A chemical analysis of a sample of the limestone from a cut on Highway 130, 2 km south-southeast of Hatillo, is included in table 5 (Field No. CM251).

The middle member forms rocky hills in a nearly continuous belt from the village of Barranca, 4.2 km west southwest of the main plaza at Arecibo, westward to an area about 4 km east of Quebradillas. It is well exposed on Highway 2 at Km 94 Hm 7 (104,710 E., 70,430 N., Quebradillas quadrangle), 5.7 km east of Quebradillas (fig. 40), where about 4 m of very pale orange calcarenite is perforated by abundant large solution cavities. The rock here contains many large foraminifers and a few prints of mollusks.

A thin section (fig. 41) of the limestone from this locality shows that the rock is biomicrite packed with foraminifers and algal remains. Many of the foraminifers are planktonic types, and some are similar to the probable globigerinids shown in figure 39. The section also includes many brown opaque grains, probably of limonite, and a few quartz grains. K. N. Sachs (written commun., 1971) recognized *Gypsina globula* in the section.

The member has not been recognized east of the Río Grande de Arecibo, although it probably is present beneath Ciénaga Tiburones between Arecibo and Barceloneta (see discussion under Thickness).

UPPER MEMBER

The upper member is a lenticular unit more than 40 m thick of chalk, sandy chalk, sandstone, sandy limestone, and limestone. It has been recognized only in the central part of the belt in the Camuy and Arecibo quadrangles.

The sandstone is near the top of the member and is best exposed near Radioville, 2–4 km west of the

FIGURE 41.—Photomicrograph of a thin section of limestone of the middle member of the Camuy Formation from cut on south side of Highway 2, 5.7 km east of Quebradillas. Biomicrite packed with foraminifers and algal remains; calcite spar fills voids and cracks; a few quartz grains and many brown opaque grains, probably of limonite.

main plaza at Arecibo; about 10 m of thin-bedded slightly crossbedded calcareous very fossiliferous sandstone crops out on the south side of Highway 2. About 3 m of pink fossiliferous calcareous sandstone from approximately the same stratigraphic position crops out at sea level on a small rocky point about 1.6 km east of the Arecibo lighthouse (Kaye, 1959b, p. 122). The sandstone appears to be at the top of the Camuy Formation.

The calcareous sandstone is well exposed directly across Highway 2 from the Ron Rico Distillery, 2.2 km west of the plaza at Arecibo (120,320 E., 70,910 N., Arecibo quadrangle). It has a gentle dip toward the north and is overlain unconformably by eolian sandstone that dips steeply south (fig. 42). At the foot of the bluff are many large very fossiliferous boulders of sandy limestone. A chemical analysis of the limestone is included as sample (Field No. AC) in table 5. A thin section of the same rock shows that it is a micrite containing abundant grains of quartz sand and a few opaque grains. The section shows many fossil fragments, including cross sections of spherical cells of foraminifers and many cigarshaped algal fragments.

FIGURE 42.—Calcareous sandstone in the upper member of the Camuy Formation (Tca) exposed on the south side of Highway 2, across the highway from the Ron Rico Distillery, 2.2 km west of the plaza in Arecibo. The dip of the sandstone is toward the camera (north), but Quaternary eolian sandstone (Qe) shown unconformably overlying the sandstone in the right part of the photograph dips south, away from the road (June 1967).

Most of the Camuy Formation mapped near the Atlantic coast by Briggs in the Arecibo quadrangle (Briggs, 1968) and in the western part of the Barceloneta quadrangle (Briggs, 1965) probably can be correlated with the upper member of the Camuy. Analyses (Field Nos. BBA393, BBA262A, BBA249A, and BBA264) in table 5 are all of samples from the upper member collected by Briggs.

The powdery dolomite north and northwest of Membrillo, about 3.6 km west of Camuy, assigned to the Camuy by Monroe (1963b) is now known to be a part of the Aymamón Limestone rather than the upper part of the Camuy Formation. The Aymamón here is raised on the north flank of the Quebradillas anticline.

Seiglie and Moussa (1975) apparently have considered this northern outcrop of the Aymamón as an upper part of their Quebradillas Limestone in the Camuy quadrangle. They pointed out that this upper part of their "Quebradillas Limestone" contains *Amphistegina* sp., bryozoans, and articulate coralline algae—all of which are present in the upper part of the Aymamón Limestone. This outcrop is far below the top of the Camuy Formation.

In westernmost Puerto Rico, Seiglie and Moussa (1975) have included in their Quebradillas Limestone some globigerine limestone interbedded with beds containing *"Ostrea" haitensis*; this unit has been mapped by Monroe (1969b) as an upper member of the Aymamón Limestone.

THICKNESS

In the type area near Camuy, the lower member is about 40 m thick, the middle member, about 25 m thick, and the upper member, about 40 m thick. At Radioville, the entire thickness of the formation is approximately 110 m, as determined by projection of the few determinable attitudes.

Briggs (1961, p. 17) reported that the upper 58 m of the Kewanee Interamerican Oil Company well 4CPR (for location see pl. 1), was drilled through chalky limestone rubble, calcarenite, and quartz sand, and his descriptions of the samples from this part of the well suggest that the rocks are from the upper member of the Camuy. The next 64 m consists of densely cemented, slightly impure pale-grayish-orange to pale moderate reddish-brown calcarenite, which resembles the middle member. No samples were recovered in the interval between 122 m and 171 m, but Briggs recorded that the drilling time was fast and regular, indicating lack of caverns. As the well was drilled by rotary methods, this interval of 49 m may well represent the soft ferruginous chalk of the lower member of the Camuy Formation. Immediately below this interval, the well entered calcarenite, dense limestone, and calcitic dolomite characteristic of the upper part of the Aymamón Limestone in the outcrop area farther west. On the basis of this interpretation of the samples and well log, the thickness of the Camuy Formation is about 170 m, which is reasonably close to estimates from outcropping rocks.

FOSSIL CONTENT AND AGE

The Camuy Formation at most places is not richly fossiliferous, but Kaye (1959b, p. 121–122) collected a large suite of mollusks, foraminifers, echinoderms, and bryozoans (USGS Coll. 17953) from a large borrow pit (119,850 E., 70,950 N., Arecibo quadrangle) on the south side of Highway 2 a few hundred meters west of the Ron Rico Distillery west of Arecibo; he collected a somewhat smaller suite of mollusks (USGS Coll. 17952) from sandstone on a small rocky point (126,050 E., 72,025 N.) 1.6 km east of the Arecibo lighthouse. Both collections are from sandstone in the upper member of the Camuy Formation. Woodring (Kaye, 1959b, p. 121) considers these fossils as late-early to early-middle Miocene.

At most outcrops of the lower part of the Camuy, the most distinctive fossil identifiable by means of a hand lens is the foraminifer *Nummulites cojimarensis* (D. K. Palmer), which can be dated only as early Miocene. This foraminifer is a good guide fossil for the Camuy Formation, for it has not been found in the underlying Aymamón Limestone.

At many places, a bed rich in oysters, probably *"Ostrea" haitensis* Sowerby, is common at the base of the Camuy, but this fossil has a considerable range and is found in the upper Aymamón in northwestern Puerto Rico.

In roadcuts on Highway 2 north of Quebradillas, C. W. Cooke (unpub. data., 1956) collected specimens of *Spondylus bostrychites* Guppy and *Chlamys* (*Aequipecten*) cf. *pleurinominis moranfensis* Woodring.

Although Woodring (Kaye, 1959b, p. 121) considers the Camuy lower Miocene on the basis of the mollusks and K. N. Sachs (written commun., 1965) agreed on the basis of the presence of *Nummulites cojimarensis*, a recent study by Bermúdez and Seiglie (1970, p. 20) of the planktonic foraminifers suggests that the formation is probably upper Miocene and "its age may be as young as Pliocene." On the basis of planktonic foraminifers, Seiglie and Moussa (1975) consider the lower part of the Camuy Formation (their Quebradillas Limestone) to be late Miocene and early Pliocene. They concluded (p. 2315) that "most of the Quebradillas was deposited during the Pliocene."

ORIGIN

Like most of the other middle Tertiary formations of northern Puerto Rico, the Camuy Formation consists of sediments deposited on the insular shelf beneath the waters of the Atlantic Ocean. These sediments, however, and the unconformity at the base of the formation record some especially important events in the Miocene history of Puerto Rico.

At the end of deposition of the Aymamón Limestone, the island probably was bowed upward along an east-trending axis, starting the erosion of the low-lying upland surface, on which during Aymamón time the larger rivers had been flowing in wide meander-type valleys, apparently at so low a gradient that the rivers were carrying very little sediment to the sea. This regime of quiet streams suddenly changed when the center of the island was uplifted; the arching was so great that the Aymamón Limestone itself was raised out of the sea. The arching apparently continued for a considerable length of time; eventually the seaward side of the Aymamón was again submerged by a transgressing sea. Erosion of the upland was renewed, and the rivers not only began to bring sediments to the sea again but also began to deepen the meanders through which they were flowing and eventually produced the great entrenched meanders so common in the larger river valleys of the upland of Puerto Rico.

The presence of abundant quartz sand in the Camuy Formation, particularly west of the Río Grande de Arecibo, shows that for the first time since San Sebastián time rivers were bringing quartz sand directly north into the sea from the Utuado batholith. This shows that the Río Grande de Arecibo is no older than the Camuy and that it probably captured the headwaters of other rivers that had been carrying sediments west, northwest, northeast, and east from the batholith.

The sand is present in all the members of the Camuy in the area west of Arecibo, but its greatest concentration is in the upper member. This can be interpreted as meaning that the Río Grande de Arecibo did not become a major transporter of sediment until late in Camuy time.

A similar case can be made for the Río Grande de Manatí and the Río Cibuco, for the Camuy Formation contains large quantities of quartz sand (especially in the upper member), at many exposures west of these rivers, suggesting that they were dumping quartz-bearing sediment into the sea at places not far from their present mouths.

Because of the abundance of planktonic foraminifers, especially in the lower member of the Camuy Formation, Seiglie and Moussa (1975) consider that the lower member (the lower unit of their Quebradillas Limestone) was deposited in deep oceanic water as a globigerine ooze. They asserted (p. 2317) that "the abundance of keeled planktonic foraminifers * * * and the common occurrence of the two genera *Sphaeroidinellopsis* and *Sphaeroidinella* * * * are indicators of the deepest levels of stratification of planktonic foraminifers." They apparently have not noted the abundance of quartz and red clay of fluvial origin associated with these foraminifers. They believe further that the deep-water phase suddenly came to an end when the middle member was deposited.

The dolomite in the Camuy north of Quebradillas is secondary, probably produced by some process of refluxing seawater through chalk, similar to the dolomitization process that altered the upper part of the Aymamón.

PHYSIOGRAPHIC EXPRESSION

The Camuy Formation forms low, gently sloping ridges roughly parallel to the strike of the formation. Although the formation is composed largely of limestone, solution phenomena are not common; several vertical shafts, some as deep as 30 m, are present, especially near Hatillo and Camuy. Bands of blanket sand between ridges in the area between Quebradillas and Arecibo may cover areas of sheet solution of limestone as is common in the belt of outcrop of the Aymamón Limestone, but mogotes and large shallow depressions, both of which are common in the area of the Aymamón, are not present in the belt of outcrop of the Camuy. No caverns have been reported from the Camuy, although small interconnected solution channels are present in the middle member.

SOUTHERN PROVINCE

The rocks of middle Tertiary age in southern Puerto Rico are very different from those of approximately the same age in northern Puerto Rico. Deposition of the rocks in southern Puerto Rico may have begun earlier than deposition of those in northern Puerto Rico and may also have ended a little earlier. Lithologic resemblance is only superficial, even though limestone is conspicuous in both provinces. The rocks in southern Puerto Rico are intensely faulted, whereas those in northern Puerto Rico are cut by very few faults. Thus far, exact correlation of strata in the two provinces has not proved feasible.

The first geologist to study the rocks in southern Puerto Rico was Berkey (1915), who recognized a basal clastic unit, to which he gave the informal name Juana Díaz, and an upper limestone unit, which he called Ponce. He called attention to faulting between the middle Tertiary rocks and the adjacent Cretaceous.

Hubbard (1920a), after studying fossils from both northern and southern Puerto Rico, accepted Berkey's name Juana Díaz shale and divided the Ponce into Lower Ponce limestone and Upper Ponce limestone.

Zapp, Bergquist, and Thomas (1948) accepted Hubbard's division of the rocks in southern Puerto Rico, and the map prepared by Thomas shows these three divisions. Although Thomas did not recognize the faulting shown by Berkey, he did recognize a few other minor faults and folds.

Mitchell-Thomé (1954) recognized lower Oligocene fossils in tuffaceous sandstone north of Cuatro Calles, east of Juana Díaz, and gave the name Cañas Arriba Formation to this sequence. Glover (1971) did not find Mitchell-Thomé's locality and did not recognize the formation. Mitchell-Thomé (1960) also proposed the name Mercedita Lentil for clastic beds in the Ponce Limestone exposed between Quebrada del Agua and Central Mercedita, but he did not designate a type locality. Presumably this lentil comprises the beds of fine sand at the top of the Juana Díaz Formation in the quarries of the Puerto Rico Cement Company, described later in the present report.

C. W. Cooke (unpub. data, 1956) showed that some of the rocks called Ponce by Thomas (Zapp and others, 1948) contain fossils found elsewhere only in the Juana Díaz and that there is no consistency in what Thomas called Upper and Lower Ponce. My own later studies confirmed this and indicated that, although mappable lithologic units are present in southern Puerto Rico, they do not correspond to the three divisions referred to by Zapp, Bergquist, and Thomas (1948). The intense faulting and poor exposures had combined to defeat all efforts to straighten out the stratigraphy.

In 1959–1960, the Kewanee Interamerican Oil Company drilled three test wells for petroleum near the southern coast of Puerto Rico—one hole near Santa Isabel, one near Ponce, and the third halfway in between (for locations see pl. 1). No cores were taken from the middle Tertiary rocks in any of these holes, and the cuttings have not been very helpful in determining relationships. The holes have confirmed the structural complexities of the area, however, for the first hole was drilled to a depth of more than 2,900 ft (884 m) through sand and gravel before entering limestone that can be correlated with the Ponce. No Ponce Limestone is known that far east, but Juana Díaz crops out about 4 km north of the well.

Stratigraphic and paleontologic studies by M. T. Moussa and G. A. Seiglie have clarified the main features of the stratigraphic relations of the middle Tertiary rocks. A preliminary report by Seiglie and Bermúdez (1969) first called attention to the major differences between the lower strata formerly included both in the Juana Díaz and the lower member of the Ponce Limestone and those included in the upper member of the Ponce. My own work has since shown an important overlapping unconformity at the base of the upper member. Seiglie and Bermúdez proposed that the name Ponce be restricted to this upper limestone. In a more complete study, Moussa and Seiglie (1970) recognized six faunal zones, which they correlated with faunal zones present in the island of Trinidad (Bolli, 1957) and elsewhere (Banner and Blow, 1965). Three of the zones of Banner and Blow are not recognized in Puerto Rico and may be represented by an unconformity in the upper part of the Juana Díaz Formation, or possibly the zones are not represented because of facies differences between Trinidad and Puerto Rico. The work of Moussa and Seiglie brought some order to the stratigraphy of the middle Tertiary rocks of southern Puerto Rico, and it forms the basis for a general stratigraphic revision (Monroe, 1973b). The lithologic relations however, are more complex than they supposed.

Only three formations of middle Tertiary age are recognized in southern Puerto Rico by the U.S. Geological Survey (Monroe, 1973b). At the bottom is the Juana Díaz Formation—consisting of a very thick lenticular mass of intertonguing mudstone, conglomerate, limestone, and a small amount of unconsolidated sand and lignite—the Juana Díaz has been redefined (Monroe, 1973b) to include the rocks formerly considered Juana Díaz and the lower member of the Ponce Limestone. The Juana Díaz is overlain unconformably by the Ponce Limestone, which is approximately equivalent to the former upper member of the Ponce Limestone and possibly to the Guánica Coral Reefs of Berkey (1915). Subordinate units could not be accurately mapped, although many minor divisions of the Juana Díaz can be recognized in individual outcrops, and Moussa and Seiglie (1970) have been able to recognize distinctive faunal zones. None of these divisions, however, can be reliably traced from outcrop to outcrop. The thickness estimates must be considered much less reliable than those in northern Puerto Rico until more wells are drilled in southern Puerto Rico, particularly in the area between Ponce and Guayanilla where the true thickness may be less than the figures used in this report. On the other hand, the structure will doubtlessly be found much more complex than described herein. In southwestern Puerto Rico, strata approximately equivalent in age to the Ponce Limestone are called the Guanajibo Formation. The areal extent of these units is shown on plate 1.

Mapping in southern Puerto Rico is much more difficult than in northern Puerto Rico because of dense undergrowth of various kinds of thornbush and because of a thick mantle of caliche in areas of limestone. Geologic observations can be made only along roads on which cuts are at least 2 m deep, in quarries, and along some of the relatively rare active stream courses. As the country is arid, streams that cut down into the bedrock are scarce. A few proved very useful in working out stratigraphic relations, but most have few, if any, cutbanks. Complicating all the other factors is the fact that faulting of considerable magnitude is very common. Some faults having vertical displacements of several hundred meters have been recognized, and marked lineation of some of the stream valleys suggests that other faults are present.

JUANA DIAZ FORMATION

NAME

The Juana Díaz Formation was named informally by Berkey (1915) for shaly beds in the vicinity of Juana Díaz "where some of the beds are distinctly sandy and rather fossiliferous and carry petrified wood" (Berkey 1915, p. 13). He called special attention to "shale beds and overlying marls and softer layers of thin-bedded character" (Berkey, 1915, p. 13) on the Río Jacaguas south of Juana Díaz. Zapp, Bergquist, and Thomas (1948) used the name Juana Díaz for their basal unit of Oligocene conglomerate, sandy limestone, and shale, but they did not designate a type locality. They suggested, however, that the formation received its name from the exposures of a thick sequence of conglomerates, shales, and sandy limestones east of the village of Juana Díaz and along the Río Jacaguas to the west.

Because of confusion as to the top of the Juana Díaz Formation, all terrigenous beds, limestone, and chalk above the rocks of Cretaceous to Eocene age and below the unconformity at the base of the Ponce Limestone (formerly upper member of the Ponce Limestone) were recently included in the Juana Díaz Formation (Monroe, 1973b), and reference localities were designated as the excellent exposures on the right (west and north) bank of the Río Jacaguas just above the concrete bridge for a secondary road, 1.4 km west-northwest of the plaza in Juana Díaz. Another reference locality is the high cliffs on the right bank of the Río Jacaguas, 2 km west-southwest of Juana Díaz. The first reference locality is within the *Globigerina ampliapertura* zone of Moussa and Seiglie (1970) ; the second includes fossils within that zone and also their *Globorotalia opima opima-Globigerina ciperoensis ciperoensis* zone. Moussa and Seiglie (1970, p. 1892) restricted the term Juana Díaz Formation to the *Globigerina ampliapertura* zone in the Río Jacaguas area, and they referred to the higher zone as "limestone in Río Jacaguas southwest of Juana Díaz" (Moussa and Seiglie, 1970, p. 1893).

AREAL DISTRIBUTION

The Juana Díaz Formation is continuously exposed, except for alluvium-filled river valleys, from Río Cañas Abajo, 4 km east-southeast of Juana Díaz, west to hills southwest of Ensenada where the formation is overlapped by the Ponce Limestone. Isolated patches of Juana Díaz crop out farther east on raised fault blocks north of Santa Isabel and on the west side of the hill at Central Aguirre. (See pl. 1). The belt of outcrop is irregular because the formation is cut into many fault blocks, but it reaches its maximum width of about 6 km in the hilly area between the Río Cañas and the Río Tallaboa.

STRATIGRAPHIC RELATIONS

At most places, the Juana Díaz Formation is in fault contact with older rocks that range in age from Cretaceous to Eocene. At a few places, however, where the depositional contact can be seen, the Juana Díaz rests on an eroded and highly irregular surface of the older rocks. The length of contact so exposed is insufficient to determine the amount of relief on the old erosion surface, but it is probably equal to the relief observed on basement rocks in northern Puerto Rico. The lower part of the Juana Díaz commonly contains abundant pebbles, cobbles, and boulders in a basal conglomerate, and the presence or absence of such conglomerate at a fault contact has proved useful in estimating the amount of vertical displacement.

Within the Juana Díaz Formation, the stratigraphic relations are complicated as pointed out by Seiglie and Bermúdez (1969) and by Moussa and Seiglie (1970). Lithologic units within the formation appear to be lenticular and to intertongue with each other. In the lower part of the formation, the strata are predominantly conglomerate and mudstone, but lenses of limestone are present at many horizons. The upper part of the formation is more generally limestone and chalk, but lenses of mudstone and gravel are present locally. These different rocks are characterized by different fossil assemblages, which complicate the unraveling of the stratigraphic relations. In the present report, internal stratigraphic relations are described, but members should not be formally defined until many coreholes are drilled in the area.

The top of the Juana Díaz Formation was truncated by erosion before the Ponce Limestone was deposited on it so that the youngest beds below the Ponce vary in age from place to place. The youngest strata of the Juana Díaz are the beds of loose sand that apparently fill a channel beneath the Ponce Limestone and that are exposed in the quarries of the Puerto Rico Cement Company at the west edge of the city of Ponce. Bermúdez and Seiglie (1970) placed these beds in the *Globigerinatella insueta* zone of the lower Miocene; Moussa and Seiglie (1975) consider them the basal unit of the Ponce Limestone. Elsewhere, as in the outcrops just west of the Río Cañas–Río Pastillo valley, the Ponce Limestone rests on beds of chalky limestone that Bermúdez and Seiglie (1970) place in the *Globorotalia kugleri* zone at the base of the Miocene. The upper part of the Juana Díaz is apparently at about this same stratigraphic position as far west as the valley of the Río Tallaboa, but on the west side of that valley, outcrops of oyster-bearing clastic beds directly below the Ponce Limestone resemble similar beds at the south end of the Puerto Rico Cement Company quarries and are said by Moussa and Seiglie (1970) to contain the *Globigerinatella insueta* fauna.

West of the Río Yauco, the Ponce Limestone rests directly on limestone rich in *Lepidocyclina undosa* that is probably equivalent to the middle part of the Juana Díaz farther east. Outcrops on the hill just east of the former site of Laguna de Guánica, about 3 km north of Guánica, show Ponce Limestone at the crest of the hill and pebbly Juana Díaz, probably near the base of the formation, on the lower slopes, suggesting that the Ponce has overlapped the limestone units in the upper part of the Juana Díaz. The Ponce apparently overlaps the entire Juana Díaz Formation between Ensenada and Bahía Montalva, and farther west, the Ponce rests directly on rocks of Cretaceous age.

LITHOLOGIC CHARACTER

The Juana Díaz Formation is exceedingly varied in lithologic character, ranging from boulder conglomerate to limestone. A large part of the formation east of the divide between the Río Tallaboa and the Río Cañas consists of clastic beds—sand, pebbles, boulders, and mudstones. Farther west, more than half of the formation is limestone. In the high hills southeast of Peñuelas, the clastic units intertongue with limestone that forms a thick reef deposit, south of Peñuelas. Until such time as formal members can be defined in the Juana Díaz, it seems best to describe a few of the more typical exposures in each of the lithologic divisions shown on plate 1—lower clastic strata of conglomerate and mudstone, limestone and chalk strata, and upper clastic beds found at the top of the formation.

LOWER CLASTIC STRATA

The oldest rocks identified in the Juana Díaz Formation are mudstones that crop out in the northeastern part of Ponce in the section known as La Rambla. During construction of this housing development, P. H. Mattson collected some samples of fossiliferous calcareous clay, which were studied by Ruth Todd. She found a very rich fauna of planktonic foraminifers that indicate an early Oligocene age (written commun., 1963). Apparently beds of similar age and lithology crop out on the right bank of the Río Jacaguas above the concrete bridge 1.4 km west-northwest of Juana Díaz. The river is bordered by bluffs 10–15 m high consisting of stratified gray fossiliferous compact sand, weathering to brownish gray, which contains beds of very fossiliferous gray to grayish-orange fine-grained sandstone 10–20 cm thick. These bluffs are here designated the principal reference section of the Juana Díaz Formation. Moussa and Seiglie (1970) reported that the formation here is in their *Globigerina ampliapertura* zone, the oldest faunal zone they recorded in the Oligocene of Puerto Rico.

Down the river, 400 m southwest of the Highway 14 bridge across the Río Jacaguas, Bergquist made a large collection of excellently preserved fossils "from north-dipping resistant, gray to tan, sandy lower Juana Díaz limestone beds exposed along the bank and in the bed of the Río Jacaguas" (Bergquist, written commun., 1945). Several ledges of limestone cross the river near here, but in 1969, I could not identify the bed from which Bergquist collected the fossils.

The most conspicuous outcrop near Juana Díaz is a bluff about 100 m high on the right (west) side of the Río Jacaguas, 2 km west-southwest of Juana Díaz. The rocks at the north end of this bluff consist of light-gray shale weathering to grayish orange, interbedded with sparse layers of hard calcareous fine-grained sandstone. The sandstone forms the principal part of the bluff 100–200 m farther downstream. It is nearly inaccessible in the bluff but is well exposed in a cut of the new Ponce–San Juan Expressway, about 1 km farther west on the east side of the valley of Río Guayo (141,980 E., 23,390 N., Ponce quadrangle), where 15 m of stratified light-gray slightly clayey sandstone is exposed (fig. 43). The sandstone weathers to grayish orange and very pale orange. The strata strike N. 70° W., and dip 35° SW.

The basal beds of the Juana Díaz Formation are not exposed near Juana Díaz, for the formation is in fault contact with rocks of early Tertiary age (Lynn Glover III, written commun., 1960). The conglomerate common at the base of the Juana Díaz crops out in scattered outcrops north and northwest of Lago Ponceño where the surface of the ground is covered with cobbles of volcanic rocks and where low cuts on the canefield roads show pebbly conglomerate.

Excellent exposures of typical grayish-orange, calcareous, silty, slightly carbonaceous clay of the Juana Díaz is exposed in a large quarry 300–600 m north of the filtration plant in the northeastern part

FIGURE 43.—Calcareous sandstone of the Juana Díaz Formation dipping steeply southwest (right) in cut on the Ponce–San Juan Expressway, on east side of the valley of the Río Guayo (February 1971).

of Ponce. Beds of interbedded calcareous sandstone strike N. 70°–80° W. and dip about 30°–40° S. Just north of this quarry in Barriada Jaime L. Drew, similar clay contains veins of crystalline gyysum as much as 3 cm thick.

The best exposures of the calcareous silty clay so typical of the Juana Díaz are near the headwaters of Quebrada del Agua 4–7 km west-northwest of the intersection of Highways 10 and 132 at the west edge of Ponce. The clay or mudstone there contains many beds of sandstone and claystone having abundant *Lepidocyclina undosa,* a fossil believed (Sachs, 1959) to be restricted to the Oligocene. A reef of *L. undosa* and the echinoid *Clypeaster oxybaphon* forms a layer of soft limestone about 4 m thick on Highway 132 at a sharp bend from west to northeast (126,120 E., 23,720 N., Peñuelas quadrangle), about 6 km northwest of the west edge of Ponce. This same bed, rich in *Lepidocyclina and Clypeaster,* crops out in a streambank 200 m farther south and can be recognized on the hills 400 m farther west and in the headwaters of Quebrada del Agua.

Very fossiliferous clayey calcareous sandstone crops out at many places and apparently at many different stratigraphic positions nearby. One of the more interesting outcrops is in the bottom of an east-flowing stream (125,950 E., 24,310 N., Peñuelas quadrangle) 4.2 km due east of Peñuelas. Here are exposed several meters of medium-bedded calcareous fossiliferous fine-grained sandstone interbedded with soft sandy limestone that contains abundant *Lepidocyclina undosa.* The strata strike about due east and dip 10° N. Twenty meters north of the creek and about 10 m up the hill there is a sudden change from the soft fossiliferous sandstone to hard tuffaceous siltstone of the Cretaceous; this change marks the fault between the Juana Díaz and the volcanic complex of central Puerto Rico .The top of the hill north of the stream, about 100 m higher, is capped by some 20 m of hard limestone of Cretaceous age.

Between Quebrada del Agua and the Río Tallaboa, much of the mudstone intertongues with hard reef limestone that will be described later. This great reef extends west to the valley of the Río Guayanilla; on the east wall of that valley, the limestone intertongues with clastic material that forms hills as far west as Yauco.

The hills west and northwest of Yauco are covered by sand and gravel, which was considered a Quaternary deposit by Zapp, Bergquist, and Thomas (1948) but which Grossman (1962) showed was typical lower Juana Díaz. The hills south of Yauco between Barinas and Palomas are composed of typical Juana Díaz mudstone that locally contains beds of *Lepidocyclina.* Zapp, Bergquist, and Thomas (1948) considered the northern edge of these hills the western part of the outcrop belt of the Juana Díaz, but they mapped sand, gravel, and mudstone east and southeast of Guánica as the lower member of the Ponce, even though *Lepidocyclina undosa,* a guide fossil for the lower part of the Juana Díaz, is common. Thomas considered that the sand and gravel was present in lenses within the limestone of his lower member of the Ponce.

The westernmost place that clastic beds of the Juana Díaz have been seen is near the foot of the densely wooded hill west of Highway 325, a kilometer southwest of the sugar mill at Ensenada. The easternmost occurrence of Juana Díaz was reported by Berryhill (1960). He collected corals on the crest of two knobs 1.4 km west of the pier at Central Aguirre that were identified by J. W. Wells as of Oligocene age. Recent excavations for a new road down the hill west of these knobs has exposed on the hillside sandy clay, gravel, and cobbles—material that resembles the lower clastic beds of the Juana Díaz farther west.

LIMESTONE AND CHALK

The Juana Díaz Formation includes many lenses of limestone, and the upper part is commonly entirely limestone or chalk, the latter constituting a part of the lower member of the Ponce Limestone of Zapp, Bergquist, and Thomas (1948). There is such complete gradation and intertonguing of the limestone and clastic beds, however, that detailed mapping of contacts between them proved meaningless. At places where limestone is present, the ground surface in southern Puerto Rico is commonly covered by a thick mass of caliche, which commonly consists of 2–3 m of soft unbedded chalk that may contain one or more indurated layers of light-brown and white semi-indurated limestone. This kind of material is present on the limestone of both the Juana Díaz and the Ponce and apparently also forms above the harder limestones of the Cretaceous. It is so thick that only the deeper roadcuts penetrate it. Its presence is somewhat useful, however, as an indicator that limestone or at least very calcareous clay is present beneath. Analyses of representative samples of limestone from the Juana Díaz Formation are shown in table 6. Insoluble residues range from 0.2 percent in limestone from a coral reef to 17.7 percent for argillaceous chalk.

TABLE 6.—*Chemical analyses of limestone in Juana Díaz Formation*

[Analyzed by rapid method (Shapiro, 1975); analyst, Lowell Artis]

Lab. No.	W175016	W175017	W175011	W175015	W175019	W175018
Field No.	Y47[1]	Y48[2]	PV9[3]	G16[4]	PE166[5]	P10[6]
SiO_2	0.66	0.00	1.0	4.8	9.4	14.3
Al_2O_3	.24	.17	.20	1.0	2.1	2.7
Fe_2O_3	.28	.07	.16	.62	.78	1.0
FeO	.08	.04	.04	.08	.08	.16
MgO	.38	.19	.32	.35	1.2	1.2
CaO	54.4	53.8	55.0	50.8	46.4	41.7
Na_2O	.00	.00	.16	.03	.23	.29
K_2O	.03	.00	.06	.06	.06	.22
H_2O-	.19	.01	.08	.35	1.8	2.1
H_2O+	.51	.41	.32	.58	.60	1.1
TiO_2	.00	.00	.00	.00	.04	.09
P_2O_5	.00	.06	.05	.01	.12	.06
MnO	.00	.00	.00	.05	.00	.00
CO_2	42.7	43.8	43.0	40.6	36.8	33.6
Total	99	99	100	99	100	99
Acid insoluble	1.4	0.2	1.3	6.6	11.9	17.7

[1] Limestone on west bank Río Macaná 3.8 km north of coast (117,070 E., 23,250 N., Yauco quadrangle).

[2] Cut at west side of trail, gorge of Río Macaná 3.5 km north of coast (117,280 E., 22,950 N., Yauco quadrangle).

[3] Limestone on east side of fault on Highway 335, 1.2 km west of Central San Francisco (110,180 E., 17,050 N., Punta Verraco quadrangle).

[4] Foraminiferal limestone in cut on Highway 333, 2 km south of Guánica (102,660 E., 13,740 N., Guánica quadrangle).

[5] Limestone ledges north of trail through saddle, 3 km west of intersection of Highways 10 and 132 (128,260 E., 19,240 N., Peñuelas quadrangle).

[6] Chalk in wall of quarry of Puerto Rico Cement Company (130,800 E., 21,270 N., Peñuelas quadrangle).

By far the most interesting mass of limestone in the Juana Díaz Formation is the thick reef limestone present south of Peñuelas. The limestone forms the prominent near-vertical cliff more than 170 m high on the right (west) wall of the Río Tallaboa south of Peñuelas, and its internal structure is well exposed in the canyon of the Río Macaná, which cuts through it north-northeast of Guayanilla. The limestone is definitely entirely of Oligocene age, for *Lepidocyclina undosa* is common beneath the limestone in many outcrops just south of Peñuelas and also above the limestone on the crest of the hills 2 km southwest of Peñuelas. The limestone contains abundant coral heads and algal laths, but two thin sections taken from beds in the canyon of the Río Macaná show nothing but the calcite spar that commonly replaces coral heads; faint markings in the calcite apparently are the traces of the walls of the coral columnals. Analyses of two samples from this reef limestone are given in table 6 (Field Nos. Y47 and Y48).

The limestone contains thick lenses of pebbles and cobbles on a secondary road (120,140 E., 24,820 N., Peñuelas quadrangle), 1.6 km due west of the plaza at Peñuelas. One of these lenses definitely rests on concretionary limestone and is overlain by limestone containing gravel and cobbles that grade upward into sand. The lens is 10 m thick, but it could not be found farther south, indicating its limited extent. It probably represents a mass of clastic material dumped on the reef by a river in flood. This lens is designated "Tj" (lower clastic strata) on plate 1.

This thick sequence of limestone is largely coralline in the area southwest of Peñuelas, but between the Río Tallaboa and Quebrada del Agua, it intertongues with typical Juana Díaz mudstone. Southwest of Peñuelas, Quebrada de los Cedros and the Río Macaná have cut nearly vertically walled canyons through the limestone. An unpaved road along the bottom of the canyon of the Río Macaná from the village of Macaná to Magas Arriba affords excellent views and outcrops of the limestone. Besides corals, many outcrops include *Lepidocyclina undosa*. Between the Río Macaná and the Río Guayanilla, the entire lower part of the limestone appears to intertongue with mudstone and with sandy, clayey limestone made up largely of *Lepidocyclina* and the echinoid *Clypeaster oxybaphon,* both of which are very common in the clastic zones of the Juana Díaz. These beds crop out in cuts on Highway 132, about 2 km north of the plaza in Guayanilla.

A much smaller reef, in which the limestone contains abundant *Lepidocyclina,* crops out in the valley of Quebrada del Agua (125,190 E., 22,700 N., Peñuelas quadrangle), about 2 km southeast of the intersection of Highways 132 and 391 in Tallaboa Alta. A cave in the limestone has been walled up to form a reservoir for local water supply. From the information available from the nearby outcrops, I could not determine whether this isolated mass of limestone (pl. 1) is a discrete reef deposit or whether it is a part of the limestone exposed farther north and northeast that has been raised by faulting.

In the area between the Río Tallaboa and Juana Díaz, many small limestone masses are present (most are shown on pl. 1), most of which were originally discontinuous nearshore reefs formed by organisms in the generally muddy sea of early Juana Díaz time. Large coral heads are characteristic of the lower part of the Juana Díaz at many places where large masses of limestone are not present. Bedded limestone is present in the southern part of the bluff on Río Jacaguas southwest of Juana Díaz, but the most accessible exposures are in cuts on the Ponce–San Juan Expressway. A cut on the west side of this highway (138,490 E., 21,970 N., Ponce quadrangle) just east of Lago Bronce (fig. 44) shows either the edge of a reef or a small fault formed during deposition of sandy shale. The limestone abuts against the shale to the northeast and is also overlain by it.

Thick limestone beds in the upper part of the Juana Díaz Formation are present throughout the area west of the Río Guayanilla. The base of the limestone appears to be slightly higher in that area than in the area southwest of Peñuelas, where the thick reef formed. Farther southwest, the top of the clastic beds in the lower part of the Juana Díaz seems to be considerably higher than it is near Peñuelas. The overlying limestone is similar but thinner. This limestone is particularly thick in the area between the Río Yauco and Guánica, especially in the northwestern part of the Punta Verraco quadrangle and the northeastern part of the Guánica quadrangle. Examination of outcrops in the area has not been adequate, for very few trails cross the rugged limestone hills and there are few cut banks along the dry valleys. So far as could be seen, however, the limestone is present throughout the area.

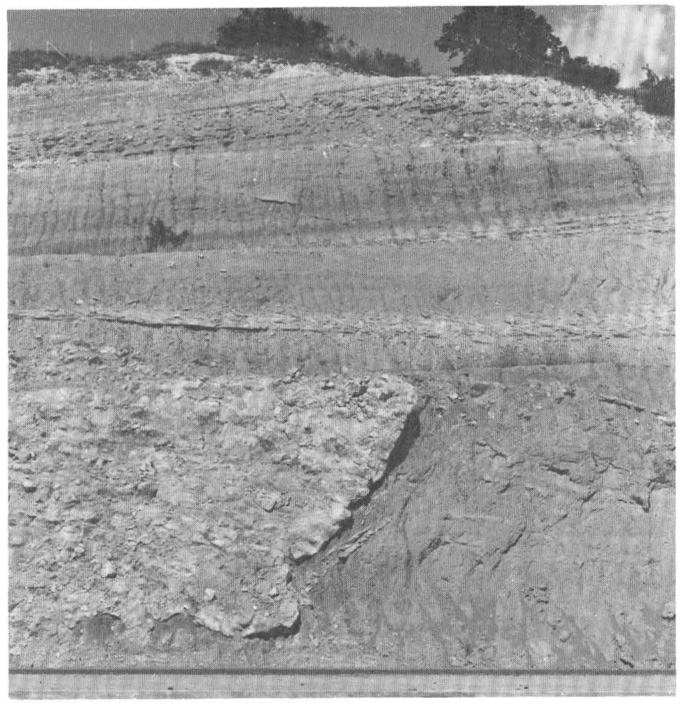

FIGURE 44.—Contact of limestone and sandy shale of the Juana Díaz Formation exposed on the northwest side of the Ponce–San Juan Expressway east of Lago Bronce. The nearly vertical contact in the lower half of the photograph may be the landward edge of a reef or possibly a fault that formed during deposition of sandy shale (February 1971).

It contains few fossils except for rare *Lepidocyclina* sp. and a few *Kuphus* tubes.

A thin section was made of a sample of this limestone taken just east of a fault that raises Cretaceous volcanic rocks on Highway 335 (110,180 E., 17,050 N., Punta Verraco quadrangle), 1.2 km west by north of Central San Francisco. The section shows that the rock is biosparite containing algae and many foraminifers, including *Lepidocyclina* sp. A chemical analysis of a sample of the limestone from this locality (Field No. PV9, table 6) shows that the rock is unusually pure calcium carbonate, containing only 1.3 percent of material insoluble in hydrochloric acid.

The overlying Ponce Limestone overlaps most of the upper limestone of the Juana Díaz Formation in the area between the Río Yauco and Bahía de Guánica. On the east side of the bay, cuts on Highway 333 show all that remains of the upper limestone. Cuts on this highway 700 m south of Playa de Guánica (102,370 E., 14,190 N., Guánica quadrangle) show the transition from brown mudstone containing abundant *Lepidocyclina undosa* upward into limestone that also contains abundant *L. un-*

dosa. Limestone is exposed continuously along the highway to the south and around several bends to a place where the road begins a straight stretch toward the south-southwest. Most of the limestone is thin bedded, but it contains thick beds of calcirudite or limestone conglomerate, which yields many coral heads. The uppermost bed is exposed at the bend in Highway 333 (102,660 E., 13,740 N., Guánica quadrangle). The limestone is thin bedded (fig. 45) and contains abundant specimens of the Oligocene species of foraminifer *Lepidocyclina undosa.* The limestone was sampled for a thin section and a chemical analysis. The section shows that the rock is biosparite containing a few grains of quartz, a few opaque grains, and many fragments of algae and large foraminifers including *Lepidocyclina.* The chemical analysis (Field No. G16, table 6) shows reasonably pure calcium carbonate containing only 6.6 percent of material insoluble in acid.

The thin-bedded Oligocene limestone is overlain on the straight stretch of road toward the south-southwest by rubbly chalk that contains the foraminifer *Marginopora* sp. This is probably the basal unit of the Ponce Limestone.

The high hills between Bahía de Guánica and Ensenada Las Pardas are capped by massive limestone that seems to be equivalent to the calcirudite exposed on Highway 333. A few small outcrops of the limestone have been found farther west in the valley known as Hoya Pozo Blanco, but all the Juana Díaz, both limestone and the underlying clastic beds, are overlapped by the Ponce Limestone between that valley and Bahía Montalva.

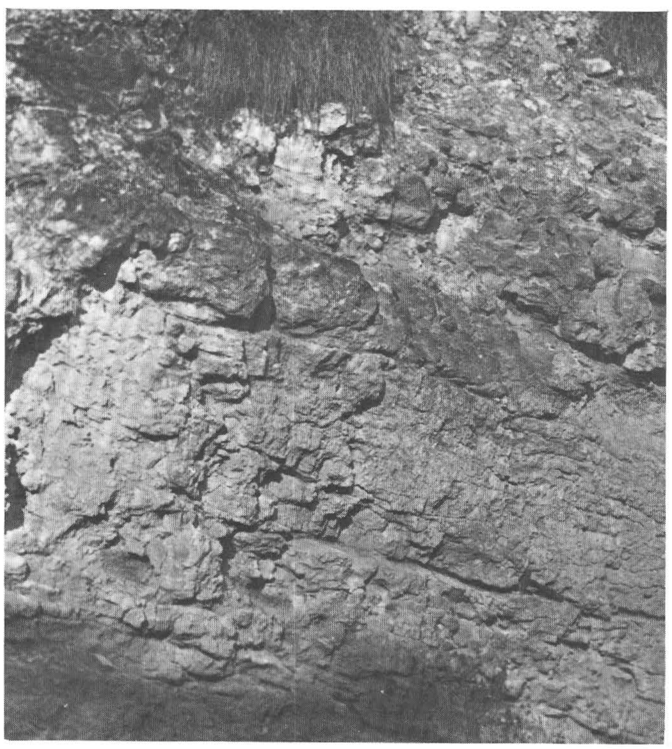

FIGURE 45.—Thin-bedded limestone at the top of the Juana Díaz Formation on Highway 333, 2 km south by east of Guánica (April 1969).

Very chalky limestone is common in the uppermost part of the Juana Díaz Formation in the area near Ponce. Probably the best exposures are in the quarries of the Puerto Rico Cement Company, 1.5 km north of the intersection of Highways 10 and 132 at the west side of Ponce. A sample of this chalk shows in thin section that it is a fossiliferous micrite containing abundant small foraminifers. Cavities are lined with calcite spar. The chemical analysis of this sample (Field No. PE10, table 6) surprisingly shows the highest percentage of material insoluble in acid, 17.7 percent, of any of the samples of the Juana Díaz Formation. As no quartz was seen in the thin section, the impurities in the chalk are probably high-silica clay. These are the strata to which Seiglie and Bermúdez (1969) gave the informal name "Angola limestone." They placed the strata in their *Globigerinoides trilobus primordium-Globigerinita dissimilis* zone, but Moussa and Seiglie (1970) placed the beds in their *Globorotalia kugleri* zone, which is slightly older but still considered early Miocene in age.

An even more accessible sequence of outcrops is on the poor road west of the Ponce city dump, (128-600 E., 19,260 N., Peñuelas quadrangle), about 3 km west by south of the same intersection. In cuts on this road and in gullies and small quarries at the side, about 135 m of alternating beds of hard clayey limestone and hard calcareous shale is exposed; it is very pale orange to yellowish orange, in beds about 30 cm thick. The strata strike N. 70°–80° W., and dip 15°–35° S.

Samples were taken from an outcrop just north of the road at the place it passes through a saddle (128,260 E., 19,240 N., Peñuelas quadrangle), 3 km west of the intersection of Highways 10 and 132. The thin section shows that the rock is biomicrite containing abundant small foraminifers and scattered opaque grains. Cavities are lined with calcite, and the section is cut by a few very thin veins of calcite. The chemical analysis (sample PE166, table 6) shows considerably less insoluble material than sample PE10 (table 6) from the same member of the Juana Díaz.

UPPER CLASTIC BEDS

At the top of the Juana Díaz Formation is a zone of clastic and carbonaceous strata that probably warrants formation rank, except that it can be mapped only in the quarries of the Puerto Rico Cement Company at the west side of the city of Ponce. These beds are probably those for which Mitchell-Thomé (1960) proposed the name Mercedita Lentil. Unfortunately Mitchell-Thomé did not describe a type locality. He merely stated: "The Mercedita Lentil is a clastic fraction of the Lower Ponce, occurring between Quebrada del Agua and Central Mercedita (Mitchell-Thomé, 1960, p. 138). Seiglie and Bermúdez (1969) found a rich fauna of planktonic foraminifers in these beds, and they placed them in their *Globigerinatella insueta* zone of Miocene age. The clastic beds consist largely of crossbedded sand and gravel and carbonaceous sand and clay. These clastic beds contain a few beds of light-gray limestone and very calcareous pebbly sandstone that contains coral heads and water-worn oyster shells. The strata appear to fill a channel cut in the underlying chalky limestone beds, and they are overlain unconformably by the Ponce Limestone. The limestone, sandstone, sand, gravel, and clay in the central part of the quarry is about 50 m thick, but at the southern end of the quarry at the edge of the cemetery San Vicente de Paul, only 15 cm of quartz sand is present between calcarenite of the Juana Díaz and the Ponce Limestone.

The clastic bed has not been seen elsewhere in the vicinity of Ponce, but it may be present in cuts on the road on the west side of the Río Tallaboa (120,630 E., 20,950 N., Peñuelas quadrangle), 800 m north of Highway 2, where 4 m of brown calcareous clay containing limestone nodules and many oysters underlies a basal limestone conglomerate of the Ponce.

Moussa and Seiglie (1970) reported that the beds below the Ponce Limestone here contain the same foraminifers (*Globigerinatella insueta-Globigerinoides sicanus* zone) as the clastic zone in the quarries of the Puerto Rico Cement Company.

The presence of planktonic foraminifers, supposed to indicate "deep-water marine origin" (Moussa and Seiglie, 1970 p. 1898), in a unit of thin-bedded and crossbedded carbonaceous sand, conglomerate, and carbonaceous clay is difficult to explain. The lithology indicates deposition in rapidly moving currents nearshore, and the presence of carbonaceous beds suggests access to water from a swamp.

THICKNESS

The thickness calculated for the lower clastic part of the Juana Díaz varies rather greatly from place to place; this variation is probably real, for the areas where coarse gravel forms the lower part of the formation seem to be places where the formation is filling old valleys on the Pre-Oligocene erosion surface. No calculation was made for the type area near Juana Díaz because the structural complications make such an estimate rather meaningless.

Calculations of thickness of the lower clastic zone north of the city of Ponce are apparently reliable. In the eastern part of the Ponce area through Barriada Jaime L. Drew, where the base of the Juana Díaz is exposed, the thickness appears to be about 410 m, and the overlying sequence of limestone seems to be about 285 m thick, for a total thickness of the formation of a little less than 700 m. Minor faulting was noted in the lower part of the sequence, but none was seen in the limestone sequence. Much of the area has been built up and paved with city streets, however, so that intraformational faulting could have been easily missed. On the western part of the hill north of the quarries of the Puerto Rico Cement Company, the lower Juana Díaz seems to be about 380 m thick and the limestone, about 150 m thick. The Juana Díaz here is in fault contact with Cretaceous rocks, however, so that the figure of 410 m found farther east seems more reliable. The upper clastic member is at least 50 m thick in the quarries of the Puerto Rico Cement Company, but the member is much thinner on the crest of the ridge north of the quarries where the thicknesses were determined probably to be only about 10 m thick. Thus, the total thickness of the Juana Díaz as calculated here is only 530 m, which is considerably thinner than elsewhere, most of the discrepancy occurring in the upper part. Probably the actual thickness of the formation at Ponce is about 600 m.

Exposures are much more continuous in the valley of Quebrada del Agua between Ponce and Peñuelas. Several faults are known in the area, but those affecting the calculations do not seem to be large. The thickness figures obtained are comparable with those at Ponce: the lower clastic beds (gravel at the base, overlain by mudstone containing a few lenses of limestone) have a total thickness of about 420 m; the overlying limestone and chalk appears to be about 310 m thick; the total thickness for the formation is about 730 m. In the area south and southwest of Peñuelas, the thick reef limestone of the Juana Díaz is present. Calculations were made for the lower clastic beds along the ridge between Quebrada de los Cedros and the Río Macaná because in that area the base of the Juana Díaz can be seen resting on Cretaceous rock. The top of the Cretaceous is probably the top of an ancient hill, but because of many faults, this hypothesis can only be determined by drilling. In that area, the lower clastic member of the Juana Díaz is about 130 m thick, and the thickness of the limestone was calculated from outcrops in the valley of the Río Macaná to be about 400 m, making the total thickness of the Juana Díaz Formation about 530 m.

There is little opportunity to obtain bedding attitudes between the Río Guayanilla and Yauco, but judging by the width of outcrop, the lower clastic member of the Juana Díaz is very thick. The long reentrant of sand and gravel of the Juana Díaz northwest of Yauco probably is in part the result of the dropping of a graben, but the abundance of gravel suggests that the formation also fills an ancient valley in which the Juana Díaz was deposited. The clastic beds in this area are estimated to be at least 380 m thick. The limestone member seems to have thinned toward the west to about 300 m.

The San Francisco fault along the east-flowing stretch of the Río Yauco brings serpentinite and other Cretaceous rocks to the surface, so an estimate of the thickness of the Juana Díaz can be made on the ridge south of the valley. The lower clastic beds seem to be about 150 m thick, and the overlying limestone, only about 200 m thick, making a total thickness of about 350 m. The slope is not very accessible, however, and several faults are present—so these estimates are not very reliable.

The westernmost place at which the thickness has been calculated is on the east side of Bahiá de Guánica. The lower clastic beds in the area are at least 100 m thick, but the base is not exposed so the thickness must be somewhat greater. It is probably considerably less than 200 m here, as exposures north of Guánica show a relatively thin sequence of clastic beds below the Ponce Limestone. The limestone of the Juana Díaz can be measured very accurately on the east wall of the bay, and it is only about 80 m thick. This seems reasonable because the stratigraphic evidence shows that the Ponce Limestone has overlapped all the upper, Miocene, part of the Juana Díaz. Thus, the Juana Díaz in this area is probably somewhat more than 180 m thick. Less than 6 km farther west, the Juana Díaz is missing on the outcrop because it has been overlapped by the Ponce Limestone.

The most reliable of the thickness figures given above are probably those for the area near Ponce and near the Río Macaná. Eventually, deep oil test wells may be drilled in the area between Ponce and the Río Tallaboa, and they may reveal that the Juana Díaz is much thicker there than anywhere else, just as the wide belt of outcrop indicates.

Although the Kewanee Interamerican Oil Company drilled three test wells between Ponce and Santa Isabel, the cuttings are not sufficiently diagnostic to determine the thicknesses of the Juana Díaz and Ponce separately. The company's well, 1CPR 1.4 km west of Santa Isabel (152,090 E., 15,180 N.), was drilled through sand and gravel interbedded with clay and silty shale to a depth of 2,975 ft (907 m) where it entered limestone, which according to K. N. Sachs (oral commun., 1970) is a part of the Ponce Limestone. According to the sample log made by Thomas W. Ambrose, geologist for the company, limestone containing a small amount of interbedded brown shale continued to a depth of 3,455 ft (1,053 m), and from 3,455 to 4,270 ft (1,053 — 1,302 m). The well was drilled through limestone, shale, and gravel in about equal amounts, but mainly through gravel between 4,070 (1,240 m) and 4,270 ft (1,302 m). The well was drilled in volcanic rocks containing some interbedded shale and limestone from 4,270 ft (1,302 m) to its total depth of 7,480 ft (2,280 m).

Although K. N. Sachs and Ruth Todd have studied samples from the well, they have not indicated in oral or written communications the exact top of the Juana Díaz; at depths of about 3,455–4,270 ft (1,053–1,302 m), however, the hole passed through sand, gravel, clay, and some limestone that is at least in part Juana Díaz. On the basis of this available information, the well was drilled through rocks of the Ponce and Juana Díaz for a total thickness of about 1,295 ft (395 m).

Kewanee's well 3CPR was drilled on the beach 5.5 km east of Playa de Ponce (137,950 E., 15,290 N., Playa de Ponce quadrangle). Samples from this well were examined both by T. W. Ambrose and by Neil E. McClymonds of the U.S. Geological Survey. Apparently the well passed from post-Ponce sand and gravel into the Ponce Limestone at a depth of about 420 ft (128 m), and it entered volcanic material at a depth of 2,848 ft (868 m), for a total thickness of rocks of middle Tertiary age of 2,428 ft (740 m). This thickness is more nearly comparable with that found on the outcrop nearby but is still much less than that calculated for the area between the Quebrada Limón and the Río Tallaboa.

The total thickness of rock below gravel presumably younger than the Ponce Limestone and above the basement rocks is rather less than the calculated thickness of the Juana Díaz. Several explanations are suggested for the discrepancy (Monroe, 1973b). The Ponce Limestone may not be as thick east of Ponce as it is farther west, either because of nondeposition or possibly because of erosion of the top. In the case of the Kewanee's well 1CPR at Santa Isabel, the Juana Díaz may be partly overlapped by the Ponce near the eastern edge of the depositional basin, just as it is west of Guánica. The most reasonable explanation, however, is that the thicknesses calculated from dips and strikes on the outcrop are too great because the section is duplicated one or more times by faults that were not observed in the course of the fieldwork.

FOSSIL CONTENT AND AGE

The Juana Díaz Formation contains abundant fossils, especially foraminifers. The foraminifers have been studied most completely by Seiglie and Bermúdez (1969) who recorded a rich fauna of many planktonic species in all parts of the formation. On the basis of their studies, they were able to recognize many faunal zones within the formation and to correlate these in a general way with faunal zones in Trinidad. Somewhat more definite correlations made later by Moussa and Seiglie (1970) were based principally on the collections studied earlier by Seiglie. Studies by Ruth Todd (written commun., 1963) on 4 samples of the lower part of the Juana Díaz Formation collected by P. H. Mattson resulted in a list of 13 planktonic species and about 130 benthonic species. All 4 samples were from the mudstone facies of the Juana Díaz exposed just northeast and northwest of Ponce.

One of the most useful fossils for field use in the Juana Díaz Formation is the large foraminifer *Lepidocyclina undosa*, which is present from the lowest part of the formation up to the base of the limestone in the Ponce area and above the limestone in the reef deposit southwest of Peñuelas. This fossil may be considered a guide fossil for the Juana Díaz, even though it does not occur in the highest beds.

Associated with *Lepidocyclina undosa* at many localities is the large echinoid *Clypeaster oxybaphon*, which is not found in the Ponce Limestone or in the upper part of the Juana Díaz. Bergquist (written commun., 1945) listed about seven other species of echinoids, some of which have a longer range.

Molluscan fossils are common in some beds in the Juana Díaz. The richest beds, according to Bergquist, are in the bank and bed of the Río Jacaguas, 400 m southwest of the bridge of Highway 14. Many of the fossils here, according to Bergquist (written commun., 1945), are preserved as calcite replacement in "gray to tan, sandy lower Juana Díaz limestone beds." He found nearly 40 species of gastropods and nearly 20 species of pelecypods at this locality. In all the collections from the beds now classed as Juana Díaz, including those formerly considered the lower member of the Ponce Limestone, Bergquist listed about 50 species of gastropods and about 35 species of pelecypods.

Coryell and Ohlsen (1929) listed 39 species of corals from the "Ponce limestone," but they pointed out that the Ponce collection was undifferentiated and included material that actually belonged for the most part in what should have been called Juana Díaz formation and the "Guánica shale."

A few specimens of silicified wood, associated with a large molluscan fauna, were observed by Zapp, Bergquist, and Thomas (1948) in sandy limestone of the lower part of the Juana Díaz in the banks and bed of the Río Jacaguas, 0.4 km southwest of the bridge of Highway 14 at Juana Díaz.

The larger fossils, including *Lepidocyclina undosa*, indicate that the lower part of the Juana Díaz Formation is Oligocene, but the evidence for the age of the chalky limestone ("Angola limestone") and the uppermost clastic beds is less clear. However, on the basis of the absence of *L. undosa* and *Clypeaster oxybaphon*, it is reasonable to assume that the upper part of the formation is Miocene, a conclusion borne out by the evidence of planktonic foraminifers as presented by Seiglie and Bermúdez (1969) and Moussa and Seiglie (1970).

The foraminifers from the lower clastic strata, collected at La Rambla by P. H. Mattson and examined by Ruth Todd (written commun., 1963) include species hitherto recorded only from the Eocene, the Oligocene, and the Miocene, as well as species recorded from both Eocene and Oligocene and from Oligocene and Miocene, and some that are longer ranging. After evaluating all the evidence, Miss Todd believes that the fossils are of early Oligocene age.

Moussa and Seiglie (1970) believed that they could zone the foraminifers to match fairly closely zones established in Trinidad by Bolli (1957). They placed the oldest Oligocene strata in southern Puerto

Rico in Bolli's *Globigerina ampliapertura* zone of early Oligocene age. This zone is overlain by what they called the *Globorotalia opima opima-Globigerina ciperoensis ciperoensis* zone. They restricted the name Juana Díaz Formation to the rocks containing these two zones, rocks that contain mainly mudstone. At the top of the Oligocene, they have the *Globigerina ciperoensis ciperoensis* zone, which includes some marlstone in Sabana Llana southwest of Juana Díaz. Their next higher zone is characterized by *Globorotalia kugleri,* which is found in the chalky limestone of "Angola" beds in the upper part of the Juana Díaz as defined in the present report; this zone is at the base of the Miocene. Above the *G. kugleri* zone, they reported that there should be two of Bolli's zones that were not recognized in Puerto Rico, the *Globigerinita dissimilis* zone and *G. stainforthi* zone. These may be represented in the unconformity between the Juana Díaz limestone beds and the upper clastic beds exposed in the quarries of the Puerto Rico Cement Company, which contain their uppermost zone, characterized by *Globigerinatella insueta* Cushman and Stainforth. Moussa and Seiglie have found this middle Miocene zone only in the sand at the Puerto Rico Cement Company quarry and in marlstone exposed in the valleys of the Río Tallaboa and Río Macaná directly beneath the Ponce Limestone. Moussa and Seiglie (1975) now consider that this zone should be designated the basal unit of the Ponce Limestone. The clastic strata of the zone, however, fill a channel cut into older rocks. These clastic rocks seem to represent more of a regressive than a transgressive unit and therefore to fit more logically with the Juana Díaz than with the Ponce.

Thus, the evidence available indicates that the Juana Díaz Formation ranges in age from lower Oligocene to middle Miocene. It includes strata older than any thus far recognized in northern Puerto Rico and also strata equivalent to the San Sebastián Formation, the Lares Limestone, and probably all the Cibao Formation.

ORIGIN

The origin of the Juana Díaz Formation presents more problems than that of any of the other formations of middle Tertiary age in Puerto Rico as it is difficult to reconcile the environment indicated by the foraminifers with the environment indicated by the lithology.

The basal beds of the Juana Díaz at the few places where they have been seen consist of cobbles and boulders of various kinds of volcanic rock, generally tuff and tuff breccia, in a matrix of sand made up of volcanic rock fragments that weather easily to silty clay. Silicified wood has been seen at a few places. Associated with these sediments at many places are large coral heads of Oligocene age. This indicates a transgressing sea in an environment like that present today along much of the southern coast of Puerto Rico where alluvial-fan material, composed of sand derived from volcanic rocks and cobbles and boulders of similar rocks, are worked by the waves into somewhat muddy shingle beach deposits, which commonly have fringing coral reefs nearby. At many places, however, the basal beds of the Juana Díaz Formation do not contain gravel and cobbles; instead, mudstone rests almost directly on volcanic material. Presumably these are areas in which the Juana Díaz was deposited on a hill on the early Oligocene erosion surface, whereas at places where thick deposits of gravel and cobbles are found, the Juana Díaz was deposited in old valleys on the drowned surface.

All the clastic strata in the lower part of the Juana Díaz suggest deposition from very muddy water into which rivers were pouring quantities of pebbles and cobbles. In this part of the Juana Díaz, however, planktonic foraminifers are very common, and these are said to indicate "deep-water marine origin" (Moussa and Seiglie, 1970 p. 1898). The only reasonable explanation seems to be that the formation was being deposited at a time when the upland to the north was being raised fairly rapidly and the sea floor was dropping rapidly, so that a great quantity of cobbles, boulders, and mud was being poured onto the subsiding shelf by rapidly flowing rivers. In order for the corals to survive, the mud must have settled to the bottom very rapidly and the reefs must have grown upward rapidly enough to remain in the sunlit zone of water.

The thick limestone mass south and southwest of Peñuelas apparently bears out this supposition, for the limestone contains relatively little sand or clay, except in thick lenses like that 1.5 km west of Peñuelas that may be a deposit resulting from a flood in the watershed of a river that entered the sea at that point. Apparently this reef began to grow in the Peñuelas–Río Macaná area while clastic material was being poured into the sea farther east and also near Yauco. Conditions may have been something like those today in the Bahiá de Jobos area, at the east end of the area shown in plate 1, where coral reefs are building up rapidly while thick clastic deposits are being deposited farther west in the area between Salinas and Santa Isabel and farther east near Guayama.

Fringing reefs apparently were present throughout most of the rest of Juana Díaz time between Guayanilla and Guánica, but in the more western part of this area, the upper part of the Juana Díaz has been overlapped by the Ponce Limestone so outcrops are not present. In the area near Guayanilla, the reef limestone apparently was succeeded for a short time by deposition of clastic sediments, as indicated by the tongue of clastic material shown on the map.

During later Juana Díaz time, probably in the early Miocene, the streams apparently ceased to bring so much coarse clastic material into the sea, and the rather chalky limestone was deposited to which Seiglie and Bermúdez (1969) gave the name "Angola." This limestone contains a little quartz sand and much clay, so it indicates deposition in slightly muddy water in which lime-secreting organisms supplied most of the sediment.

One of the most interesting and puzzling units of the Juana Díaz is the bed of sand and clay at the top in the quarries of the Puerto Rico Cement Company, the unit which Moussa and Seiglie (1970) placed in the Miocene *Globigerinatella insueta* zone. The lithology of these "upper clastic beds" indicates deposition nearshore—deposition of carbonaceous matter, probably in swamps, alternating with deposition of quartz sand by rapidly moving currents. However, the presence of abundant planktonic foraminifers, which constitute more than 90 percent of the total foraminiferal population according to Seiglie and Bermúdez (1969), suggest to them deposition in water of oceanic depth. Seiglie and Bermúdez also stated that the benthonic fauna indicate deposition in deep water. The evidence provided by the lithologic character of the deposits and provided by the microfauna appear to be completely contradictory.

PHYSIOGRAPHIC EXPRESSION

The topographic expression of the Juana Díaz Formation varies with the lithology of the formation. The mudstone and lower clastic beds give rise to gently rolling hills in all areas where they are exposed, such as in the area east-northeast of Ponce, in the headwaters of Quebrada del Agua, and in the hills northwest of Yauco. Outcrops of lenses of calcareous sandstone and limestone produce slightly steeper slopes and in some places vertical cliff walls. Examples include the hills of the development El Monte, 5 km northeast of Plaza Degetau in Ponce, the steep-sided ridge between Magueyes and Pastillo Cana about 4 km north-northwest of the intersection of Highways 10 and 132 at the west end of Ponce, and the limestone-capped hills in the headwaters of Quebrada del Agua. The chalky limestone in the upper part of the Juana Díaz seems to produce a slightly more rugged topography than the clastic beds; in passing from one lithologic type to the other, the limestone hills have somewhat steeper slopes.

In contrast to the rest of the Juana Díaz, the thick reef limestone in the Peñuleas–Río Macaná area has been dissolved into a typical karst terrane—characterized by sinkholes, probably collapse dolines, caves, and collapse karst valleys of the kind described by Moussa (1969). This is the most fully developed karst topography in the middle Tertiary rocks in southern Puerto Rico, although a few small sinks and caves are also known in the Ponce Limestone. A sink more than 30 m deep is found 1.3 km west-southwest of Peñuelas, and several smaller sinks are present nearby. The valleys of Quebrada de los Cedros and the Río Macaná that cut through the limestone mass are nearly vertical-walled canyons that are probably collapsed caves—in fact the stream of Quebrada de los Cedros is still partly underground, flowing through Cueva El Convento. I could find no evidence of the sinkholes reported by Mitchell (1922, p. 246) "in the vicinity of kilometer 67.0 on the Ponce–Peñuelas road."

PONCE LIMESTONE

NAME

The Ponce was named by Berkey (1915) as the Ponce chalky limestones and marls, but he included them in his Arecibo Formation. He also referred to "Guánica coral reefs," which he thought might be slightly younger than Ponce. Berkey may have been referring to the chalky limestone now placed in the upper part of the Juana Díaz Formation rather than to the still younger limestone herein referred to as the Ponce. Hodge (1920) and Mitchell (1922) used the name Ponce formation for all the rocks of middle Tertiary age in southern Puerto Rico. They did not name a type locality, but Mitchell stated that the chalky limestone is best developed northwest and west of Ponce. Hubbard (1920a), after studying fossil collection from both northern and southern Puerto Rico, divided the Ponce into "Upper Ponce (including Guánica) limestone" and "Lower Ponce limestone" and correlated them with formations cropping out in northern Puerto Rico. Zapp, Bergquist, and Thomas (1948) accepted Hubbard's divisions but did not designate type localities. In 1973, Monroe (1973b) restricted the name Ponce Limestone to the uppermost unit, hitherto known as the upper member of the Ponce Limestone, or Upper Ponce limestone. A type locality was suggested as the upper "Yellow" limestone beds in the quarry of the Puerto Rico Cement Company (131,000 E., 21,030 N., Peñuelas quadrangle) in the southwestern part of the city of Ponce, and a reference locality was given as the extensive quarries of the Puerto Rico Cement Company (128,250 E., 19,700 N., Peñuelas quadrangle), west of the Río Pastillo. Even more accessible as a reference locality is the series of cuts on Highway 2 between the valleys of the Río Tallaboa and Río Macaná (this highway has been relocated farther north since the base map of plate 1 was compiled).

AREAL DISTRIBUTION

The Ponce Limestone is exposed continuously, except for cover by alluvium in river valleys, from the valley of the Río Pastillo just west of Ponce to Bahía Montalva 8 km west of Guánica. It is further exposed at the crest and at the foot of southern slopes of hills in the city of Ponce and in large quarries on the southern slopes of the hills of Sabanetas, about 2 km east of the Degetau Plaza in Ponce. Farther east, the formation has been recognized on the surface only in two areas: on several small outliers south of a fault in barrio Sabana Llana between the valleys of the Río Inabón and the Río Jacaguas, and east of the Río Jacaguas in small outcrops at the foot of the hill where a vocational school is located (145,900 E., 20,900 N., Río Descalabrado quadrangle), just north of Fort Allen, east of Highway 149 and 2.8 km north of Highway 1. The formation has been recognized in a well drilled at Santa Isabel (K. N. Sachs, oral commun., 1970) by the Kewanee Interamerican Oil Company, but it is not known to crop out that far east.

Characteristic rocks of the formation are present in outliers on the south flank of the Sierra Bermeja west of La Parguera, covering most of Isla Cueva, and on the two hills that form tombolos at Cabo Rojo at the southwestern corner of Puerto Rico. The formation is said also (Mattson, 1960) to be present at one place on the south flank of Peñones de Melones, about 5.5 km southwest of Boquerón.

STRATIGRAPHIC RELATIONS

The Ponce Limestone rests unconformably on the youngest known rocks of the Juana Díaz Formation in the quarries of the Puerto Rico Cement Company at the west edge of Ponce and on the western side of the valley of the Río Tallaboa, as described in the section of this report on the upper clastic beds of the Juana Díaz. Elsewhere, it rests on older parts of the Juana Díaz. Westward from the valley of the Río Yauco to the valley of Hoya Pozo Blanco, the Ponce rests on successively older beds of the Juana Díaz; farther west it rests directly on rocks of Cretaceous age. Presumably the Ponce also overlaps the Juana Díaz to the east, but the easternmost outcrops of the formation are on rocks fairly high in the sequence of the Juana Díaz Formation.

The Ponce is also present on Isla Caja de Muertos, 16 km southeast of Ponce, because Bergquist (written commun., June 1945) collected fossils there not known to occur below the Ponce elsewhere. According to Kaye (1957), the Ponce Limestone there rests on volcanic sandstone of probable Eocene age (Glover and Pease, written commun., 1960).

LITHOLOGIC CHARACTER

The principal reference locality for the Ponce Limestone is in the quarries of the Puerto Rico Cement Company at the west edge of Ponce. The quarries are principally on the west and south slopes of a large hill; Ponce Limestone is exposed at the top of the hill and on the south slope, dipping 18°–25° generally south. In the upper part of the quarries near the top of the hill, about 25 m of pale-yellowish-orange to dark-yellowish-orange compact indurated very fossiliferous limestone is exposed. The limestone contains abundant molds of pelecypods and gastropods, including *Orthaulax, Kuphus* tubes, many coral heads and abundant molds of solitary cuplike corals, and abundant large foraminifers. K. N. Sachs (written commun., 1968) reported that a small collection sent to him contains abundant *Marginopora vertebralis* Quoy and Gaimard and *Archaias angulatus* (Fichtel and Moll). Cooke (unpub. data, 1956) made a large collection of fossils, mostly represented by molds. He reported the presence of "*Archaias, Flabellum, Conus, Orthaulax, Pachycrommium, Ostrea haitensis* Sowerby, *Pecten* aff. *barretti* Woodring, two other species of *Pecten, Amusium, Cardium, Miltha, Lucina janus* Dall?, *Kuphus incrassatus* (Gabb), *Clypeaster cubensis* Cotteau, and sirenian ribs."

The Puerto Rico Cement Company also has quarries on the west side of the valley of the Río Pastillo (Quebrada Limón in pl. 1), and these present a face of Ponce Limestone nearly a kilometer long, interrupted at the south by a large normal fault that

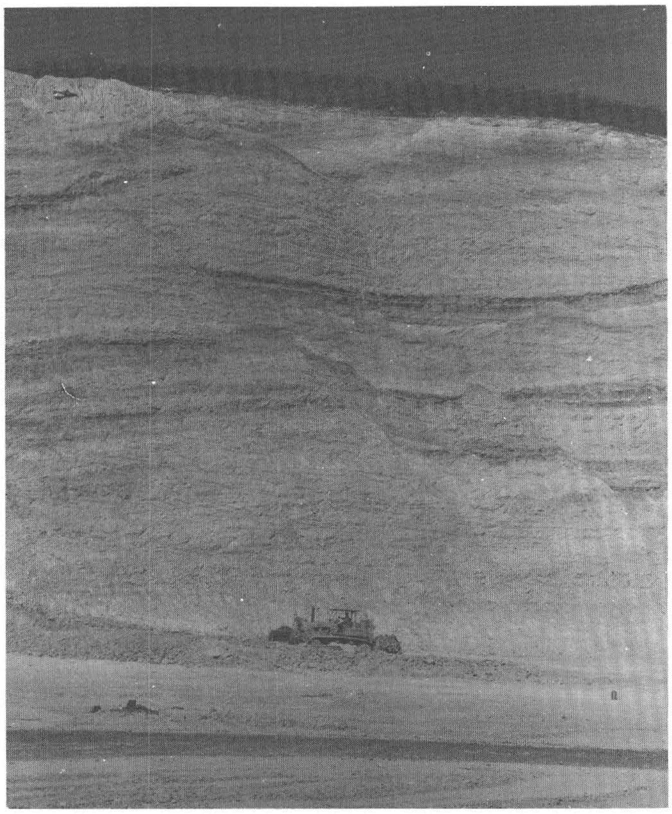

FIGURE 46.—Ponce Limestone exposed in quarry of Puerto Rico Cement Company on west side of Río Pastillo. The limestone here is cut by small normal faults down to the north (right) (April 1968).

brings up chalky limestone of the Juana Díaz to make the type locality of the Angola limestone of Seiglie and Bermúdez (1969). Several small faults of 5–10 m displacement (fig. 46) cut the bedding of the Ponce Limestone in the quarry face; the limestone varies in attitude in different fault blocks, but has a dip ranging from 14° N. to 10° S. The limestone is much like that in the main quarries east of the valley, ranging from pale yellowish orange to grayish orange and containing abundant molds of mollusks. Near the northern end of the quarries, the limestone contains two layers of light-brown clay about 15 m apart.

The basal contact of the Ponce is exposed in Puerto Rico Cement Company quarry 1 at the south end of the company's main quarries. Another accessible exposure of the contact is in a small quarry east of Highway 132 (128,640 E., 21,650 N., Peñuelas quadrangle), 3.1 km northwest of the intersection with Highway 10 at the west edge of Ponce. Here, more than 20 m of yellowish-orange fossiliferous limestone of the Ponce rests sharply on 5 m of interbedded very light gray clay and limestone in beds, as much as 30 cm thick, of the upper part of the Juana Díaz Formation (fig. 47). The contact strikes N. 80° W. and dips 15° S. Moussa and Seiglie (1970) reported that the Juana Díaz part of this sequence belongs to their *Globorotalia kugleri* zone, which indicates that the Ponce Limestone has overlapped all of the uppermost Juana Díaz represented in their *Globigerinatella insueta* zone.

The best outcrops of Ponce Limestone known are in the cuts of Highway 2 between the valleys of the Río Tallaboa and the Río Macaná north of the refinery of the Commonwealth Oil Refining Company. The cuts have nearly continuous exposures of Ponce Limestone over a vertical distance of more than 80 m, probably exposing at least 100 m of the formation. Most parts of the outcrop are very fossiliferous, mostly containing molds of mollusks, but echinoids, including *Clypeaster cubensis,* are common, as is the small cup-shaped coral *Flabellum* and

FIGURE 47.—Contact of the Ponce Limestone on limestone in the upper part of the Juana Díaz Formation in quarry east of Highway 132, 3.1 km northwest of the intersection with Highway 10 at Ponce. Contact offset by small fault just above figure of H. R. Bergquist (February 1969).

TABLE 7.—*Chemical analyses of Ponce Limestone*

[Analyzed by rapid method (Shapiro, 1975); analyst, Lowell Artis]

Lab. No.	W175020	W175012	W175013
Field No.	PE278[1]	PV7[2]	PV141[3]
SiO_2	0.91	5.5	0.15
Al_2O_3	.34	1.1	.05
Fe_2O_3	.26	.42	.07
FeO	.04	.02	.04
MgO	.44	4.4	6.7
CaO	53.4	44.4	46.6
Na_2O	.13	.33	.03
K_2O	.00	.32	.00
H_2O-	.10	.60	.08
H_2O+	.40	.70	.43
TiO_2	.00	.02	.00
P_2O_5	.03	.04	.02
MnO	.00	.06	.05
CO_2	42.9	40.9	45.0
Total	99.	99.	99.
Acid insoluble	1.5	7.1	0.3

[1] Cut on south side of Highway 2, 1.6 km west of Río Tallaboa, (119,430 E., 20,190 N., Peñuelas quadrangle).

[2] Cut on north side of Highway 335, 1 km northwest of Central San Francisco (110,670 E., 17,350 N., Punta Verraco quadrangle).

[3] Recrystallized limestone, north side of jeep trail, 1.9 km west-southwest of Punta Ventana (110,180 E., 13,540 N., Punta Verraco quadrangle).

such common Miocene foraminifers as *Marginopora vertebralis* and *Gypsina globula.*

A sample of the Ponce Limestone was collected from the cuts on Highway 2 (119,430 E., 20,190 N., Peñuelas quadrangle), 1.6 km west of the Río Tallaboa. An analysis of the limestone (Field No. PE278, table 7) shows that it is fairly pure calcium carbonate containing only 1.5 percent of material insoluble in hydrochloric acid. A thin section of the same sample shows that the rock is a micrite containing abundant fossils, especially algae and foraminifers, including *Marginopora* sp. Cavities in the rock are bordered by calcite spar.

The lithologic character of the Ponce Limestone is much the same in abundant roadcuts and quarries as far west as the Río Yauco. One cut on Highway 335 on the northern side of the valley of the Río Yauco (111,730 E., 17,450 N., Punta Verraco quadrangle), 900 m north-northeast of Central San Francisco, consists largely of relatively unconsolidated yellowish-orange chalk containing abundant *Kuphus* tubes and molds of mollusks. It also includes a layer 40–100 cm thick made up of irregular pieces of hard limestone in brown clay; this layer represents either a forereef deposit or a collapsed cave.

Ponce Limestone, somewhat less pure than usual, was sampled in a cut about 1 km farther west on Highway 335 (110,670 E., 17,350 N., Punta Verraco quadrangle), about 1 km northwest of Central San Francisco. The analysis of the sample (Field No. PV7, table 7) shows an unusually high percentage of material insoluble in acid, 7.1 percent; apparently much of this is quartz sand, for the thin section cut from the same sample contains very fine angular quartz grains and a few angular opague grains in a biomicrite containing algal fragments, coral(?) fragments, and many foraminifers, including *Marginopora* sp.

The Ponce Limestone is present on the southern slopes of the ridge between Central San Francisco and Bahía de Guánica, but much of it has been recrystallized to very pale orange and light-gray limestone. It contains the usual common molds of mollusks, the solitary coral *Flabellum,* and rare specimens of *Marginopora* sp. The best exposures of the limestone are along the unpaved road, Highway 334, from the sharp bend to the south 1.6 km east-southeast of Guánica, southwest to a point 200 m north of the sharp bend toward the east that leads down to the intersection with Highway 333.

The exposures described above are all within the Bosque Estatal de Guánica, and in several exposures of the base of the Ponce within the forest, the hard limestone is underlain by several meters of unconsolidated chalk that contains *Marginopora* and *Archaias.* Beneath the chalk is limestone that contains *Lepidocyclina undosa.* The chalk may be a basal unit of the Ponce Limestone in this area, for paleontologically it is more closely related to the Ponce than to the underlying Juana Díaz, but possibly it is equivalent to the upper clastic beds of the Juana Díaz Formation.

Exposures along the coast from Punta Ventana (fig. 48) west to Bahía de Guánica are all limestone of Miocene age that has been almost completely recrystallized. At a few places, the limestone contains the echinoid *Clypeaster cubensis* and the foraminifers *Marginopora* sp., and *Archaias angulatus* and *Archaias floridanus* (K. N. Sachs, Jr., written commun., 1970). A sample of this limestone was collected (110,180 E., 13,540 N., Punta Verraco quadrangle) from the north side of a jeep trail near the coast, 1.9 km west-southwest of Punta Ventana. The analysis (Field No. PV141, table 7) shows that the rock is magnesian limestone that contains very little material insoluble in acid. The thin section shows that the rock is micrite containing widely scattered foraminifers and algal remains. Sparry calcite surrounds all cavities showing in the section. The outcrop is near the sea, and the magnesium may have come originally from sea spray.

The peninsula known as Monte de la Brea, which is south of Ensenada Las Pardas, is composed en-

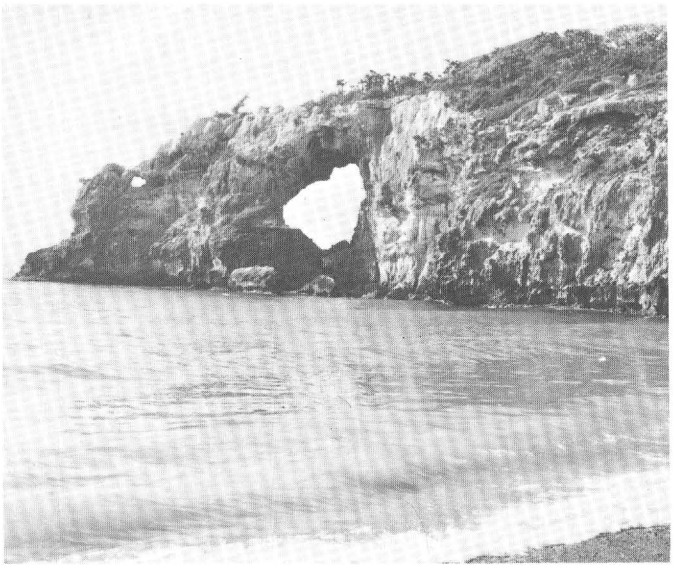

FIGURE 48.—Window carved by the sea in a thin wall of Ponce Limestone at Punta Ventana, 6.5 km south of Guayanilla (January 1970).

tirely of Ponce Limestone, mostly recrystallized but containing the usual molluscan molds and *Marginopora* sp. Especially good examples are in the sea cliffs on the headland at the south side of the village of Salinas de Guánica.

At Punta Montalva (94,200 E., 14,150 N., Guánica quadrangle) on the east side of Bahía Montalva, a large fault passes beneath the sea. To the north are volcanic rocks of probable Cretaceous age; to the south are middle Tertiary rocks questionably assigned to the Ponce Limestone. At the point (Punta Montalva), grayish-orange chalky limestone, much like that in the upper Juana Díaz, strikes N. 70° W., and dips 80° S. South of this limestone is thinly laminated limestone that also dips 80° S. A few meters farther south, the laminated limestone is horizontal. The only fossils seen are *Kuphus* and an oyster. I believe that this material is basal Ponce Limestone, because a cut at the crest of the ridge on the trail approximately 1 km farther east (95,180 E., 13,980 N.) exposes soft grayish-brown limestone that contains similar abundant large oysters, *Kuphus* tubes, and scattered molds of mollusks of the kind common in the Ponce. Outcrops on the same trail 820 m farther south by east (95,440 E., 13,200 N.) and 45 m lower in altitude show typical hard recrystallized very pale orange calcarenite containing abundant molds of mollusks and of *Flabellum* and the usual *Kuphus* tubes—all characteristic of the Ponce Limestone.

Farther west, the Ponce is present only in isolated outliers resting on volcanic rocks of Cretaceous age. The contact of the Ponce on the older rocks is marked at many places by a layer of coral heads; this layer is overlain by calcarenite rich in molds of mollusks. The exposures on the eastern hill of the double tombolo at Cabo Rojo consist of very pale orange to yellow sandy calcarenite that contains obscure fossil prints. Near sea level on the east side of the hill is thinly laminated limestone very much like that seen at Punta Montalva.

THICKNESS

In the type area, the Ponce Limestone is less than 50 m thick, but these outcrops are on the crest of a hill, and undoubtedly much of the formation has been eroded away. The most complete sequence of outcrops is in the hills between Ponce and the Río Tallaboa in the southern part of the Peñuelas quadrangle and the northern part of the Punta Cuchara quadrangle. Calculation of the thickness of the Ponce in this area results in the figure of 1,600 m, which does not seem at all probable in comparison with other areas. Although no faults are known to cut the formation in the area, the Juana Díaz just to the north is cut by many faults; therefore, the area of outcrop of the Ponce Limestone may be far wider than it should be because parts of the formation have been duplicated by faulting. The outcrops west of Río Tallaboa, north of the refinery of the Commonwealth Oil Refining Company, yield a calculated thickness of 850 m, but this area is known to be cut by several small faults (see fig. 47) so this estimate also may be too great. All that one can say certainly is that the Ponce Limestone is thicker than 200 m, for that thickness is exposed in single hills between Ponce and Tallaboa.

FOSSIL CONTENT AND AGE

The Ponce Limestone contains abundant molds of many kinds of fossils, but most of them are not specifically identifiable. The presence of abundant molds, however, has in itself proved of value in distinguishing the Ponce from older and younger beds. One of the most diagnostic molds is that of the small cuplike solitary coral *Flabellum,* which has not been seen in any of the older rocks. Other corals present have not yet been studied systematically.

The formation has not yielded any planktonic foraminifers, which is not surprising because it probably was formed as a shallow-water fringing reef, but it commonly contains abundant specimens of *Marginopora vertebralis*. In places where that is not common, it contains *Archaias angulatus* and *A. floridanus*. Somewhat rarer, but diagnostic of the Ponce Limestone, is the spherical foraminifer *Gypsina globula*.

The echinoid *Clypeaster cubensis* is present in the formation at many places but has not been found in the Juana Díaz Formation. Bergquist (written commun., 1945) recorded 2 other echinoids that appear to have longer ranges. Bergquist also listed 6 species of gastropods and 10 species of pelecypods in the formation. Many other species probably are present, but as they occur only as interior molds, it is difficult to identify them specifically. Tubes of *Kuphus incrassatus* are common in many places, but they are present also in the underlying limestone strata of the Juana Díaz. Van den Bold (Bold, 1969) has studied ostracodes from the Ponce Limestone and listed about 13 species.

Most paleontologists consider that the Ponce Limestone is of Miocene age, but they disagree on what part of the Miocene. In view of the marked unconformity at the base, the formation is probably considerably younger than the uppermost Juana Díaz, which suggests an upper Miocene age. The formation contains many foraminifers, however, which are present in the Aguada and Aymamón Limestones in northern Puerto Rico, but those common in the Camuy have not been recognized, and this suggests a lower Miocene age. The Camuy may have a facies fauna different from that of the Ponce, however, and the formations may be of somewhat similar age.

Van den Bold believes that "the whole of the Middle Miocene and possibly the early part of the late Miocene is absent in southern Puerto Rico" (Bold, 1969, p. 119). Van den Bold placed the Ponce in the lower part of his *Mutilus confragosus* zone, which includes uppermost Miocene and Pliocene strata; he considers the Ponce, then, uppermost Miocene.

ORIGIN

The Ponce Limestone is entirely an organic reef deposit characterized by various kinds of corals, algae, and mollusks. It probably formed as a fringing reef on the southern coast of Puerto Rico in Miocene time and became thicker as the coastal shelf slowly subsided. As pointed out earlier in the discussion of the origin of the Aguada and Aymamón Limestones, Cloud (1952) stated that the presence of *Marginopora,* which is common in the Ponce Limestone, indicates that the rock was formed on a reef flat.

The overlap of the Juana Díaz by the Ponce in the southwestern part of Puerto Rico is consistent with an origin of the Ponce as a fringing reef, much like some of the limestone reefs forming today on the southern coast of Puerto Rico.

PHYSIOGRAPHIC EXPRESSION

The Ponce Limestone is recrystallized reef limestone that resists erosion; hence, it gives rise to steep-sided hills that tend to be characterized by a small north-facing cuesta scarp. In the larger areas of outcrop, such as the entire northern part of the Punta Cuchara quadrangle and the southern part of the Peñuelas quadrangle, between the valleys of Quebrada del Agua and the Río Tallaboa, the formation has been eroded into very steep-walled canyons, commonly having nearly vertical cliffs. Many of these cliffs have scooped-out solutional scars.

The limestone is so hard and relatively pure and the climate so arid that karren or lapiés are common on exposed surfaces. These are probably the common rillenkarren, grooves that form rapidly on bare limestone over which rain water flows. Some caves are known in the formation, and several, such as Cueva Murciélagos north of Bahía de la Ballena and 4.2 km due west of Punta Ventana, are large enough to have a dark zone, although most are little more than rock shelters.

GUANAJIBO FORMATION

The Guanajibo Formation was named by McGuinness (1948, p. 226–227) for "light-yellow to gray limestones, sandy or earthy and ranging from soft to fairly hard, and sands, silts, and clays" penetrated in wells at Mayaguez. McGuinness (1948, p. 30–31) reported that J. A. Cushman examined foraminifers from the wells and correlated them with forms from Buff Bay, Jamaica, which are probably of late Miocene or Pliocene age. Kaye (1957) observed similar limestone cropping out on the northern side of the Lajas Valley, a little more than 3 miles southwest of Lajas, and stated that so far as he knew, that was the only outcrop of middle Tertiary rocks on the west coast. Gorden (1961b) collected fossiliferous crumbly light-yellow chalky limestone on the north side of Highway 4, and from it be obtained a small fauna consisting largely of benthonic foraminifers similar to those found in the Ponce Limestone.

In April 1970, a reconnaissance search was made for middle Tertiary strata in the Lajas Valley. One small roadcut on the north side of Highway 101 (81,600 E., 22,700 N., San Germán quadrangle), 800 m east of Llanos crossroad, about 5 km west-southwest of Lajas, shows prints and molds of mollusks in light-yellowish-brown siltstone. At the top of the cut, 10 m farther east, the material grades upward into silty chalk. Druid Wilson (written commun., 1970) recognized a small specimen of *Orthaulax*, but the other prints were not identifiable. Ruth Todd (written commun., 1970) recognized *Ammonia beccarii* and *Elphidium lens* and a few other foraminiferal genera but nothing having stratigraphic value. No limestone could be found in the vicinity, but this outcrop is undoubtedly a part of the same body of limestone from which Gordon 1961b collected.

Gordon found many ostracodes in the limestone, and these were studied by van den Bold (Bold, 1969), who found 18 species present, of which 12 are also present in the Ponce Limestone. Two of the ostracodes in the beds in the Lajas Valley are brackish-water species, whereas all the species that van den Bold has studied from the Ponce Limestone are strictly marine. He considers the deposits equivalent to the Ponce Limestone and probably of late Miocene age.

Mattson (1960) has mapped several outliers of sand and sand and gravel farther west in the Lajas Valley. These strata have not yielded any fossils and are not certainly of middle Tertiary age, but they are shown in plate 1 of this report as Guanajibo; they may be the basal beds of the unit.

CALICHE

In southern Puerto Rico, nearly all areas underlain by limestone are covered by a mantle of chalk and chalky limestone of secondary origin, designated in this report as caliche. Although its age is indeterminate, it is probably Quaternary and may be largely Holocene. This limestone mimics some of the chalk in the upper part of the Juana Díaz, but it can usually be distinguished by its massive nature, by its lack of fossils of any kind (except in occasional included blocks of bedrock limestone), and by characteristic banding. The thickness commonly is about 1 m, but in some places, a thickness of more than 2 m has been seen. In the Punta Verraco quadrangle, the top of a low rounded ridge 2.5 km east by south of Central San Francisco has been scraped off to provide fill for a causeway across a swamp. Brown pebbles of unknown age are scattered over the scraped surface. The pebbles resemble those seen in the lower part of the Juana Díaz Formation, but all outcrops at lower altitudes nearby are of Ponce Limestone, so I assume that the pebbles are the remains of a terrace deposit laid down on a wave-cut surface of Ponce Limestone. They might, however, belong to the Juana Díaz in an upthrown fault block. Near the middle of the borrow pit, a pillar (fig. 49) of the material removed elsewhere still remains (113,780 E., 15,820 N., Punta Verraco quadrangle). At the top of the pillar is a bed of compact chalky limestone banded in white and light brown, 27 cm thick, which is underlain by 1.5 m of indurated rubbly chalky limestone and soft-banded chalk containing a few pieces of hard limestone that resembles Ponce Limestone; this unit rests on 2 m of soft rubbly chalk.

A thin section of the top bed in this pillar shows that the rock consists of very ferruginous micrite, which has calcite spar filling the cavities. The section contains scattered small quartz grains and one

FIGURE 49.—Column of caliche remaining in center of borrow pit 2.5 km east by south of Central San Francisco. The upper beds described in the text are shown in the photograph (November 1970).

fragment of sparite that contains the cross section of a foraminifer. A chemical analysis of the same bed is given in table 8.

TABLE 8.—*Chemical analysis of caliche*

[Analyzed by rapid method (Shapiro, 1975); analyst, Lowell Artis]

Lab. No.	W175014
Field No.	PV142[1]
SiO_2	1.1
Al_2O_3	.50
Fe_2O_3	.43
FeO	.04
MgO	.35
CaO	53.0
Na_2O	.03
K_2O	.00
H_2O-	.28
H_2O+	.72
TiO_2	.00
P_2O_5	.00
MnO	.06
CO_2	42.0
Total	99
Acid unsoluble	2.5

[1] Indurated layer at top of chalk in pillar near center of quarry near west end of Punta Verraco, 2.6 km east of Central San Francisco (113,780 E., 15,820 N., Punta Verraco quadrangle).

Similar material has been seen throughout the area underlain by both Juana Díaz and Ponce limestones, and it appears in the float that has slumped downhill from areas underlain by much harder limestone of Cretaceous age. The caliche creates problems for the field geologist, for in the belt of middle Tertiary rocks it so conceals the bedrock that the nature of the underlying limestone can be determined only in deep excavations as in quarries or roadcuts. Near its base, the caliche may contain abundant solution cobbles of the underlying limestone.

A characteristic outcrop of caliche at the side of a road is shown in figure 50. Here, 30 cm of compact chalky limestone banded with brown chalk rests on 40 cm of compact white chalk. The chalk continues on the surface down the hill to the west.

The origin of the caliche is related to the arid climate of southern Puerto Rico. A caliche probably forms when slight solution of the limestone during the infrequent rains forms an aqueous solution of calcium bicarbonate. The rains are followed almost immediately by sunshine that evaporates the water, resulting in reprecipitation of the calcium carbonate. Bicarbonate-bearing water still in the rock will be drawn to the surface by capillary attraction, thus making the precipitate somewhat thicker. Over a period of centuries, this process could produce the thick capping of soft chalk, and the action of current rainfall would produce the cap of indurated limestone at the surface just as in northern Puerto Rico (Monroe, 1966a). The areas covered by caliche in the Ponce-Guánica area are not shown separately on plate 1, for nearly all areas underlain by limestone are covered by the caliche.

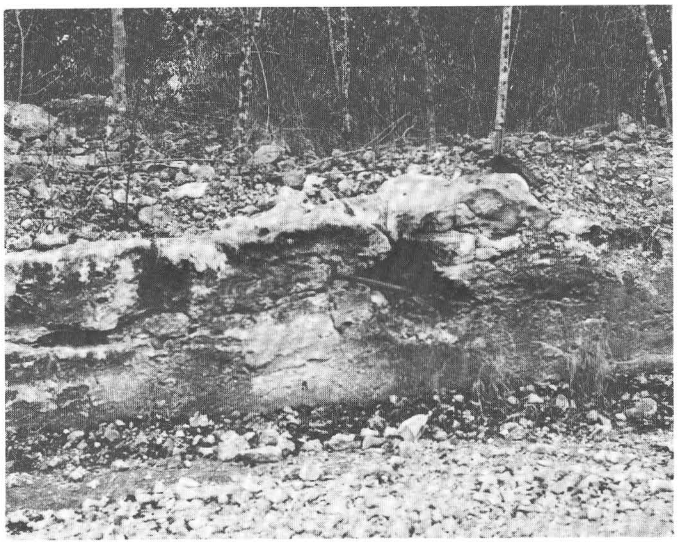

FIGURE 50.—Roadcut in caliche on north side of Highway 334 (104,490 E., 14,450 N., Guánica quadrangle), 2.4 km east of Guánica. The commonly indurated bed is at the top of the cut, and it rests on crumbly chalk (April 1970).

STRUCTURAL GEOLOGY

The areas of outcrop of the middle Tertiary rocks in Puerto Rico are less structurally deformed than is the central mountainous core of the island, but study of the structure and stratigraphy of the middle Tertiary rocks yields information on the dating of some of the structural features in the older rocks. Structural features that aid in interpreting the Tertiary geologic history of Puerto Rico include unconformities, folds, faults, and joints; certain of the stratigraphic features, such as sand and gravel lenses in middle Tertiary rocks, yield clues as to the ages of orogenic movements. Epeirogenic movements also took place, but they may have resulted only in the raising of the entire island from the sea. Most movements that can be recognized are apparently orogenic, and even those movements that seem to have resulted merely in raising and lowering the island may be in a broad scale orogenic, related to plate movements and to the foundering of the Puerto Rico Trench.

The inclination of the middle Tertiary rocks in northern Puerto Rico is commonly about 5°–8° N.

near the outcrop of the older rocks of the basement, and only 1°, more or less, near the coast. This is probably the result of repeated tilting northward during deposition of the strata.

In southern Puerto Rico, the attitudes are much more irregular and much steeper, ranging from a few degrees to as much as 30°. The direction of dip is generally south, but it is much influenced by the faulting commonly present in that area. Studies of the unfaulted rocks of the Ponce Limestone west of La Parguera may show the regional tlting that has taken place in southern Puerto Rico.

UNCONFORMITIES

The strata of Oligocene and younger age contain many unconformities. The most profound is the one that separates the basement of Cretaceous to Eocene rocks from the overlying rocks of Oligocene age. The older rocks had been folded, faulted, uplifted, and eroded into a rugged landscape before the strata of northern Puerto Rico and the Juana Díaz Formation of southern Puerto Rico were deposited upon them. Presumably, the unconformity represents an erosion period that extended from approximately middle Eocene to early or middle Oligocene time.

The onlap of the sea that deposited the Juana Díaz and the San Sebastián, especially the part of the San Sebastián that is now deeply buried, probably coincided with an early part of the foundering of the Puerto Rico Trench about 100 km north of Puerto Rico. The contrast between structural trends in the Cretaceous to Eocene strata and those of the middle Oligocene strata has been pointed out earlier, and a probable date for inception of the trench has been suggested as late Eocene or early Oligocene (Monroe, 1968d). Sporadic foundering of the trench throughout Tertiary time may have been offset by arching of the landmass that is now Puerto Rico and eventually by raising of the island to heights greater than the present height of the mountains.

Renewed uplift of central Puerto Rico, probably arching of the axis of the island, is recorded in the change in lithology from the limestone of the Lares to the marls and clays of the Cibao Formation and by many small intraformational unconformities, such as the gently angular unconformities in the Lares, in the Río Indio, and in the limestone in the Juana Díaz east of Guánica Bay to which Kaye (1957, pl. 2) referred. None of these unconformities have been traceable very far, so they are probably, at most, of local significance.

In northern Puerto Rico, the intraformational unconformity of most consequence is that at the base of the Miranda Sand Member of the Cibao Formation, which records a sudden upward movement in the highlands south of the marine deposits represented by the Lares Limestone and the lower part of the Cibao Formation. This upward movement probably was an arching upward of the entire landmass, which was accompanied by a downward movement north of present-day Puerto Rico and a corresponding downward movement south of the landmass. However, correlations of rocks from northern Puerto Rico to southern Puerto Rico are still so imprecise that which part of the Juana Díaz Formation is contemporaneous with the upper Cibao is uncertain. The movement was great enough, however, to accelerate erosion in the upland and to increase the gradient of rivers sufficiently to carry jasper and other siliceous rocks from the central highlands northward to the coast.

In northern Puerto Rico, there is a probable diastem at the top of the Aguada Limestone. As discussed in the section on lithologic character of the Aguada, the top is composed of shallow-water calcarenite deposited in a high-energy environment as indicated by the cross lamination. Also, at some places, the shallowness of the water is indicated by desiccation cracks in the top of the formation. In contrast, the Aymamón Limestone was deposited in a much quieter regime, probably in slightly deeper water. The contrast between the two formations indicates some tectonic movement, during which the Aguada surface was lowered when the Aymamón sea swept over the terrane. There is no evidence whatever for a hiatus of any magnitude at this horizon, however.

At the top of the Aymamón Limestone is an erosional unconformity and a strong change in character of deposition. Almost certainly, this unconformity represents a time when strong uplift took place in the axial region of central Puerto Rico, so that the sea completely drained off the old Aymamón surface. The change in sedimentation from nearly pure calcium carbonate in the Aymamón to ferruginous limestone and chalk containing abundant quartz sand in the Camuy indicates an uplift in the highlands and erosion of the Utuado batholith and perhaps other quartz-bearing intrusive rocks. The thin bedding in the lower part of the Camuy contrasts sharply with the massive limestone of the upper Aymamón and indicates a change in energy relationship from quiet water to moving water. Undoubtedly, this unconformity is the most important within the middle Tertiary rocks of northern Puerto Rico. Still greater is the unconformity that is still in process of forming and that has been forming sporadically since withdrawal of the Camuy sea in late Miocene or perhaps Pliocene time.

In southern Puerto Rico, an apparent unconformity, certainly erosional and perhaps representing some tilting, separates the upper clastic unit of the Juana Díaz Formation from the underlying limestone and chalk. The base of this unit of the Juana Díaz has been recognized at so few places, however, that the nature of the unconformity is not clearly understood. Moussa and Seiglie (1970) stated that two foraminiferal zones present in Trinidad are missing at the base of this clastic unit, so the hiatus between the chalky limestone ("Angola limestone") and the sand may be large. Certainly in the quarries of the Puerto Rico Cement Company, the sand was deposited in an erosional channel by very actively flowing water, a regime quite different from that of relatively quiet water during which the chalky limestone was deposited.

The most profound unconformity within the middle Tertiary sequence in southern Puerto Rico, however, is at the base of the Ponce Limestone. The Ponce overlaps various parts of the Juana Díaz Formation between Juana Díaz and Guánica, truncating the entire upper, or Miocene, part of the formation; west of Ensenada, the Ponce overlaps the entire Juana Díaz and rests directly on rocks of Cretaceous age. The time interval represented by this unconformity is undoubtedly a fairly long one, but there is little paleontological evidence for the duration of the hiatus. Bermúdez and Seiglie (1970) and Moussa and Seiglie (1970) stated that the rocks at the top of the Juana Díaz are early Miocene, but estimates of the age of the Ponce range from middle Miocene to Pliocene. The time interval representd is probably at least a third of Miocene time. The unconformity between the Juana Díaz Formation and the Ponce Limestone may be coeval with the one between the Aymamón Limestone and the Camuy Formation.

Future studies may be able to tie the stratigraphic breaks in northern Puerto Rico more closely to those in southern Puerto Rico, with the help of such a correlation, a sequence of periods of uplift or arching and of quiescence for the entire Oligocene-Miocene period of time may possibly be worked out.

FOLDS

Folding is not as conspicuous as faulting in the structure of the middle Tertiary rocks of Puerto Rico, but Tertiary folding may be important in the mountainous parts of Puerto Rico—certainly with respect to the arching that is so evident from the unconformities and the clastic deposits within the rocks of middle Tertiary age.

In northern Puerto Rico, several folds are shown by structure contours on the published maps of quadrangles. The westernmost fold is a syncline south of Aguadilla. In the eastern part of the Aguadilla quadrangle (Monroe, 1969c), a sharp anticline plunges gently toward the north-northwest; this anticline was mapped by Zapp, Bergquist, and Thomas (1948). It does not seem to be related to structural features in the older rocks farther southeast (McIntyre, 1971) in the Central La Plata quadrangle, but it undoubtedly affects the underlying older rocks, which must be fairly close to the surface near Aguadilla.

Another fold was discovered in the Moca quadrangle when stratigraphy was being checked for the present report. This fold is not reflected by the structure contours on the published detailed map (Monroe, 1969b) but it has been shown by the revised outcrop pattern on plate 1. The feature is characterized by a flattening of the strata followed by a sharp dip toward the north along Highway 112. The fold is obscure, and it could be merely the draping of strata over a buried hill in the basement rocks. One would expect a thicker sequence of the compressible San Sebastián Formation on the sides than on the top of such a hill, and when the overlying strata began to compress the San Sebastián, there would be greater depression of the overlying strata on all sides of the hill than on the crest.

Somewhat similar is a small arch in the Aymamón-Camuy contact east of Isabela, shown on the geologic map of the Quebradillas quadrangle (Monroe, 1967). Just east of that structure is a large broad anticline, mostly east of the Río Guajataca that is north of a steep-sided syncline trending east through Quebradillas (Monroe, (1967). The syncline has such steep dips on the south flank that faulting may be present, but no fault displacement was found.

In the southeastern part of the Barceloneta quadrangle, Briggs (1965) observed a small plunging anticline affecting the Aguada Limestone just west of the Río Grande de Manatí. The maximum displacement of structure contours on this anticline is only about 20 m. Still farther east, Monroe (1962, 1971) observed a small plunging anticline in the southeastern part of the Manatí quadrangle affecting several members of the Cibao Formation.

The broad valley at Vega Alta is apparently the geomorphic expression of a small dome or structural terrace affecting the Aguada and Aymamón limestones. The anticline plunges north-northwest parellel to a syncline just to the west, heading up the valley of the Río Cibuco. East of Vega Alta, the rocks dip north in a rather featureless monocline as far as the San Juan area, where a broad gentle arch raises the basement rocks and the Mucarabones Sand to a level where one would expect Aguada Limestone, or possibly Aymamón.

Geophysical surveys show some of the folds described above. An aeromagnetic map prepared by Aero Service, Ltd., for Mr. A. D. Fraser and published by Briggs (1961) shows a strong magnetic high north of Aguadilla that may be related to the north-northwest-plunging anticline. The map shows another magnetic high over the dome just east of Isabela but contains no expression of the anticline and syncline just to the east near Quebradillas. Another large positive magnetic anomaly centers just south of the dome at Vega Alta. These anomalies suggest that the structural features worked out by surface geology are probably reflections of structure that includes the basement. The aeromagnetic map shows two other positive anomalies for which no surface structure has yet been detected. One of these is in the southwestern part of the Arecibo quadrangle about 7½ km south of Arecibo; the other is in the center of the Barceloneta quadrangle. The aeromagnetic map extends southward only about as far as the contact of the Aguada and Aymamón limestones.

Southern Puerto Rico is so cut by faulting that it is impractical to portray the structure with contour lines, but judging by the bedding attitudes, folding is not especially prominent. There is a general uniformity of attitudes within a given fault block. Commonly, the dip is south, and the strike is within 10° E.

Two notable exceptions shown by Zapp, Bergquist, and Thomas (1948) are a large anticline trending west-northwest from Juana Díaz and another probable anticline of unknown trend south of Peñuelas. The axis of the Juana Díaz anticline crosses the Río Jacaguas about 700 m west-southwest of the bridge of Highway 14 over the river and thence trends west-northwest to the village of Jacaguas where it bends to the west to pass near the southeastern edge of Lago Ponceño. North of the anticlinal axis, all dips are north to a zone within about 100 m of the large boundary fault where there is a sharp reversal of dip to 45° S. probably resulting from drag along the fault. It is surprising that when the dip is so continuous to the north the basement is not brought to the surface near the crest of the anticline because the strata exposed on the crest of the anticline must be about 350 m lower stratigraphically than those exposed at the side of the boundary fault farther north. As much of the intervening area is covered by alluvium, however, subsidiary anticlines or faults may be present that produce some duplication of section. South of the axis of the anticline, the dips are generally south and range from 15°–35°.

Only the northern flank of the anticline at Peñuelas is easily seen. In the cliff face on the west side of the Río Tallaboa the limestone has an apparent northerly dip of about 15°. Unfortunately, outcrops are not common on the crest of the ridge or at many places on the eastern and western slopes. The attitudes that could be measured are highly variable; beds trend in all directions and range in dip from 5°–25°. This lack of consistency is probably due to faulting, but so little bedrock is exposed that the relations are not clear. Possibly the anticline does not exist, and the north-dipping rocks are in a tilted fault block that constitutes the northern kilometer of the ridge between Río Tallaboa and Quebrada de los Cedros.

FAULTS

Large faults are common in southern Puerto Rico, but only a few small faults have been observed in northern Puerto Rico. The contrast in structure is notable. Berkey (1915) called attention to a large boundary fault in southern Puerto Rico separating his Arecibo Formation from the older rocks, and Mitchell (1922) showed a continuous fault between his Ponce formation and the older rocks. The existence of the latter fault was denied by Lobeck (1922), who explained the apparent faulting as a solution phenomenon. Thomas (Zapp and others, 1948) recognized a fault in the valley of the Río Tallaboa south of Peñuelas and another near Guánica. Kaye (1957) recognized a boundary fault north of Cerro del Muerto, about 6 km north of Santa Isabel, and several faults cutting Isla Caja de Muertos, about 13 km southeast of Playa de Ponce. The fault north of Cerro del Muerto, although it probably exists, is not shown on plate 1, as it does not appear on the map of the Río Descalabrado quadrangle by Glover and Mattson (Glover, 1971), which was the source used in preparing that part of plate 1. The faults on Isla Caja de Muertos have been modified from Kaye's results by later mapping by Lynn Glover III, M. H. Pease, Jr., and Ted Arnow (written commun., 1961), but they are essentially as shown by Kaye. Glover and Mattson (Glover, 1971) in their geologic map of the Río Descalabrado quadrangle showed the large fault north of Juana Díaz, which forms the northern boundary of the Juana Díaz Formation for about 7 km. The vertical displacement along this fault is not known but is probably on the order of several hundred meters.

From the Río Portugués westward and southwestward, the north edge of the rocks of middle Tertiary age is almost continuously a fault contact in which Juana Díaz, commonly fossiliferous, is in juxtaposition with much more indurated rocks of Cretaceous to Eocene age.

The presence of pebbles and cobbles in the Juana Díaz exposed in the river valleys, and the absence of gravel along the fault where it crosses the adjacent hills, as in outcrops between the Río Canas and Quebrada Limón, suggests that the Juana Díaz in the river valleys is near the base of the formation. This gives a minimum vertical displacement of the fault in that area of about 180 m; the actual displacement may be very much greater. A boundary fault is well exposed in a valley that flows east into Quebrada Limón (125,980 E., 24,340 N., Peñuelas quadrangle). At this locality, calcareous fossiliferous fine-grained sandstone and soft sandy limestone, both of which contain abundant *Lepidocyclina undosa*, are faulted against tuffaceous mudstone, which continues up the hill to the north to outcrops of tightly cemented limestone of Cretaceous age. The crest of the hills to the north is more than 100 m above the Juana Díaz sandstone in the valley, and no Juana Díaz was seen on the crest. The vertical displacement of this fault is, therefore, more than 100 m, for the basal Juana Díaz is not exposed nearby. The same fault is crossed by Highway 132 (124,780 E., 24,170 N.), about 3 km east of Peñuelas. At this point, the fault is represented by several meters of gouge with bedded siltstone to the north and calcareous sandstone and sandy limestone to the south.

The fault pattern at the northern boundary of the Juana Díaz is somewhat complex near Peñuelas where the common east-trending faults are cut by prominent north-trending faults. The pattern in the eastern part of the Yauco quadrangle, north of Guayanilla, is fairly regular; several subsidiary faults diverge from the main fault. The fault pattern at Yauco is complex and very well exposed, especially the triangular block of Juana Díaz, which has been dropped into the Cretaceous volcanic rocks at the western edge of the business district. From Yauco southwest, the contact makes a zigzag pattern in which the Juana Díaz is interrupted by fault blocks of Cretaceous limestone and Eocene tuffaceous rocks.

The fault extending from Bahía de Guánica to Bahía Montalva is plainly visible at many places; in the east, it separates sand and gravel of the Juana Díaz from the older rocks, and farther west, it forms the northern boundary of the Ponce Limestone. Cutting the boundary faults at many places are north-trending faults, commonly covered by the alluvium of rivers that have followed the fault zones to the south. Perhaps the most interesting fault complex in southern Puerto Rico is reflected by the intricate pattern west of Central San Francisco in the Punta Verraco quadrangle, in which Cretaceous rocks have been faulted up against the Ponce Limestone, as originally pointed out by Grossman (1963). The Cretaceous rocks include tuffaceous beds and serpentinite, which are faulted against both clastic and limestone members of the Juana Díaz and against Ponce Limestone under the alluvium of the Río Yauco. The total displacement of the fault in the bottom of the Río Yauco is not known, but it must amount to more than 300 m.

The area north of Central San Francisco, known as Montes de Barina, is not well understood. A zigzag fault is shown crossing the area between the Juana Díaz and the Ponce, but the only evidence for the fault is poor exposures on a trail at the west end above the valley of the Río Yauco. The fault (pl. 1) follows valleys that show a pronounced lineation, but nearly all the valleys traversing the Montes de Barina run in straight lines and meet other valleys with noticeable angularity. Most of these valleys may follow faults, or they may merely follow joints. However they are certainly structurally controlled. The true contact between the Juana Díaz and the Ponce in the area may be sedimentary, or it may be a fault, as shown.

The valleys of most of the streams in the part of the coastal area of Puerto Rico between Juana Díaz and Guánica seem to be structurally controlled, and judging from the abundant faulting evident in the upland, the valleys probably follow faults.

In contrast to southern Puerto Rico, faulting is relatively rare in northern Puerto Rico. A small fault zone has been mapped near the northwestern corner of the island (Monroe, 1969c), on the southwestern flank of the anticline east of Aguadilla. The zone contains four small faults, all raised on the west, but none of the faults has a displacement greater than 30 m. Briggs (1965) mapped a small fault, upthrown on the east, about 8 km south of Barceloneta; the maximum displacement on this fault is less than 15 m. Another small fault of only about 15 m displacement and upthrown on the north raises Lares against Cibao 4.4 km north of Morovis (Berryhill, 1965). The only other observed faults in northern Puerto Rico are small ones near Bayamón and San Juan described by Kaye (1957). An outcrop 1.4 km north of Canovanas shows Cibao Formation in juxtaposition with volcanic sandstone of the Cretaceous Frailes Formation.

In northern Puerto Rico, the only possibly large fault has been postulated by Briggs (1961, p. 11) along the southern border of the swamp known as Ciénaga Tiburones, but Briggs admits that the evidence for the existence of the fault can be explained easily in other ways without invoking faulting. Geophysical surveys and a small amount of core drilling to evaluate a possible site for an atomic reactor farther east near Laguna Tortuguero, showed no evidence of the displacement that would be expected if the supposed fault extended to that area.

JOINTS

Search for joints in quarry faces, roadcuts, and streambanks in the middle Tertiary deposits of both northern and southern Puerto Rico has been unsuccessful except for cracks related to present-day oversteepening of slopes and incipient landslides. This is surprising because many of the landforms, especially in northern Puerto Rico, can be best explained by jointing. Zanjones are long parallel trenches (Monroe, 1964b) that trend for long distances with little change in orientation. In some places they trend generally north-northeast, elsewhere west-northwest, and in other places due west. They seem to be joints that have been enlarged by solution and by spalling off of the sides, but nearby roadcuts do not show prominent joints. The east-trending valleys of the tributaries of the Río Camuy 4–6 km south of Hatillo seem the result of enlargement of joints, but traverses along the bottom of the valley of the river in this area did not reveal jointing in the cliff faces. The parallelism of mogotes in the Barceloneta and Manatí quadrangles seems almost certainly to have a structural cause, for the Mogotes do not represent ancient coral reefs, as has been suggested by various workers in the past, and the Aymamón Limestone of which they are composed does not seem to be subject to differential erosion that might produce that form.

J. N. Rinker, U.S. Army Corps of Engineers Topographic Laboratories, Fort Belvoir, Va., made an analysis from aerial photographs of the lineations of topographic features in the area between the Río Guajataca and the Río Arecibo (unpub. data, 1976). In his observations, he found that the larger sinks are present at the places where several lineations cross.

In southern Puerto Rico most alinement of valleys seems related to faulting, but the many alined streams, especially in Montes de Barina between Yauco and Central San Francisco, may be the surface expression of joint patterns. However, until a systematic study is made of the joint patterns in the middle Tertiary strata, little can be said about the nature and significance of jointing. The best study thus far made was by Kaye (1957, p. 112–113), who called attention to the topographic alinements in northern Puerto Rico.

ECONOMIC GEOLOGY

Details of the economic geology for specific areas, such as locations of quarries and pits, have been shown on detailed geologic maps of the various quadrangles and will not be repeated in this summary statement. The principal economic resources of the middle Tertiary rocks are limestone, dolomite, and semiconsolidated material used for landfill.

LIMESTONE AND DOLOMITE

Most of the quarries opened in limestone of the middle Tertiary rocks produce crushed rock used as concrete aggregate and in some places as "marble" in the manufacture of terrazzo. Quarries of this kind are especially common along Highway 2 west of Bayamon and between Vega Baja and Manatí. Some quarries in less consolidated material, such as those about 7.5 km east-southeast of Arecibo, produce material used mainly as fill.

Quarries that produce limestone used in the manufacture of portland cement have been opened in the Aguada Limestone at the west edge of San Juan, 2.5 km south of Cataño, and south of Highway 2, about 4 km east-southeast of Vega Alta. Much larger quarries west of Ponce produce limestone for cement from the upper limestone unit of the Juana Díaz Formation and from the Ponce Limestone. Some of the Ponce Limestone, unfortunately, contains more than 3 percent magnesium oxide, the upper limit tolerable in the manufacture of portland cement (see analyses of samples PV7 and PV141, table 7). At most of the cement plants in Puerto Rico, volcanic rocks from various quarries are added to the limestone to supply the necessary silica and alumina.

Limestone for agricultural use is produced from quarries in the Lares Limestone, 2.8 km north-northwest of Ciales (Berryhill, 1965, p. 107) and 3 km southwest of Florida (Nelson and Monroe, 1966, p. C20).

Dolomite of unknown thickness is found at many places near the coast in the upper part of the Aymamón Limestone and near Quebradillas in the lower part of the Camuy Formation. Much of this dolomite has as much as 18 percent MgO and could be used in refractories. The area in which it is most common is in the northern part of the Quebradillas quadrangle (Vázquez and others 1957; Monroe, 1967). So far as is known, no core holes have been drilled in the dolomite to determine its thickness, and it may be only a thin coating on a body of calcitic limestone.

OIL AND GAS POSSIBILITIES

The sequence of 1,200–1,850 m (4,000–6,000 ft) of sedimentary rocks in northern and southern Puerto Rico makes both belts of interest in prospecting for oil and natural gas (Monroe, 1973b). Through 1970, only four wells had been drilled to test the strata for petroleum—three in southern Puerto Rico and one in northern Puerto Rico, all four wells were drilled by Kewanee Interamerican Oil Company. None of the four holes had any shows of petroleum, but all showed some permeability in the limestone, and all four were drilled into rock saturated with salt water.

The stratigraphic section that might produce oil or gas is believed to be thicker in northern Puerto Rico, but no test holes have been drilled in southern Puerto Rico between Ponce and the mouth of the Río Tallaboa where the section may be much thicker than it is farther east where Kewanee drilled its test holes. Several favorable places to drill test holes in northern Puerto Rico are described in the section of this report discussing folding and summarized in a shorter report (Monroe, 1973b). These places are: the dome between Quebradillas and Isabela, the anticline north of Quebradillas, and the structural terrace or anticline just west of Vega Alta. Before drilling deep test holes in these localities, it would be well to do more concentrated geophysical work and perhaps some shallow core drilling to select the most favorable site for a deep test well. Other places in northern Puerto Rico that might prove favorable for oil, if they can be located accurately, are the northern slopes of buried hills of volcanic rock, like the exhumed hills near Dos Bocas dam. At such places, beds of Lares Limestone and San Sebastián Formation may butt against impermeable volcanic rock, and any petroleum present that tended to migrate updip toward the buried hill would reach a natural trap similar to an anticline or dome. Such buried hills will be difficult to find, but they might be detected by gravimetric or seismic-reflection surveys.

In southern Puerto Rico, the abundant faults can be considered encouraging for prospecting for petroleum, especially faults that are downthrown on the updip side, as is the large fault trending west from the Río Canas Valley west of Ponce (pl. 1). The most favorable area for prospecting seems to be the area near the Caribbean coast between Ponce and the Bahía de Guayanilla. The projected dips of the outcropping formations indicate that this area has the thickest sequence of rocks of middle Tertiary age in southern Puerto Rico, and the many recognized faults promise structural traps for any petroleum that may be present. Much of this area is difficult to traverse, however, so the geology shown on plate 1 is only approximately correct. Therefore, much additional work should be done in the area before any test holes are drilled. Probably a detailed gravimetric survey should be supplemented with seismic-reflection surveys. Any holes that are drilled should penetrate the volcanic section for at least several hundred feet in order for the test to be adequate.

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