Some Tropical Landforms of Puerto Rico

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1159

Some Tropical Landforms of Puerto Rico

By WATSON H. MONROE

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Landforms on a tropical island in the belt of the easterly tradewinds

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1980

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

Library of Congress Catalog-card No. 80-600071

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

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CONVERSION FACTORS

Metric unit		Inch-Pound equivalent
Length		
millimeter (mm)	= 0.03937	inch (in)
meter (m)	= 3.28	feet (ft)
kilometer (km)	= .62	mile (mi)
Area		
square meter (m^2)	= 10.76	square feet (ft^2)
square kilometer (km^2)	= .386	square mile (mi^2)
hectare (ha)	= 2.47	acres
Volume		
cubic centimeter (cm^3)	= 0.061	cubic inch (in^3)
liter (L)	= 61.03	cubic inches
cubic meter (m^3)	= 35.31	cubic feet (ft^3)
cubic meter	= .00081	acre-foot (acre-ft)
cubic hectometer (hm^3)	= 810.7	acre-feet
liter	= 2.113	pints (pt)
liter	= 1.06	quarts (qt)
liter	= .26	gallon (gal)
cubic meter	= .00026	million gallons (Mgal or 10^6 gal)
cubic meter	= 6.290	barrels (bbl) (1 bbl=42 gal)
Weight		
gram (g)	= 0.035	ounce, avoirdupois (oz avdp)
gram	= .0022	pound, avoirdupois (lb avdp)
metric tons (t)	= 1.102	tons, short (2,000 lb)
metric tons	= 0.9842	ton, long (2,240 lb)
Specific combinations		
kilogram per square centimeter (kg/cm^2)	= 0.96	atmosphere (atm)
kilogram per square centimeter	= .98	bar (0.9869 atm)
cubic meter per second (m^3/s)	= 35.3	cubic feet per second (ft^3/s)
Specific combinations—Continued		
liter per second (L/s)	= .0353	cubic foot per second
cubic meter per second per square kilometer [(m^3/s)/km^2]	= 91.47	cubic feet per second per square mile [(ft^3/s)/mi^2]
meter per day (m/d)	= 3.28	feet per day (hydraulic conductivity) (ft/d)
meter per kilometer (m/km)	= 5.28	feet per mile (ft/mi)
kilometer per hour (km/h)	= .9113	foot per second (ft/s)
meter per second (m/s)	= 3.28	feet per second
meter squared per day (m^2/d)	= 10.764	feet squared per day (ft^2/d) (transmissivity)
cubic meter per second (m^3/s)	= 22.826	million gallons per day (Mgal/d)
cubic meter per minute (m^3/min)	= 264.2	gallons per minute (gal/min)
liter per second (L/s)	= 15.85	gallons per minute
liter per second per meter [(L/s)/m]	= 4.83	gallons per minute per foot [(gal/min)/ft]
kilometer per hour (km/h)	= .62	mile per hour (mi/h)
meter per second (m/s)	= 2.237	miles per hour
gram per cubic centimeter (g/cm^3)	= 62.43	pounds per cubic foot (lb/ft^3)
gram per square centimeter (g/cm^2)	= 2.048	pounds per square foot (lb/ft^2)
gram per square centimeter	= .0142	pound per square inch (lb/in^2)
Temperature		
degree Celsius (°C)	= 1.8	degrees Fahrenheit (°F)
degrees Celsius (temperature)	= [(1.8×°C)+32]	degrees Fahrenheit

SOME TROPICAL LANDFORMS OF PUERTO RICO

By WATSON H. MONROE

ABSTRACT

Puerto Rico is in the northeastern corner of the Caribbean Sea. The island is roughly rectangular, about 175 km long from east to west and about 60 km wide from north to south; the total land area is slightly less than 8,500 km². Altitudes range from sea level to a maximum of 1,338 m at Cerro de Punta on the Cordillera Central.

A large variety of landforms in diverse geographic provinces make the island of Puerto Rico an especially interesting area for the study of geomorphology. The landforms are characteristic of tropical areas in the trade-wind belts where high mountains cause convectional rain, which result in an extremely varied rainfall. In Puerto Rico, yearly rainfall averages from about 760 mm in areas of "rain shadow" to a maximum of slightly more than 4,000 mm in a rain forest near the northeastern corner of the island. Rock types in Puerto Rico include such diverse kinds as lava, tuff, intrusive rocks, metavolcanic rocks, limestone, and unconsolidated sand and clay; such diversity is reflected in many contrasting kinds of topography within small areas. In common with other tropical areas, many features resulting from torrential rainfall are found in Puerto Rico; many similar features are found in temperate zones, but only in arid and glaciated areas.

The rivers of Puerto Rico have had a long, active history, which can be deciphered from sediments in rocks of middle Tertiary age. Many rivers have been beheaded by more actively growing streams, and several record long periods of flow on nearly level surfaces followed by downcutting during which meanders have been entrenched more than 200 m.

The island can be divided into three principal physiographic areas of greatly contrasting topography: (1) coastal lowlands, (2) a belt of karst features in northern Puerto Rico, and (3) an upland, which is exceedingly varied in physiographic features because of complex geologic structure, variations in lithology, and a long and complicated history of erosion.

INTRODUCTION

Puerto Rico is the easternmost island of the Greater Antilles and stands near the northeastern corner of the Caribbean Sea (fig. 1). It has roughly a rectangular shape – about 175 km east-west and 60 km north-south – and an area of 8,497 km². In its political territory are several smaller islands, including Isla de Vieques and Isla de Culebra to the east, Isla Desecheo and Isla Mona to the west, and Isla Caja de Muertos to the south. Puerto Rico and its offshore islands all lie in the area between lat 17°37' and 18°31' N., and long 65°14' and 67°56' W. Puerto Rico lies about 160 km south of the Puerto Rico Trench, which reaches depths of about 8,365 m – the deepest known part of the Atlantic Ocean. The main island is bounded on the east by the Vieques Passage (Pasaje de Vieques) and on the west by the Mona Passage (Canal de la Mona).

Puerto Rico has a great variety of landforms, particularly those related to a tropical climate, because it is a high island subject to rapid erosion, its climate varies from warm humid to semiarid, and it has a variety of rock types that have different erosional characteristics.

Most of the island is mountainous (pl. 1). The Cordillera Central, from 15 to 25 km from the south coast, extends from the west coast eastward for about 100 km; farther east, the Sierra de Cayey continues east-southeast to the southeast corner of the island. The Sierra de Luquillo is an east-trending range in the northeastern part of the island. Several other less prominent mountain ranges are described in a later part of this report. This mountainous terrain is the Upland province.

In north-central and northwestern Puerto Rico, dissolution of limestone has resulted in a belt of karst topography 15-23 km wide and about 135 km long – the Northern Karst province.

Near the sea, lowlands form a discontinuous Coastal Plains province, consisting of coalescing flood plains, alluvial fans, and a variety of beach and lagoonal deposits.

PREVIOUS INVESTIGATIONS

The first scientific study of the physical geography of Puerto Rico was made by R. T. Hill (1899a, b, c) and was based on a visit he made at about the time of the Spanish American War. Hill's observations were very general, but he called attention to the principal mountain ranges of Puerto Rico; to the "pepino hills," called now the Northern Karst province; to "playa plains," here described as coastal plains; and to several features, such as the "parting valley," by which he meant valleys between coastal hills and the central mountains, such as the Lajas Valley in southwestern Puerto Rico. Hill also described in very general terms the geology, soils, mineral resources, and forest conditions of Puerto Rico.

In 1913 the Council of the New York Academy of Sciences (Britton, 1919) proposed that the Academy

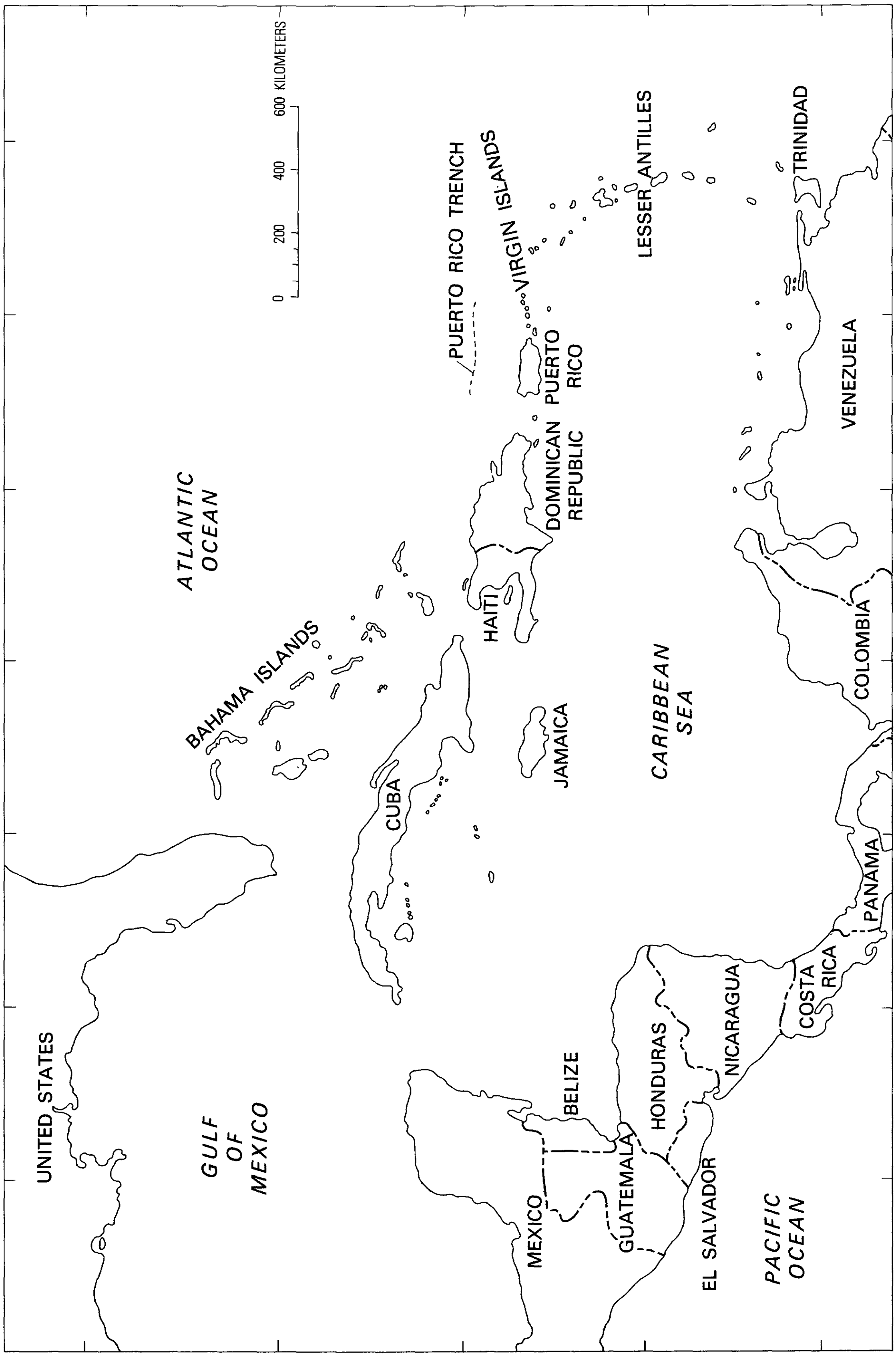

FIGURE 1.—Map showing location of Puerto Rico in the Caribbean region.

sponsor a scientific survey, which would include the geology, paleontology, botany, zoology, and anthropology of Puerto Rico. Geological and geographical investigations began in August and September 1914 with a reconnaissance by C. P. Berkey (1915) and C. N. Fenner. More detailed studies followed, including a comprehensive survey of the physiography by Lobeck (1922). Local, more detailed studies of the physiography were made by Hubbard (1923) and Meyerhoff (1927). The geological and geographical investigations of the island made by the New York Academy were summarized by Meyerhoff (1933) in a general account of the geology of Puerto Rico. Meyerhoff (1938) also made major contributions to the description of the karst topography comparing it with that of Cuba.

The most comprehensive studies yet made on the geography of Puerto Rico were by Picó (1950; Picó and others, 1954), who recognized 11 topographic regions in Puerto Rico. With the collaboration of Zayda Buitrago de Santiago and Héctor Berríos, he (Picó and others, 1969) later prepared a comprehensive study of the physical, economic, and human geography of Puerto Rico, which is now considered the most authoritative reference. An English translation (Picó, 1974) was published in 1974.

The karst areas of Puerto Rico have been studied intensively by many geographers and geologists. Lehmann (1954) and Gerstenhauer (1964) made intensive studies of the areas of cone karst. Blume (1968, 1970) described in detail the cuestas and cuesta scarps made by the Lares and Aguada Limestones and related the shape of the scarp to the karst features. Moussa (1969) discussed stream capture of a small drainage system in southern Puerto Rico by headward development of a cave system. The course of the Río Tanamá through the karst area of northern Puerto Rico was explored for the first time during an expedition led by Gurnee (1972). A comprehensive report by Monroe on the karst landforms of Puerto Rico was published in 1976.

The beaches of Puerto Rico were studied by Guillou and Glass (1957), and such special features of the coast as beaches, beachrock, dunes, and stillsands of the sea were described by Kaye (1959b).

CLIMATE

Puerto Rico has a warm, generally pleasant climate dominated by the easterly trade winds and by rainfall generally scattered throughout the year but characterized by sudden showers.

The trade winds (fig. 2) not only provide a nearly constant breeze that makes high temperatures comfortable,

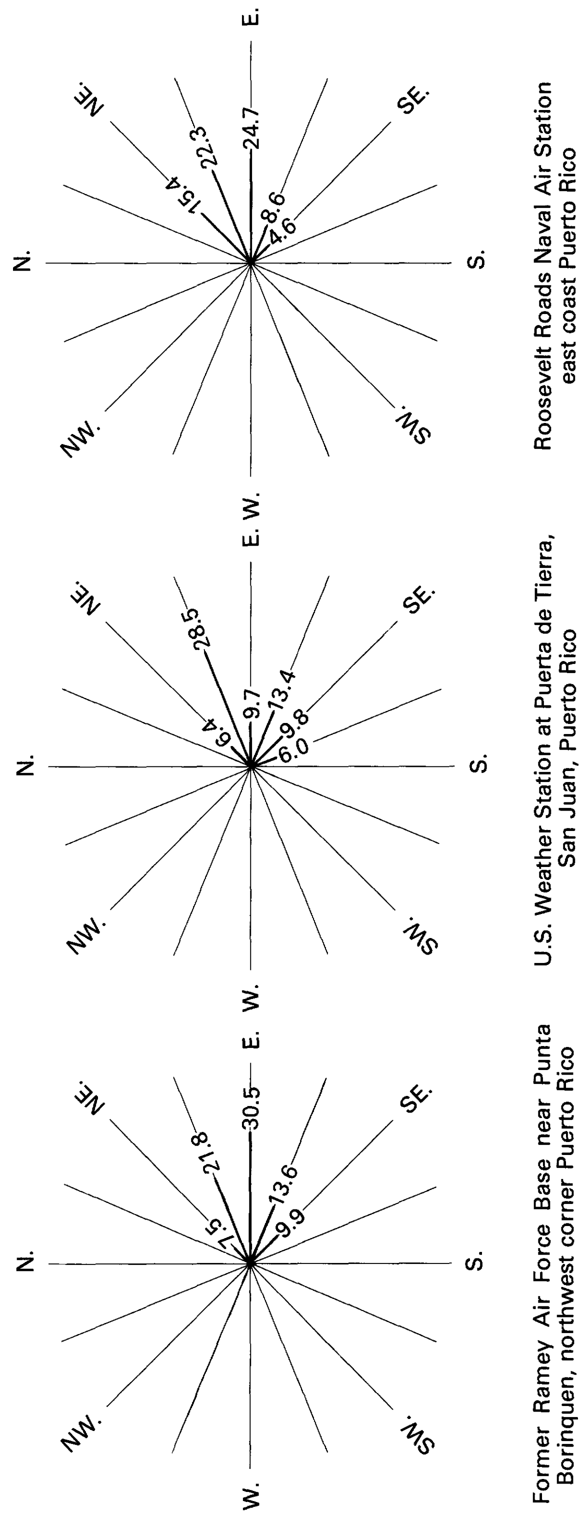

FIGURE 2.—Wind directions at three coastal stations in Puerto Rico. Prepared from data published by U.S. National Weather Service. Numbers indicate mean annual percentages of wind in a certain direction; percentages of less than three percent are not shown.

but the constant direction has had a noticeable effect on the topography, particularly of the limestone hills near the northern coast. At San Juan the wind direction from the easterly quarter continues for more than two-thirds of the year. At the military airfields at Roosevelt Roads (the U.S. Naval Base on the northwest shore of Radas Roosevelt) on the eastern coast and the area previously known as Ramey Air Force Base (inactive) in the northwestern corner of the island near Punta Agajereada, this dominance from the easterly quarter is even more marked and continues for more than three-fourths of the year. Normally the winds are not very strong. Less than 1 percent of the time, they exceed 38 km/h, and less than 5 percent of the time, they exceed 24 km/h (Calvesbert, 1970). These velocities are greatly exceeded, of course, on the rare occasions when hurricanes pass over Puerto Rico. At such times the wind velocity may exceed 250 km/h.

The temperature range at San Juan is commonly less than 10° C. The mean maximum is 30° C, and the mean minimum is 21° C. In the higher mountains, the range is somewhat greater. At Guineo Dam, 8 km east of Cerro de Punta on the Cordillera Central (pl. 1), the mean maximum is about 25° C and the mean minimum about 13° C. The highest temperature ever recorded in Puerto Rico was at Patillas near the southeastern coast, where a high of 40° C was measured once. The lowest recorded temperature was 6° C at Aibonito in south-central Puerto Rico at the east end of the Cordillera Central. When the trade winds are occasionally diverted to the south or north, even moderately high temperatures are very unpleasant.

Rainfall in Puerto Rico is fairly well distributed throughout the year, though in general about twice as much rain falls per month from May through October as does from January through March (Calvesbert, 1970). The winds and the high mountains of central Puerto Rico combine to produce an orographic distribution of rainfall as shown in figure 3. The greatest annual rainfall of 4,000 mm is in the Sierra de Luquillo, where the moisture-laden winds from the Atlantic Ocean are forced upward and rapidly cooled and precipitation results. An area of similarly great but less intense precipitation is along the Cordillera Central. Even the higher hills near the southern edge of the Northern Karst province between Lares and San Sebastián have a narrow belt of precipitation greater than that to the north and south. The areas in the lee of all these ranges of hills are in rain shadows that are most marked in the southwestern part of the island, where some stations record less than 800 mm of rainfall a year.

The relative humidity in the San Juan area averages about 80 percent throughout much of the year, and the average annual dewpoint is about 21° C. The rate of evaporation is very high. In San Juan, the long-term average annual rate of evaporation is 2,072 mm, where-

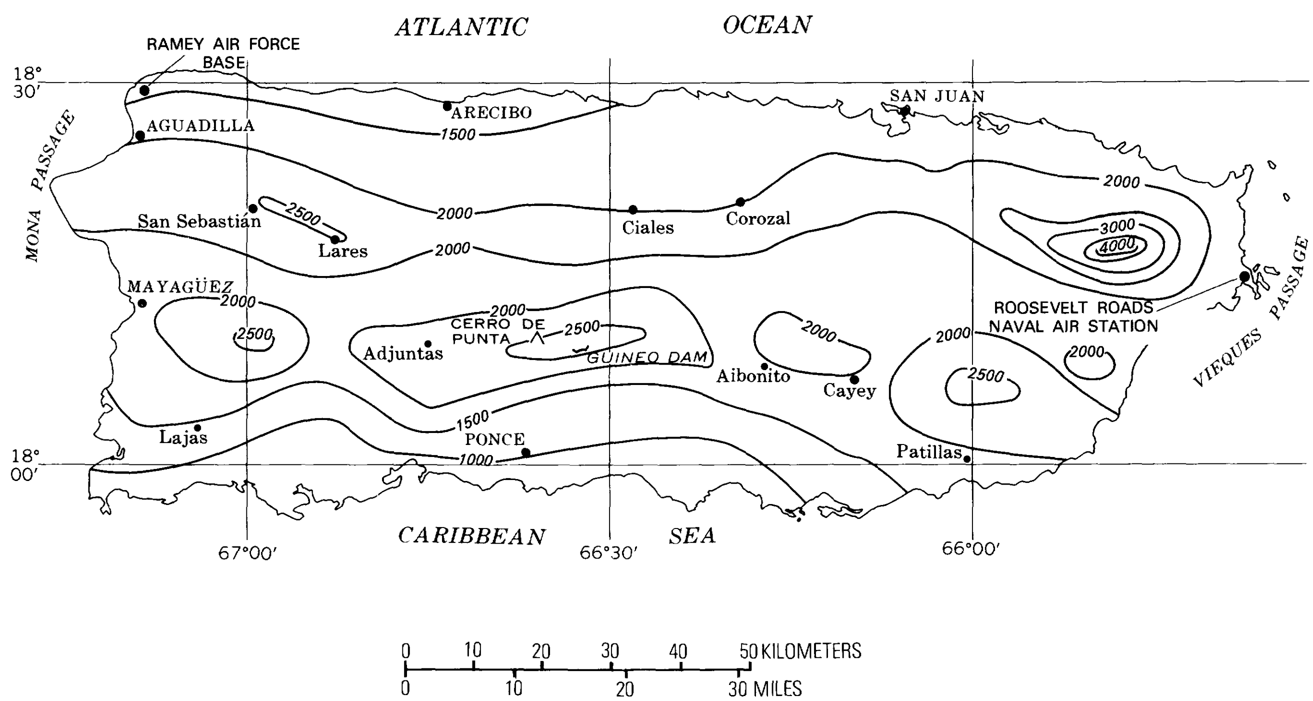

FIGURE 3.–Annual rainfall in Puerto Rico, contoured in millimeters. Data from U.S. National Weather Service.

as the annual precipitation is only 1,631 mm. Rates of evaporation have been recorded at only a few places but are considerable everywhere, even in the mountains where rainfall is plentiful. At Adjuntas near the Cordillera Central, where the rainfall is 2,146 mm, the rate of evaporation is 1,294 mm a year.

In southwestern Puerto Rico in the lee of the Cordillera Central, the combination of high temperature, constant wind direction, and large evaporation rate has produced a distinct rain shadow. At several stations the rainfall is less than 800 mm, and the rate of evaporation at the agricultural experiment station at Lajas is more than 2,000 mm. This part of Puerto Rico has a semiarid, or steppe, climate.

Most rainfall in Puerto Rico is in the form of sudden showers that have sharp boundaries, so that the path of the rain is plainly marked. The showers tend to be torrential but generally last only between 15 and 30 minutes. The National Weather Service (Calvesbert, 1970) reported that nearly half of their 40 weather stations show that from 30 to 50 days a year have more than 12.7 mm of rain. As long-lasting rainstorms are relatively uncommon in Puerto Rico, except during hurricanes, these figures indicate that showers amounting to 2–10 mm are relatively common. Such torrential rainstorms have caused rapid downcutting of valleys and an asymmetric shape of hills of limestone. They are also responsible for the formation of several landforms more generally associated with arid climates, such as broad alluvial fans, which are common especially in southern Puerto Rico, and bajadas, or coalesced alluvial fans, which extend along the north side of the Río Gurabo on the south flank of the Sierra de Luquillo (Broedel, 1961).

Puerto Rico is in the belt where hurricanes can be expected every year, but owing to its long east-west shape, most of these tropical storms pass north or south of the island. Only four hurricanes have passed over Puerto Rico since 1900 (Calvesbert, 1970), but several others have been close enough to cause considerable damage. The principal effect has been extremely heavy rainfall – at times as much as 400 mm in a day – accompanied by strong wind. The National Weather Service predicts that winds of 175 km/h can be expected at least once a century. The heavy rainfall accompanying the hurricanes causes extensive erosion and flooding and may be responsible in large part for the very steep sided valleys in the island.

GEOLOGY OF PUERTO RICO

Puerto Rico consists of a central east-west axis of predominantly volcanic rocks, flanked on the north and south sides (Briggs and Akers, 1965; Beinroth, 1969; Cox and Briggs, 1973) by younger sedimentary rocks (fig. 4). Near the coast on all sides of the island are discontinuous coastal plains of alluvium. The different kinds of rocks have their own weathering and erosion characteristics, which result in distinctive landforms.

The igneous core of Puerto Rico consists predominantly of Lower Cretaceous to middle Eocene volcanic rocks. The Lower Cretaceous rocks are exposed mostly near the center of the island near Orocovis, Barranquitas, and Cidra and in belts that extend south from Cidra through Cayey to Guayama and eastward north of Caguas. These rocks are mainly submarine volcanic-ash deposits interspersed with lava flows. Near the top of the Lower Cretaceous sequence, the volcanic rocks are interlayered with a few discontinuous beds of reefoid limestone.

The Lower Cretaceous rocks are overlain by Upper Cretaceous interbedded volcanic and sedimentary rocks that include sandstone and conglomerate, derived from volcanic rocks, and limestone deposited as reefs around volcanic islands. The Cretaceous rocks are intruded by a number of masses of plutonic rock, generally of granodiorite to diorite composition, that were emplaced in very Late Cretaceous or early Tertiary time. The largest masses of intrusive rock are the San Lorenzo batholith, which is near San Lorenzo, Las Piedras, Humacao, Yabucoa, and Maunabo, and the Utuado batholith, which crops out in a wide belt between Jayuya and Lares. Smaller instrusive bodies are present at many places in the island, including areas on the south side of Sierra de Luquillo, near Morovis, and at Ciales. In western Puerto Rico several bodies of serpentinite are present in linear belts transecting Cretaceous rocks.

The Cretaceous rocks are overlain by Paleocene to middle Eocene rocks consisting of tuff and sedimentary rocks, including conglomerate that contains fragments of granodiorite eroded from the intrusive rocks. Most of these rocks are present on the northern and southern flanks of the central core, but some are also present in a faulted belt that extends west-northwest across west-central Puerto Rico.

The Cretaceous and lower Tertiary rocks have been folded and intensely faulted into hundreds of fault blocks (Cox and Briggs, 1973).

The folded and faulted Cretaceous and lower Tertiary rocks are overlain unconformably in both northern and southern Puerto Rico by conglomerate, sand, and clay of Oligocene age, derived from soils that had formed on igneous rocks over a period of millions of years and later were reworked by the sea. The contact between the older rocks and the overlying sediments is irregular and has a moderate relief of a few hundred meters. The Oligocene sediment is overlain by limestone of Oligocene and Miocene age that in northern Puerto Rico is more than 1,400 m thick and in southern Puerto Rico is more than 1,000 m thick.

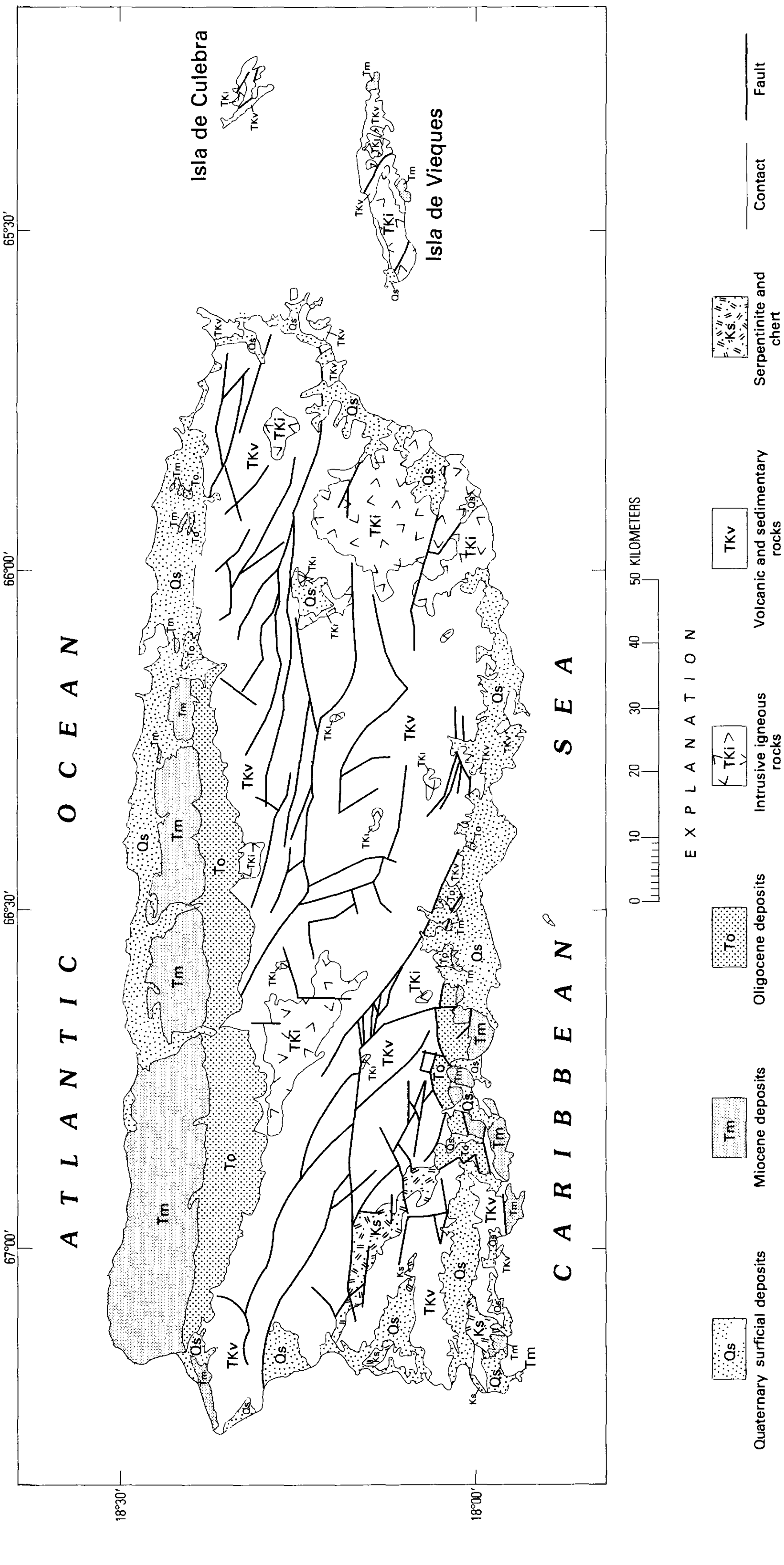

FIGURE 4.—Generalized map of the geology of Puerto Rico.

Variations in the lithology of the Oligocene and Miocene formations provide keys to the Tertiary geomorphic history of central Puerto Rico. Hence more detailed stratigraphic information is presented than for the older Cretaceous and lower Tertiary rocks. Table 1 describes the lithology of the recognized stratigraphic units, and figure 5 shows the same information in graphic form.

TABLE 1.—*Strata of middle Tertiary age in northern Puerto Rico*

Age	Unit and description	Thickness (meters)
Miocene	Camuy Formation: sandstone, limestone, and sandy, ferruginous chalk.	0–170
	Unconformity.	
	Aymamón Limestone; very pure chalk indurated on surface to hard limestone; slightly ferruginous chalk in upper part, northwestern Puerto Rico.	190
	Aguada Limestone; hard stratified limestone grading downward into chalk; locally sandy.	70–110
	Cibao Formation:	
	Upper member; chalk and soft limestone	10–80
	Guajataca Member; (in western area only) fossiliferous calcareous clay and limestone containing lenses of sand and gravel as much as 15 m thick.	
	Miranda Sand Member; (in eastern area only) sand and gravel, sand and sandy clay.	0–15
Miocene to Oligocene.	Montebello Limestone Member; (in center area only) friable pure calcarenite, indurated on exposure to an erosion-resistant limestone.	0–210
	Quebrada Arenas Limestone Member; (in eastern area only) finely crystalline stratified limestone.	10–60
Oligocene	Río Indio Limestone Member; (in eastern area only) compact, chalky yellowish-orange weakly bedded limestone.	0–90
	Typical chalk or marl; (in eastern and western areas) sandy and silty clayey chalk.	0–250
	Lares Limestone; thin to thick-bedded fairly pure limestone, lower part locally contains grains of quartz and limonite sand, intertongues to west with sand and gravel, mapped with San Sebastián Formation.	0–280
	San Sebastián Formation; mostly thin-bedded sand and clay, some sandy limestone, locally, especially in west, sand and gravel.	0–155
	Unconformity (angular).	
Eocene to Cretaceous.	Volcanic, sedimentary, and intrusive rocks.	

Lenses of sand and gravel in the generally calcareous lower Miocene part of the Cibao Formation in northern Puerto Rico record ancient rivers that carried sediment from central Puerto Rico into the sea (Monroe, 1966a). Slightly later in early Miocene time the island apparently had been eroded almost to base level, for the Aymamón Limestone is nearly pure calcium carbonate containing as impurities only a few percent of quartz silt and red clay. This suggests that the streams of the

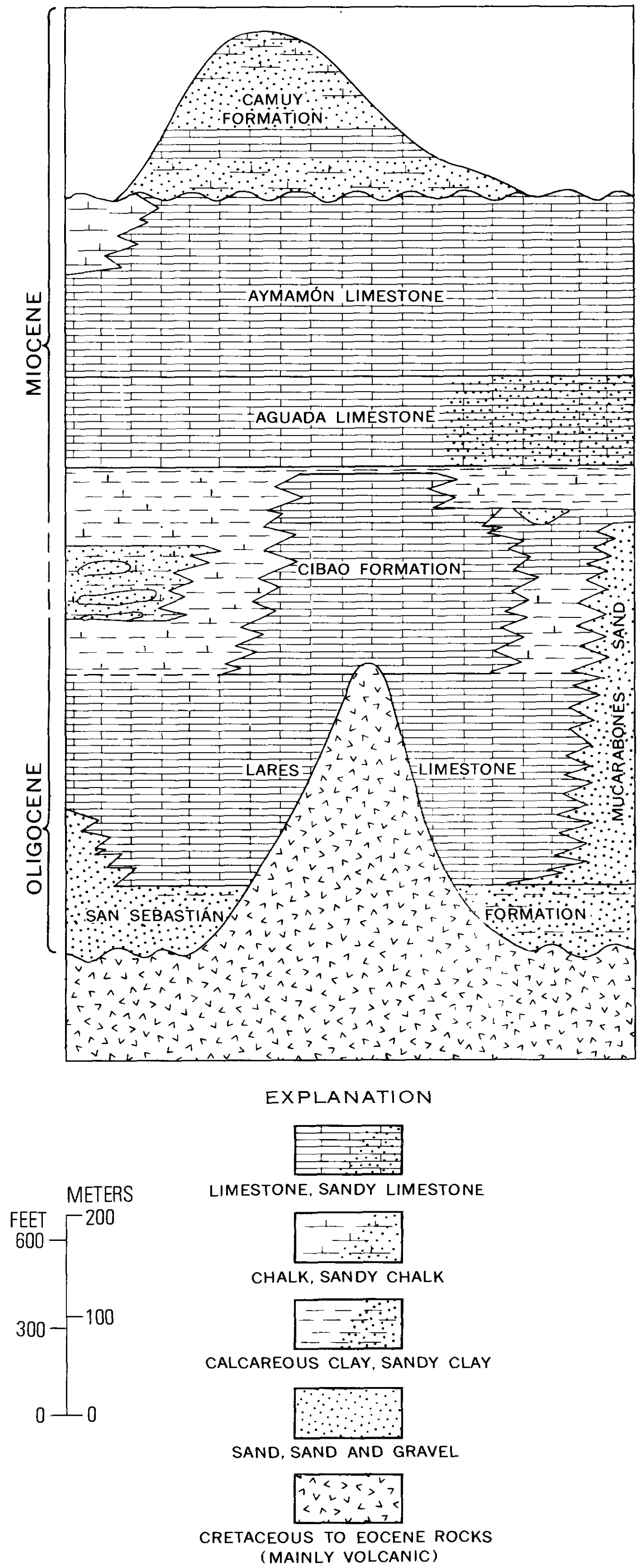

FIGURE 5.—Columnar section of middle Tertiary age rocks in northern Puerto Rico.

island, whose mouths and courses can be inferred from the sediments in the Cibao Formation and from ancient river courses still present on the upland in central Puerto Rico, were carrying practically no sediment into the sea during Aymamón time. The fossils in the Aymamón, however, are all relatively shallow water species of corals, gastropods, and pelecypods. The younger Miocene rocks of the Camuy Foundation above the Aymamón Limestone consist of a heterogeneous sequence of ferruginous limestone, chalk, and sandstone, which indicate renewed erosion of the uplands.

Resting uncomfortably on the Cretaceous and Tertiary rocks are many kinds of alluvial and beach deposits, probably mostly of Quaternary age. These rocks include sandy clay, sand, sandstone, and gravel. Most were deposited in flood plains and coastal plains of rivers, but a few were deposited along the strand. Some are dune sands blown into place by the wind.

THE PHYSIOGRAPHIC DIVISIONS OF PUERTO RICO

Puerto Rico can be divided into three major physiographic provinces or divisions (pl. 1): an Upland province, a Northern Karst province, and a Coastal Plains province. These provinces have distinctive characteristics both in relief and in landforms. The Upland province shows primarily the effects of erosion on a structurally complex sequence of many kinds of igneous and sedimentary rock. The Northern Karst province shows the effects of the solution of limestone. The Coastal Plains province is an area predominantly of deposition. Each of the provinces can be divided into smaller units of local significance.

As most of the rivers of Puerto Rico flow through more than one of these provinces, they are described in some detail before the individual landforms of the provinces are discussed.

RIVERS OF PUERTO RICO

Most of Puerto Rico is well drained by surface streams, except in the Northern Karst province, where most of the local drainage is underground. All the larger rivers are north of the Cordillera Central and drain into the Atlantic Ocean. A few long rivers flow west and drain into the Mona Passage (Canal de La Mona). On the south side of the Cordillera Central, several short rivers have steep profiles, dropping from 800 m, or more, down to sea level. Profiles of the longest river in Puerto Rico, the Río de La Plata, and of one of these short, steep, southward-flowing rivers, the Río Jacaguas, are plotted on plate 1 to show how different they are. Several more short rivers drain east into the Sonda de Vieques, the Pasaje de Vieques, and the Caribbean Sea.

The larger rivers, from east to west, that enter the Atlantic Ocean on the north coast are discussed in the following sections.

RÍO GRANDE DE LOÍZA

The easternmost large river in Puerto Rico is the Río Grande de Loiza, which has the largest drainage basin of any river system on the island, about 800 km^2. The river drains much of the area of the San Lorenzo batholith (see pl. 1) and the Caguas Valley. It then flows north in a deep gorge to a northern coastal plain, where it flows into the Atlantic Ocean at Loíza Aldea. The river has had a complex Cenozoic history, when it lost several headwater tributaries by stream piracy. The very wide valley some 4 km south of San Lorenzo and the absence of eastern tributaries, south of the junction with the Río Cayaguas near San Lorenzo, suggest that the Río Guayanés may have decapitated the southeastern part of the Río Grande de Loíza. This possibility is supported somewhat by very thick terrace deposits on the sides of the upper part of the Río Guayanés valley (Rogers and others, 1979), which in that area is a relatively small stream that has only a small drainage area.

Quebrada Honda, one of the headwaters of the Río Gurabo, a tributary that enters the Río Grande de Loíza at Caguas, has been captured near Las Torres by two short, steep east-flowing streams, as shown in figure 6. These two tributaries formerly flowed into Quebrada Honda, which is one of the headwater streams of Río Gurabo, but one is now the head of Quebrada de Peña Pobre, a tributary of the Río Blanco, and the other is head of Quebrada Mambiche, a tributary of the Río Antón Ruiz.

A large stream flowing southeast to the Río Grande de Loíza was captured by the Río Guaynabo near the village of La Muda, some 15 km south of San Juan, probably during the Pliocene or the Quaternary. Pease (1968a) recorded discontinuous patches of alluvial terrace deposits more than a kilometer wide in the upper part of the Guaynabo drainage basin. At a point 2.7 km due south of La Muda, the Río Guaynabo abruptly changes direction from northeast and east to north, flowing in a much narrower valley. About 1.5 km east of this bend, Pease recorded a wide, thick mass of terrace deposit, apparently an extension of that in the upper Guaynabo Valley but forming a valley far too wide for the relatively small Quebrada Arena and Río Cañas that trend southeast to the valley of the Río Grande de Loíza (Pease, 1968a).

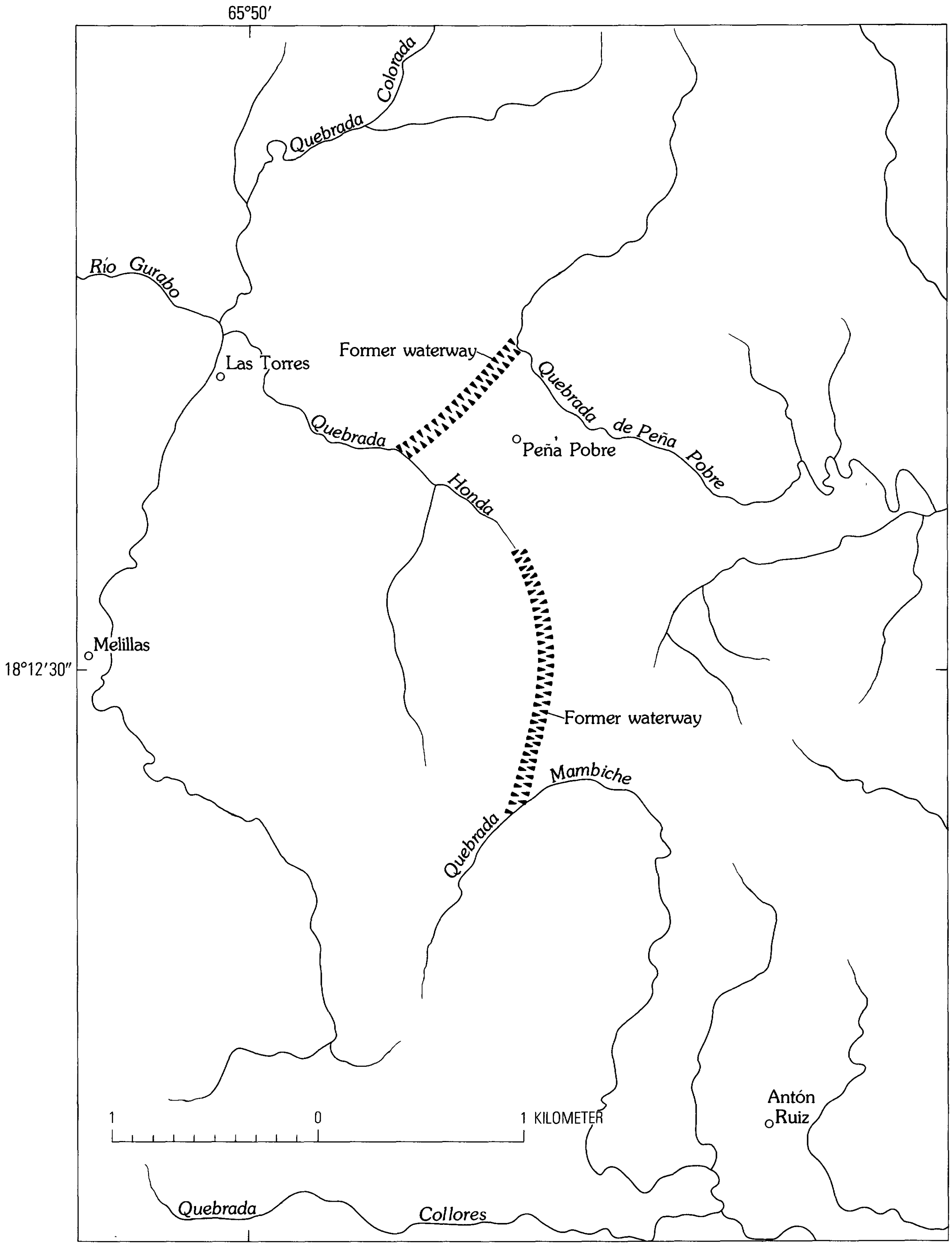

FIGURE 6. – Sketch map showing stream piracy in headwaters of Río Gurabo, 7 km north of Humacao.

North of the Caguas area, the Río Grande de Loíza flows generally northward in a sinuous valley, having its course controlled at least in part by faulting (Pease, 1968a). At the town of Trujillo Alto, the river bends sharply toward the east-northeast for about 5.6 km, still controlled by faults (Seiders, 1971b), and flows mainly over Cretaceous formations subject to rapid weathering and erosion. The river then abruptly turns north toward the town of Carolina and enters the coastal plain. Large quantities of sand and gravel are extracted from the alluvium in this area, which has formed a center of deposition of much of the debris carried north from the crystalline rocks of the San Lorenzo batholith and the Caguas Valley.

During a considerable part of the Pleistocene Epoch, the Río Grande de Loíza flowed north to northwest from Carolina to the Atlantic Ocean and formed a broad deltalike deposit of alluvium. At times, however, the deposition of alluvium was so great that the river was deflected toward the east, and changed its course several times (Monroe, 1977). Abandoned stream beds, now long lakes, show that the river nearly returned to its old course by several routes through a range of hills of Miocene limestone, but each new route was blocked by thick deposits of alluvium, until the deflection toward the east caused the river to reach the eastern end of the range of limestone hills near the town of Loíza (Canóvanas). At that point the river makes an abrupt turn to the northwest against the end of the range of limestone hills and then flows in an almost perfectly straight course 6 km north northeast to the Atlantic Ocean.

This abnormally straight course has been in existence throughout historic time, for it is shown so on the first reasonably accurate Spanish maps made in the 17th century. This straight stretch is lined by low natural levees that slope gently away from the river into coastal swamps. The straight course resembles a dredged canal, but there is no historical record of Europeans excavating such a canal, and it seems most unlikely that the pre-Columbian inhabitants would have had the need or desire or the energy available to make the excavation. This straight reach of the river, of which 4 km has not even a minor bend, may be unique in the world, for Leopold and Wolman (1957 p. 53) stated, "Extremely short segments or reaches of the channel may be straight, but it can be stated as a generalization that reaches which are straight for distances exceeding ten times the channel width are rare." In this part of the Río Grande de Loíza the channel is 70–90 m wide, and the entirely straight reach is about 50 times the width.

The ancient mouths of the river are well marked by the composition of the beach sands. East of the present mouth of the river near Loíza Aldea, the beach and accompanying beach ridges are composed of calcite sand derived largely from seashells crushed and polished by wave action; on the other hand, west of the mouth as far as Punta Vacía Talega the sand is predominantly quartz and contains minor amounts of iron oxide and ferromagnesian minerals derived from the igneous rocks mainly of the San Lorenzo batholith (Monroe, 1977). Between Punta Vacía Talega and Punta Maldonado, farther west, the sand is composed almost entirely of calcite, but still farther west as far as Punta Las Marías the sand is predominantly quartz, deposited when the mouth of the Río Grande de Loíza was near Punta Maldonado.

RÍO BAYAMÓN

West of the Río Grande de Loźa, the next large stream is the Río Bayamón, which flows north from Cidra to the Atlantic Ocean. The river is fairly straight, but it has a few deeply entrenched meanders, and many of its tributaries enter from hanging valleys at places where the erosion of the smaller streams could not keep pace with that of the main stream. One of the larger tributaries, entering the Río Bayamón at grade, is the Río Guaynabo, which, as previously described, apparently has captured some of the headwaters of the Río Grande de Loíza.

The most interesting part of the Río Bayamón is that below (north of) the city of Bayamón, where at some time in the past, the river has built a large delta (Monroe, 1973b), in which the distributaries, now abandoned, remain as sloughs, such as Caño Aguas Frias. The delta was probably built into a lagoon, which is now filled in to form the large swamps north of Sabana Seca. During floods the river still flows into these swamps, although recently dredged drainage canals can carry all flood waters except those of the very largest. The river still has two mouths, one into Ensenada de Boca Vieja and another farther east into Bahía de San Juan. At most times the river follows the longer route into the Bahía de San Juan.

RÍO DE LA PLATA

Still farther west is the mouth of the Río de La Plata, which is the longest river in Puerto Rico. Its drainage basin is 48 km long (Picó, 1974), but the length of the main channel, which follows many meanders, is about 102 km long (pl. 1). The river rises in southeastern Puerto Rico in the Sierra de Cayey; one of its principal tributaries is only 4.6 km north of the Caribbean Sea.

The river has had a long, active history. The headwaters probably originally flowed north through what is now Lago de Cidra into the Río Bayamón and hence directly to the Atlantic Ocean; this may account for the abnormally wide valley north of the city of Bayamón. At some time in the past, probably during the Miocene, the Río de La Plata beheaded the ancient Río Bayamón. Between the possible capture point near Cayey, at a point about 80 km above the mouth, the river flows to Comerío through a series of nearly 20 loops of deeply entrenched meanders, in which the river level is more than 200 m below the general upland level (see pl. 1).

At La Plata (Pease and Briggs, 1960), 4 km east of Aibonito, the river once flowed in a great loop (fig. 7) almost a kilometer west of its present course and around a hill that was formerly east of the river and is now west of it; at this place Quebrada Honda follows the old river channel. Since abandoning this meander loop, the river has cut a new channel 30 m deeper. The level at which the river was flowing when it occupied the now abandoned meander loop is preserved upstream by a series of erosional terraces about 30 m above the present river level.

Similar terraces about 30 m above the present river level are present from 33 to 36 km upstream from the mouth, 4 km due east of Naranjito, and another abandoned meander, floored with terrace deposits, is present on the right bank, 25–30 m above the present river level about 29 km upstream from the mouth, 5 km northeast of Naranjito (Pease, 1968b).

The Río de la Plata north of Highway 2 has had a very active history during the Quaternary. At one stage, when the bed of the river was at an altitude of about 18 m above present sea level (about 16 m above its present channel), the river flowed northwest past the village of Higuillar into a large lagoon south of the ridge on which Dorado now stands. At a later date the river flowed

FIGURE 7.–Alluvium and terrace deposits along an abandoned meander near La Plata. Detail from map of the Comerío Quadrangle from Pease and Briggs (1960). Qa, alluvium; Qt, terrace deposit.

northwest from the present site of Toa Baja and then turned northeast and followed the present channel known as Río Cocal (Monroe, 1963, 1973b), entering the sea just west of Punta Salinas. At the time that the first Spanish colonists settled in Puerto Rico, the river had two mouths, the present one and the mouth of Río Cocal. The town of Toa Baja is built on a natural levee, and in times of high water the river flows over this dike in a sheet that empties north of Sabana Seca into the large swamps, which also receive flood waters of the Río Bayamón. During the flood of September 1960, the river rose to 8 m above sea level, above the altitude of Toa Alta.

RÍO GRANDE DE MANATI

West of the Río de la Plata is the Río Cibuco, which is notable mainly because it and its tributaries were the lower reaches of parts of the Río Grande de Manatí during the Miocene and because of the prominent delta that the river built north of the present Highway 2 (Monroe, 1963) The next large river is the Río Grande de Manatí, which has the second longest drainage basin in Puerto Rico. This river has had a long history that is recorded in the sediments of the Oligocene and Miocene rocks of northern Puerto Rico. The river rises in central Puerto Rico near Barranquitas and then flows north in a deeply incised canyon that is characterized by notable hanging valleys (fig. 8) that are similar to those that are common in glaciated areas but formed in Puerto Rico because the main valley of the river deepened much more rapidly than did the valleys of its smaller tributaries. The river then flows west through a number of deeply entrenched meanders, much like those of the Río de La Plata, to the vicinity of Ciales, and thence north and northwest to the Atlantic Ocean. The course through the Coastal Plains province north of Highway 2 is notable because of the classic development of meanders on the flat plain (Briggs, 1965).

During the early Miocene the upper part of the Río Grande de Manatí flowed north in a flood plain a few hundred meters wide and entered the Atlantic Ocean at a point about 4 km north of the site of the town of Corozal (Monroe, 1963; Nelson, 1967). The flood-plain deposits, known as the Miranda Sand Member of the Cibao Formation, consist of sand and gravel about 10 m thick containing fragments of jasper from rocks that crop out today in the valley of the Río Mavilla and the upper part of the Río Grande de Manatí. The flood plain cannot be recognized south of the outcrop of the lower Miocene part of the Cibao Formation, but the trend of the flood plain suggests that the ancient river coincided more or less with the upper part of the valley of the present Río Mavilla.

Deposits of sand and gravel at the same and lower stratigraphic positions in the Cibao Formation farther west record other ancient rivers (Monroe, 1966a) that entered the Atlantic during the late Oligocene and early Miocene; these correspond to the trends of larger present tributaries of the Río Grande de Manatí, such as the Río Bauta and Río Matrullas, which seem to have been captured by the Río Grande de Manatí during the late Tertiary or early Quaternary.

The Río Cialitos, a tributary from the southwest, appears to be entirely a Pleistocene feature because it cuts across drainage that apparently deposited alluvial material in meandering channels on the middle Tertiary limestone; some of these channels open into alluvium-filled abandoned meanders of the Río Grande de Manatí north of Ciales (Monroe, 1974).

The Río Grande de Manatí has had a number of mouths into the Atlantic Ocean that are recorded in sand and gravel deposits near the present beaches (Briggs, 1965) and in the presence of quartz and magnetite sand in the beach deposits; to both the east and the west, in contrast, the beach deposits are composed almost entirely of calcite sand formed from ground sea shells.

RÍO GRANDE DE ARECIBO

The next large stream west of the Río Grande de Manatí is the Río Grande de Arecibo, whose tributaries rise in the highest part of central Puerto Rico, at the sides of Cerro de Punta, altitude 1,338 m, and in the Utuado pluton. It then flows northward to the Atlantic Ocean through the Northern Karst province in a spectacular gorge 800–1,200 m wide that has nearly vertical walls as much as 200 m high composed mostly of bare limestone. The river flows through the gorge in giant meanders whose reaches are as long as 1.5 km – far exceeding the limits suggested by Leopold and Wolman (1957).

The date of the beginning of the erosion of this valley can be determined almost exactly because all the formations in the middle Tertiary sequence in the area (fig. 5) are nearly pure calcium carbonate deposited in organic reefs in a sea into which no sediment was being carried until the end of deposition of the Aymamón Limestone in the early Miocene. In contrast, the overlying Camuy Foundation contains a high proportion of quartz sand derived from the Utuado pluton; this sand is especially abundant west of the Río Grande de Arecibo. This proves conclusively that no streams were carrying clastic sediment into the sea in this area until Camuy time, when the sea became loaded with sand. Presumably until the end of the Aymamón deposition, the present upper drainage area of the Río Grande de

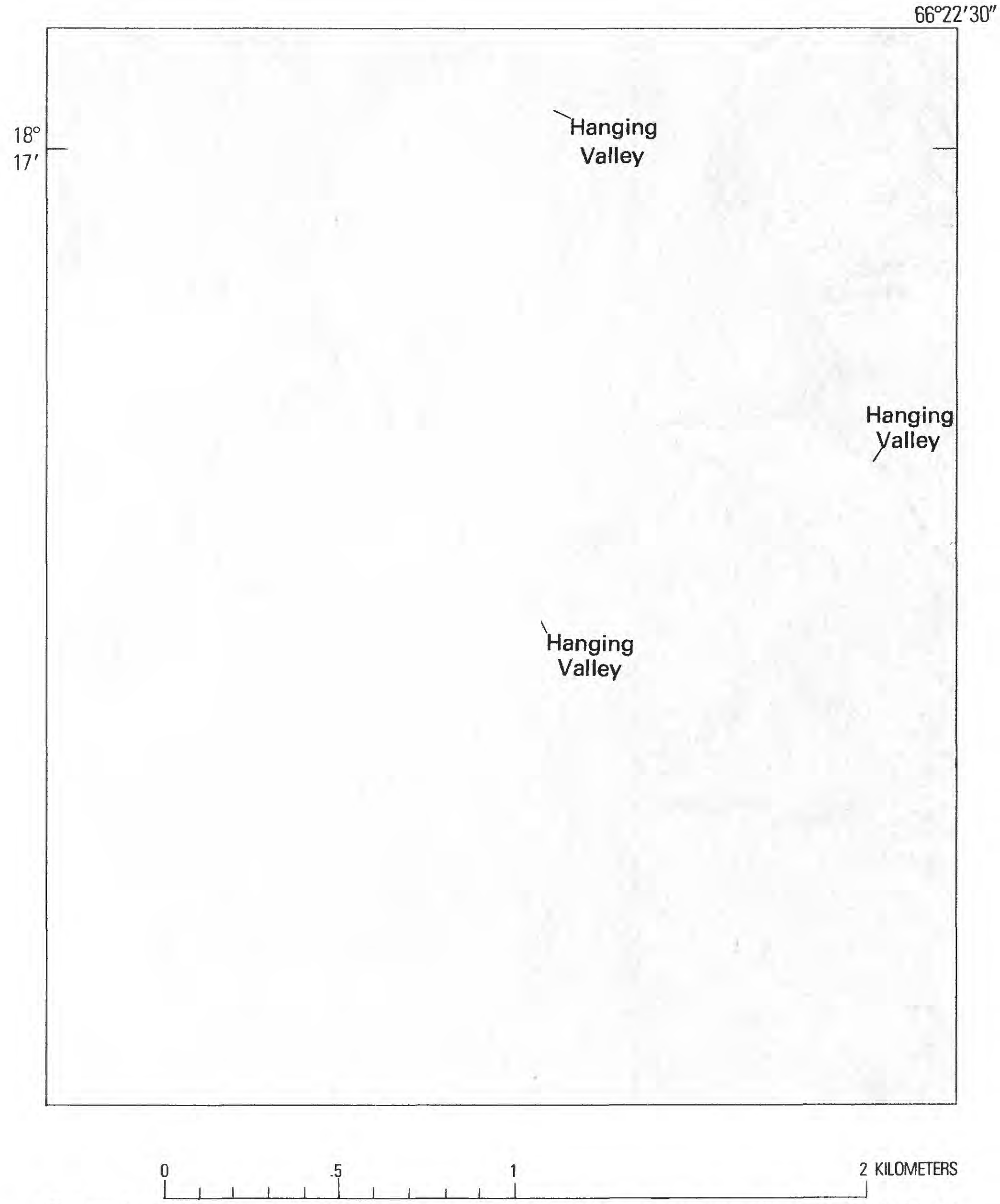

FIGURE 8.—Part of Ciales Quadrangle, Puerto Rico, showing hanging valleys of tributaries to the Río Orocovis, which is a tributary to the Río Grande de Manatí.

Arecibo was drained by streams that flowed mainly northeast and west-northwest and entered the sea possibly at San Sebastián or farther west. In the middle Miocene, however, the Utuado pluton, composed of quartz diorite and granodiorite (Nelson, 1967), began to be eroded by the young Río Grande de Arecibo, and the tremendous flow of quartz-loaded water was able to cut rapidly down through the relatively soft Tertiary limestones.

Various levels of the valley are marked by bedrock terraces cut into the limestone so long ago that typical cone karst has had time to form on them, as pointed out by Lehmann (1954). These areas of karstified terraces are well shown on the geologic maps of the Utuado (Nelson, 1967) and Arecibo (Briggs, 1968) Quadrangles. The highest peak in the southernmost part of the cone karst formed on the bedrock terrace has an altitude of 130 m; peak altitudes of 120 m are common on the eroded terrace 500 m farther north (fig. 9). At that point, the altitude of the present flood plain of the river is about 40 m, so the terrace stood at least 80 m higher than the present river. Another area of karstified terrace is about 1 km farther northwest; here the altitudes of the highest peaks are about 90 m. These figures suggest that the slope downstream of the terrace was about 3 percent, or 30 m/km. About 4.5 km farther north at San Pedro (Briggs, 1968), another area of karstified terrace is characterized by low hills having an altitude of 50–60 m, about the same altitude as the tops of hills on a small outlier in the valley 2 km still farther north. These hills are all about 35 m above the present flood plain, which is nearly flat in that area. If these remnants are from the same terrace, the slope is much gentler downstream, only 0.8 percent, or 8 m/km. The slope of the present flood plain is about 0.4 percent, or 4m/km in the stretch between the higher terrace remnants and those that are lower.

The Río Grande de Arecibo flows out of its canyon in the limestone belt into a wide alluvial plain marked by many former channels of the river. The alluvial fill is at least 70 m deep (Monroe, 1976); the flood plain, less than 10 m above sea level, indicates that sea level was at least 60 m lower in the past, presumably in a low stage of the sea during the Pleistocene.

The mouth of the river is complex. During normal river stages the river flows east behind the beach to a mouth just south of Punta Morrillos, but during flood stages the river enters the sea in a washed-out temporary channel cut through the beach 700 m farther west at the east end of the city of Arecibo. Like several of the larger rivers in northern Puerto Rico, the Río Grande de Arecibo is marked below sea level by a deep submarine canyon cut across the insular shelf.

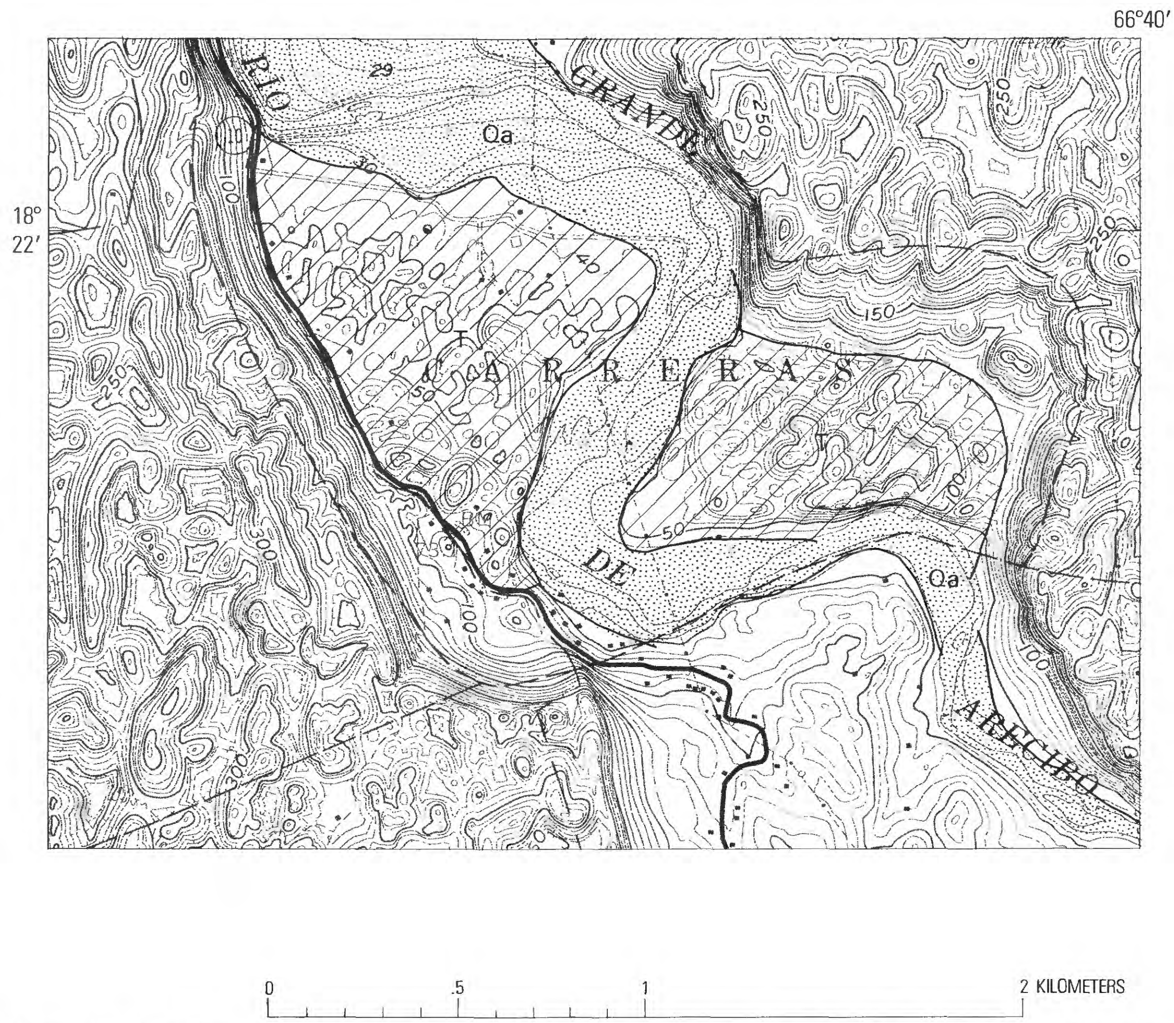

FIGURE 9.–Alluvium (Qa) and karstified terraces (T) cut into limestone at the side of the Río Grande de Arecibo (detail of the Utuado Quadrangle).

RÍO TANAMÁ, RÍO CAMUY, AND RÍO GUAJATACA

The Río Tanamá, the Río Camuy, and the Río Guajataca are three similar streams that rise in the volcanic rocks of the Upland province and then flow across the Northern Karst province to the sea (the Río Tanamá actually is a tributary of the lower part of the Río Grande de Arecibo). All three rivers began in river caves, all three flow over alluvial material composed largely of quartz and pebbles of volcanic rock, and the cave roof has collapsed along most of the routes of all three. The Río Camuy is still an underground river for much of its course through the lower part of the middle Tertiary limestone sequence. The Río Tanamá is mostly subaerial, but throughout its course across the lower part of the limestone terrain it flows through short tunnels and underneath a number of natural bridges (Gurnee, 1972). The Río Guajataca is almost entirely subaerial; its canyon's steep walls and very great depth however are so similar to those along parts of the other two rivers' canyons that it too probably originally flowed in a river cave, whose roof has now collapsed. All three river valleys have notable karst features, which are described by Monroe (1976, pp. 24–26).

WESTWARD-FLOWING RIVERS

Several large rivers flow generally westward to the sea. The largest of these is the Río Grande de Añasco, which rises in central Puerto Rico just west of a low divide separating it from the Río Grande de Arecibo. This river flows through a valley characterized by entrenched meanders and ends in a wide flood plain north of Mayaguëz. The upper tributaries of the Río Grande de Añasco – the Río Blanco and the Río Prieto – probably originally flowed west-northwest along the general course of the Río Culebrinas and constituted the principal drainage of the Utuado pluton and the upper part of the basin of the Río Grande de Arecibo before the latter cut its gorge through the limestone. This hypothesis is strengthened by the great mass of epiclastic deposits that constitute the lower part of the middle Tertiary sequence that farther east is made up of limestone. Several sharp changes in the direction of such tributaries of the Río Grande de Añasco as the Río Prieto and the Río Guaba suggest a history of stream piracy, but the area has not yet been thoroughly studied geographically.

The only other westward-flowing river of much consequence is the Río Guanajibo, which rises in southwestern Puerto Rico and empties into the Canal de La Mona about 6 km southwest of Mayaguëz. The principal feature of interest in this river is the manner in which it has so aggraded its lower valley that flood waters have formed a series of lakes and swamps about 2 km north of the town of Cabo Rojo. Most of the drainage basin of the Río Guanajibo is semiarid; therefore, little cover of vegetation is present, and erosion is great after showers.

STREAMS FLOWING INTO THE CARIBBEAN

The rivers south of the Cordillera Central are all short and fairly direct and drain into the Caribbean Sea. The long profile of the Río Jacaguas, one of the longest of these rivers, which enters the Caribbean about 8 km east of Ponce, is shown below the relief map (pl. 1). Quebrada de los Cedros, 5 km northeast of Guayanilla, has a short underground course through a cave known as El Convento (Beck, 1974). Grossman (1963) pointed out that the Río Yauco, in southwestern Puerto Rico, follows an anomalous course, involving a sharp bend from south to east that is controlled by faulting, furthermore the mouth of the river has been diverted several times by growth of beaches.

EASTERN STREAMS

A few short streams in the eastern part of the island drain east into the Pasaje de Vieques, the Sonda de Vieques, the Caribbean Sea, and the Atlantic Ocean. Some of these short streams appear to have captured headwaters of the Rio Grande de Loiza.

THE UPLAND PROVINCE

The Upland province includes the mountainous areas of Puerto Rico, the foothills to the mountains, and several lowland areas surrounded by mountains. Altitudes of the province range from sea level at the east and west ends of the islands, where the province has been warped down beneath the sea, to 1,338 m (4,390 ft) above sea level at the highest point in the island at Cerro de Punta, north of Ponce. The rocks and sediments exposed in the province include all the Cretaceous and lower Tertiary volcanic and sedimentary rock sequences, the various bodies of intrusive rocks, Oligocene and Miocene sediments in southern Puerto Rico, and large areas of much younger sediments, such as the flood plains of rivers, terrace deposits, and landslide debris.

Although many attempts have been made to divide the province into smaller areas, no systematic organization of these seems valid. Therefore, in the present account, several individual geomorphic features are described, but no attempt is made to classify the features into subdivisions. A general description of the principal mountain ranges and of the principal lowland areas is followed by descriptions of landforms especially well represented in the province.

CORDILLERA CENTRAL

The Cordillera Central–the highest ridge on the island–forms the backbone of Puerto Rico. It is the divide between the Atlantic Ocean and the Caribbean Sea throughout its length. It extends from Aibonito on the east to Maricao on the west; it is about 35 km south of the Atlantic coast and from 15 to 25 km north of the Caribbean coast. East of Aibonito it is succeeded by the Sierra de Cayey that continues east-southeast to the southeast corner of the island. West of Maricao it breaks up into a number of lower ridges that plunge into the sea on the west coast. The rocks of the Cordillera Central are principally volcanic sediments and lava, but near Maricao the ridge is composed of serpentinite. The ridge is very asymmetric, sloping very steeply toward the southern Coastal Plains province and gently toward the north, especially in the area of Barranquitas and Orocovis. Some of the lava has been eroded into steep-sided peaks (fig. 10).

The Cordillera Central is the remnant left by headward erosion of the streams draining into the Caribbean toward the south and those draining into the Atlantic toward the north.

The Sierra de Cayey bends into a U-shape around the headwaters of the Río de La Plata. In this region it is underlain by volcanic rocks, some of which are the oldest in eastern Puerto Rico (Berryhill and others, 1960). Farther east it splits into the Sierra de Guardarraya and the Cuchilla de Panduras, both of which are underlain by granodiorite and quartz diorite. A lower extension of the Sierra de Cayey extends northeastward toward Humacao, where it finally disappears in the lowland of the San Lorenzo batholith.

West of the Río Rosario, the Cordillera Central is represented by Sierra Las Mesas, which is underlain by serpentinite.

SIERRA DE LUQUILLO

The northeastern corner of Puerto Rico is dominated by the Sierra de Luquillo, which extends from Gurabo east to Fajardo. Most of the sierra is a fairly low divide between the Río Gurabo and the streams draining directly into the Atlantic Ocean, but in its central area it has several high peaks of nearly identical altitude, including El Yunque, 1,065 m, and El Toro, 1,074 m. The sierra is strongly asymmetric, sloping very steeply

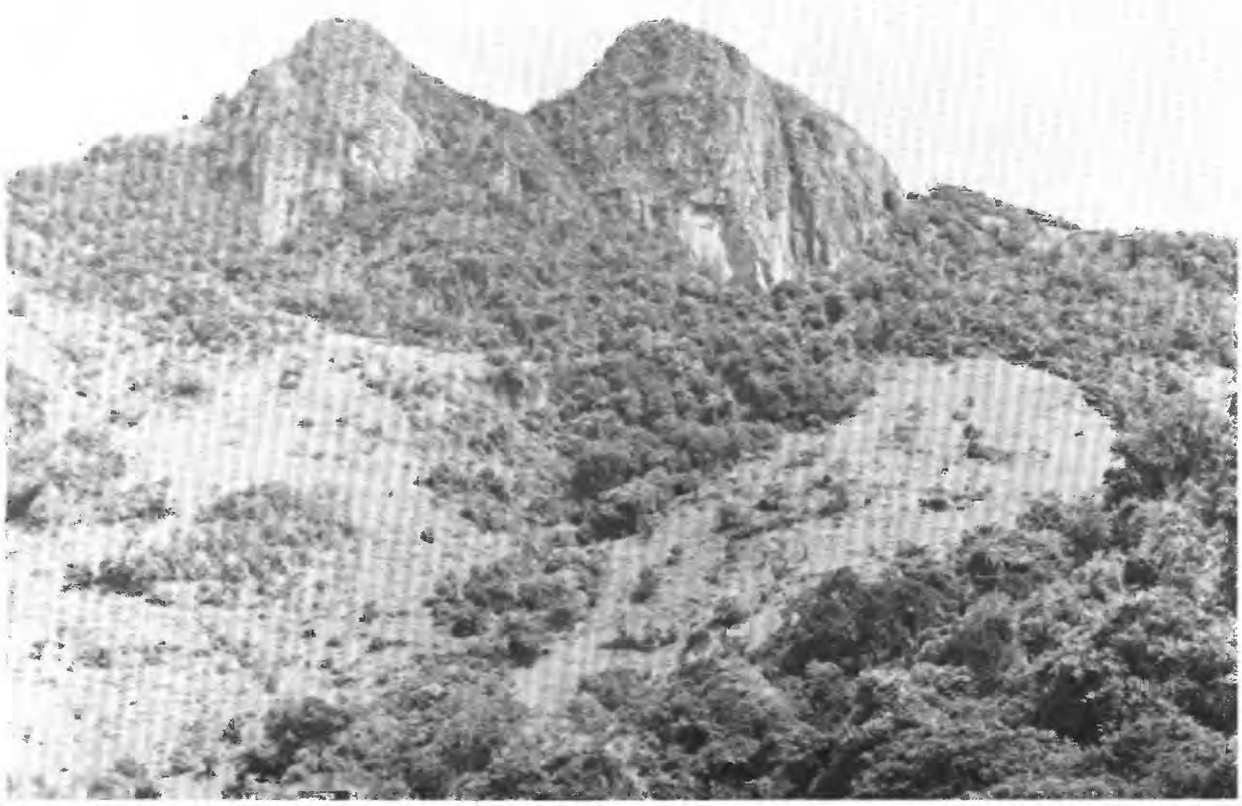

FIGURE 10.–Twin peaks of lava, Las Tetas, on west side of Highway 1, about 7 km west southwest of Cayey. These hills of Cretaceous lava are outliers 1.5 km south of the Cordillera Central.

southward and much more gently toward the north. Most of the sierra is underlain by volcanic rocks, but south of El Yunque the headwaters of the Río Blanco drain an amphitheater underlain by quartz diorite, which is surrounded by hills of slightly metamorphosed volcanic rocks (Seiders, 1971a). The south slope of the sierra is a fault-line scarp, north of a fault that is present beneath alluvium. The asymmetric shape of the sierra suggests that it is a complexly fractured fault block.

SIERRA BERMEJA

The Sierra Bermeja is the mountain range south of the Lajas Valley in southwestern Puerto Rico. It is composed of a complexly faulted mass of volcanic rocks, chert, serpentinite, and gneissic amphibolite that may represent the oldest rock in Puerto Rico (Renz and Verspyck, 1962).

CERRO DE LAS CUEVAS

Cerro de las Cuevas and discontinuous extensions toward the east-southeast, a range of hills of limestone near Juana Díaz, is a fault block capped on its south side by limestone of Paleocene or Eocene age, some of which has been indurated into a hard rock that is quarried commercially as marble (Glover, 1971).

SOUTHERN FOOTHILLS

Near Ponce is a series of low ridges of clastic sediments and limestone of Oligocene and Miocene age (Monroe, 1973a), equivalent in age to the limestone of the Northern Karst province. Although geologically these hills are included in the southern Coastal Plains of Puerto Rico, topographically they seem more closely related to foothills of the Upland province than to the sandy Coastal Plains province to the south, especially as they have been cut by many faults. Under more humid climatic conditions, parts of this belt of hills would probably form a karst topography comparable with the Northern Karst belt. Quebrada de los Cedros, a small flowing stream 5 km northeast of Guayanilla, has a short underground course (Beck, 1974; Moussa, 1969) in a river cave known as El Convento from its cathedrallike windows. On the upland on both sides of this creek are the only known large dolines in the middle Tertiary limestone of the southern coast of Puerto Rico.

BARRANQUITAS EROSION SURFACE

Just north of the Cordillera Central in central Puerto Rico is a dissected upland surface, on which summit elevations are generally concordant. Many of the flatter parts of this surface are underlain by many tens of meters of soil and residuum (Briggs and Gelabert, 1962; Briggs, 1971), which suggest that the surface has been exposed to weathering for a long time. The surface slopes generally north from the foot of the Cordillera Central; altitudes of the broad, gently rolling surfaces are 950–1,000 m. The most perfectly preserved part of the surface is near Barranquitas where it forms a rolling upland from 600 to 700 m above sea level. This erosion surface is underlain mostly by volcanic and sedimentary rocks. Where lava flows, breccia, or limestone are present, the surface is higher; where intrusive rocks are present, the surface is lower. This surface was called the St. John peneplain by Meyerhoff (1927, 1933).

The Barranquitas erosion surface was probably eroded to a low plain during the Miocene just before the very pure Aymamón Limestone (Monroe, 1973a) was deposited in shallow water of the Atlantic Ocean. While the Aymamón was being deposited, virtually no sediment was being transported to the Atlantic by the rivers in existence at that time, except in the northwestern part of the island, as indicated by impure limestone in the Aymamón. After deposition of the Aymamón, the island was bowed upward, and erosion of the Upland area was renewed, as is shown by the sand and impure limestone beds of the Camuy Formation (Monroe, 1973a).

Characteristic of the high erosion surface are deep canyons in the form of entrenched meanders that score the upland surface. These canyons record the courses of rivers that once flowed on a nearly level surface in large meander loops similar to those that may be seen today near the coast in the valley of the Río Grande de Manatí between Manatí and Barceloneta. They now flow in deep canyons because the land was raised to a much higher level, and they have been able to cut their channels to much greater depths. Such entrenched meanders are common in all parts of the upland in Puerto Rico, but the most striking examples are in the valleys of the Río de La Plata and the Río Grande de Manatí, where the present rivers are about 200 m below the upland surface, at places in gorges having nearly vertical walls (fig. 11).

Such deep entrenchment of the meander loops of the rivers below the general upland surface indicates a downcutting by the river that is more rapid than is the widening of the valleys by weathering and mass wasting of the valley walls. As a consequence of this rapid downcutting, many of the tributaries have not been able to keep pace with the main streams and have been left as hanging valleys much like those found in glaciated regions.

The large meander loops of such rivers as the Río de La Plata and the Río Grande de Manatí record the time when the present upland surface was eroded to a nearly flat plain during deposition of the Aymamón. The entrenchment of the meanders began during Camuy time and has continued to the present.

FIGURE 11.—Entrenched meander of Río Grande de Manatí, 3.6 km south-southeast of Morovis. The peak west (left) of the river is 120 m above the river, which at this point has an altitude of 150 m. This ridge rises to 270 m west of the river, and a matching ridge to the east rises to 400 m.

LOWLAND AREAS

Included in the Upland province are several large low areas surrounded by high mountains. Some of these lowland areas, such as the Cayey plain south of the valley of the Río de La Plata and the valley at Cidra, are remnants of an old upland erosion surface. Most of the lowland areas, however, are places where weathering has proceeded much more rapidly than elsewhere and, consequently, has been followed by deep erosion. Most such areas are underlain by intrusive rocks such as granodiorite or quartz diorite, which, after decomposition by chemical weathering, contain enough quartz to serve as a scouring agent. Many of these areas are relatively small, such as the wide valley of the Río Grande de Manatí between Morovis and Orocovis at the southern edge of the Morovis stock of granodiorite (Berryhill, 1965), but two of the areas are large.

In the area between Jayuya and Utuado in west-central Puerto Rico, the surface is covered with loose clayey sand that is residual from underlying granodiorite and quartz diorite. Because the quartz acts as a scouring agent, the clay is easily eroded, and the countryside is carved into many closely spaced gullies. Erosion has been so rapid relative to the adjacent soils derived from volcanic and metamorphic rocks and not bearing quartz that the area of the Utuado batholith is now a basinlike lowland surrounded by such high mountains of volcanic rocks as Cerro Roncador and Cerro Morales.

The largest lowland of this kind is the area of the San Lorenzo batholith that covers most of the southeastern corner of Puerto Rico between Las Piedras and Maunabo and between San Lorenzo and Humacao. The granodiorite and quartz diorite in this area has weathered to slightly ferruginous clayey sand, and the rapid erosion common in sandy soils rich in quartz has caused the landscape to be eroded into a close network of gullies, which are small hillside valleys having steep sides and are separated one from the next by sharp ridges.

Especially striking in this area are the thousands of granitic core stones, which give Las Piedras its name (fig. 12). These core stones are the centers of joint blocks of quartz diorite and granodiorite. Ground water containing plant-derived carbonic acid seeps down places where granitic rocks have been cut by widely spaced joints, causing weathering of some of the minerals in the granitic rock at the joint sides. The rock near the joint is thus changed into clayey sand. This soillike material is easily eroded, and the joint is widened into a small gully. Eventually, under conditions of rapid erosion, all the weathered rock is removed, leaving fresh rock exposed only in the center of the blocks. When the weathered rock has been removed from the fresh rock, weathering almost ceases, and the stone remains on the surface as a residual core stone. Such stones cap many of the hills in the Las Piedras area.

The Caguas Valley is another lowland related in origin to other areas of outcrop of granitic rocks but modified by deposition of alluvial-fan deposits on the sides of the valley, similar to those on the north side of the Río Gurabo at the foot of the Sierra de Luquillo (Broedel, 1961).

FAULT-LINE SCARPS AND VALLEYS

The rocks of the Upland province have been cut by thousands of faults. At the sides of the faults the rocks have been shattered by the movements into a gouge where ground water can seep easily; the seepage causes more rapid weathering than elsewhere in the rock mass. This so facilitates erosion that faults in the mountains of Puerto Rico are commonly marked by notches or valleys (Monroe, 1966b).

The best examples of fault-line valleys in Puerto Rico are along the Río La Venta, 10 km due north of Jayuya (for exact location, see the Florida Quadrangle topographic or geologic maps, Nelson and Monroe, 1966). The trend continues along several other valleys towards the east-southeast. At places where the movements along the fault have brought into juxtaposition two kinds of rock having different weathering and erosion characteristics, the fault may be marked by a fault-line scarp. The south wall of the valley of Río La Venta (Nelson and Monroe, 1966) and the other valleys along the same trend show the characteristics of such a fault-line scarp. Perhaps the most prominent of such fault-line scarps in Puerto Rico are the nearly straight mountain fronts on the north side of the Río Gurabo (Seiders, 1971b), which marks the line of the fault at the south side of the Sierra Luquillo, and the scarp at the north side of the Río Añasco in northwestern Puerto

FIGURE 12.–Core stones on crest of hill of quartz diorite about 2 km southeast of Juncos, in the Las Piedras area.

Rico, which marks the fault at the south side of La Cadena San Francisco (Cox and Briggs, 1973).

Midway between Barranquitas and Aibonito, the Río Usabón has cut the deep Cañon de San Cristóbal (for location see Barranquitas Quadrangle topographic or geologic maps, Briggs and Gelabert, 1962), characterized by several right-angle bends as the river follows joints and faults of various displacements. The deepest part of the canyon (figs. 13 and 14) follows a fault; here the canyon is about 170 m deep, and the sloping edges at the top of the nearly vertical walls are about 200 m apart.

Many of the valleys in the middle Tertiary rocks in the foothills in southern Puerto Rico between Ponce and Guánica follow faults and possibly joints (Krushensky and Monroe, 1978, 1979). This structural control of drainage is especially noticeable in the triangular hilly area south of the line between Guayanilla, Yauco, and Guánica. Grossman (1963) called attention to the anomalous course of the lower part of the Río Yauco and correctly ascribed the sharp changes in direction of the valley to fault control.

THE NORTHERN KARST PROVINCE

The Northern Karst province lies north of the Upland province and locally extends to the Atlantic Ocean. The province extends about 135 km from Loíza Aldea on the east to Aguadilla on the west. The belt reaches its maximum width of about 23 km south of Arecibo. In the eastern 25 km of the belt, from the western part of San Juan to the outcrops east of the Río Grande de Loíza, south of Loíza Aldea, most of the limestone rocks of the belt are buried beneath a series of alluvial deposits of a number of rivers.

From San Juan west, the karst belt is interrupted only by the relatively wide alluvial valleys of rivers, which have their headwaters in the upland area and which pass through the belt to the Atlantic Ocean.

Aside from these through-flowing rivers and some relatively short tributaries, all the rest of the drainage of the karst belt is underground. Streams that rise in the relatively impermeable chalk and marl of the Cibao Formation have subaerial courses for short distances, but they sink underground as soon as they reach the

FIGURE 13.—A part of the Cañón de San Cristóbal eroded into the Barranquitas erosion surface, which here has an average altitude of 600 m. The canyon is about 200 m wide at the top, and it is about 170 m deep. View is toward the east.

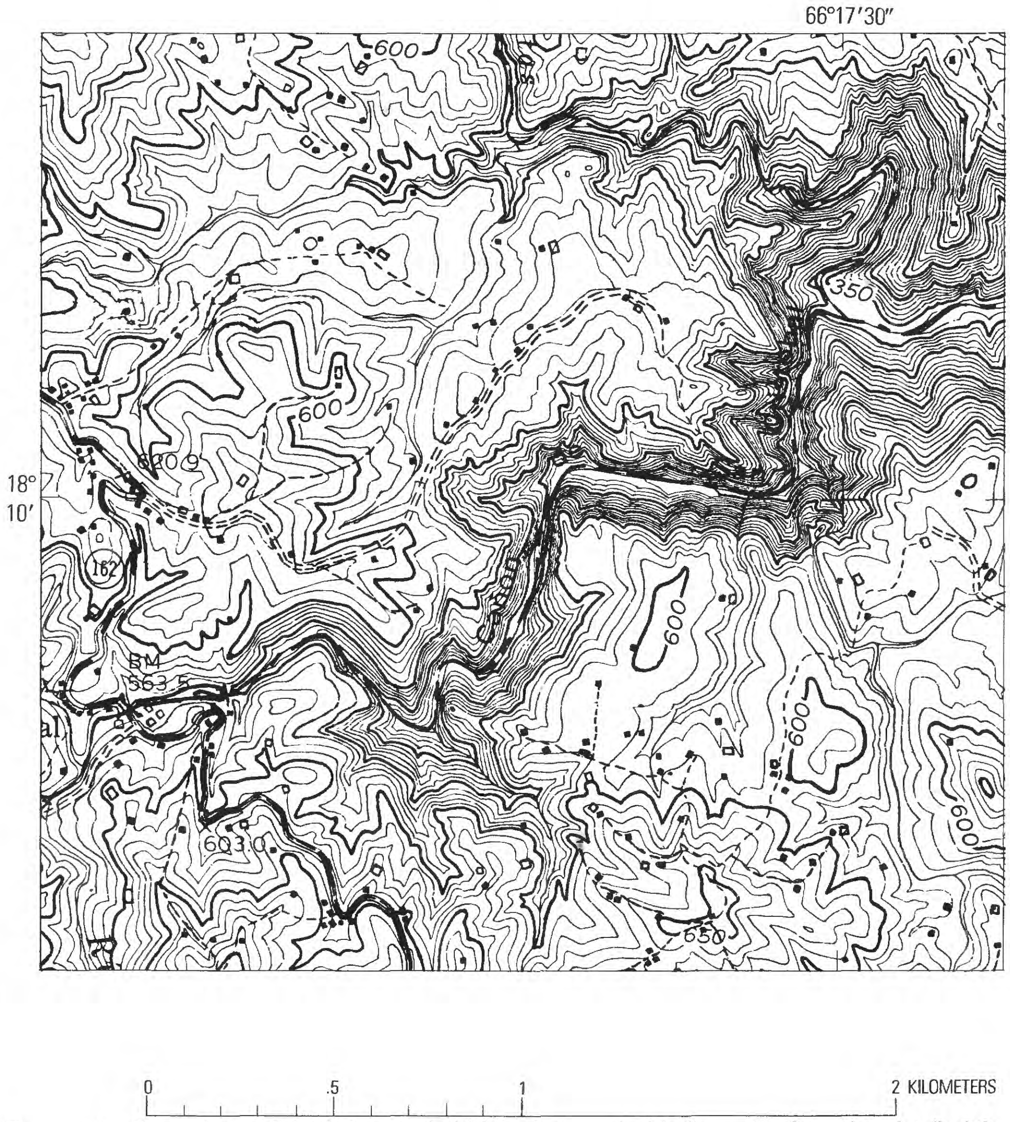

FIGURE 14.—Cañón de San Cristóbal, part of which is photographed in figure 13, shown in a detail of the Barranquitas Quadrangle, Puerto Rico.

karstifiable upper part of the Cibao or the Aguada Limestone. Some of the underground courses of streams are in large spectacular caves and some are in tubelike caves that are as smooth walled as an artificial sewer, but most of the drainage seems to be through a spongework of interconnected passageways only a few centimeters in diameter. In many of the closed depressions in the karst belt, a small stream originates at a spring, flows across the depression, and then disappears underground again into soil in a hole less than a meter in diameter. At some places, fairly rapidly flowing streams disappear underground and can be heard flowing rapidly over rapids and falls for a short distance. They are then lost, for very few successful tracing studies have been made in northern Puerto Rico.

The karst area is divided into several somewhat lenticular belts of topography corresponding closely to the lithology of the underlying rocks. These rocks vary considerably in susceptibility to erosion (Meyerhoff, 1938), and they dip generally to the north. Dips range from about 5° along their southern border to less than 1° near the Atlantic Ocean. The combination of variations in resistance to erosion and a constant northerly dip has given rise to a series of cuestas, which have been studied by Blume (1970). Each of these cuestas is characterized by a south-facing scarp and a long gently sloping northerly slope, commonly obscured and interrupted by a wild array of solution features, such as closed depressions, dolines, cone karst, mogotes, and zanjones.

The most conspicuous single feature of the karst area is the Lares cuesta scarp that extends continuously from San Sebastián to Corozal, interrupted only by the alluvial valleys of the major rivers that cross the belt. The scarp is the result primarily of differential erosion of the easily weathered and eroded San Sebastián Formation and volcanic rocks below and to the south of the much more resistant limestone above and to the north (Blume, 1970); secondarily, it is the result of great landslides (Monroe, 1964a) that have created a steep cliff where blocks of limestone have broken away because of the diminishing support below as the underlying material is eroded by gullying and sheet wash and as they clay of the San Sebastián Formation becomes water soaked and forms a gliding surface.

The altitude of the top of the scarp ranges from a maximum of about 530 m near Caguana (7.5 km west of Utuado), between the Río Tanamá and the Río Grande de Arecibo, to a minimum of about 200 m near Corozal to the east and near Moca and San Sebastián to the west. The relative altitude of the scarp varies, however, with the depth to which a bordering stream has cut its channel. Thus, the steepest and relatively highest part of the scarp is just west of Lago Dos Bocas, where the water level of the lake is about 90 m and the top of the scarp is about 430 m, a difference in altitude of 340 m. In contrast in the area just to the west near Caguana, the San Sebastián Formation crops out on an only slightly eroded flat at an altitude of about 430 m, and the top of the scarp rises to about 480 m, a difference of only 50 m. The latter represents what might be considered the "normal" differential erosion, uncomplicated by landsliding induced by nearby rapidly incising streams.

CONE KARST

Immediately north of the Lares scarp is a discontinuous belt of conical hills that form cone karst, or cockpit karst, typical of many tropical areas (Lehmann, 1954). The conical hills are surrounded by sinuous or star-shaped depressions (Sweeting, 1958; 1972, p. 273–281). Early observers (Hubbard, 1923; Meyerhoff, 1933) believed that the hills were residual left by collapse of caverns of underground streams similar to such through-flowing rivers as the Camuy and the Tanamá. Lehmann (1954), however, attributed lineation of the conical hills to joint control. More recently, Monroe (1974; 1976, p. 27–29) suggested that some of the hills may be residuals left by erosion by streams that originally flowed on a former mantle of detrital material and cut down into the limestone. This erosion has been supplemented by solution of the limestone.

SINKS

To the traveler by air over northern Puerto Rico, the most conspicuous karst features are the sinks (dolines) and mogotes. The thousands of sinks present a lunarlike landscape (fig. 15). The karst area contains more than 1,300 depressions in which the lowest parts are more than 30 m (100 feet) deeper than the lowest point on the rim. Of these, nine are deeper than 70 m. Most of the very deep sinks are in a belt of outcrop of limestones that contain alternating beds of hard limestone and softer marlstone. The bottoms of most of these sinks are floored by a clay soil, in part residual from solution. Solution beneath this soil tends to cause the sinks to become still deeper. As they become deeper, the sides collapse to form vertical cliffs, and soil washed from the sides accumulates in the bottom to form an even thicker soil, which is a reservoir for water; further deepening is thus promoted.

FIGURE 15. – Doline karst area 3–4 km southwest of Manatí.

Very different in morphology and origin are collapse sinks that have been formed by collapse of caverns along the courses of underground streams, such as the Río Camuy and Río Tanamá in western Puerto Rico. Cavern collapse has produced an abundance of lines of sinks that have nearly vertical walls. One such sink is about 120 m deep and 140 m wide at the top (fig. 16).

CAVES

Hundreds of caves are in Puerto Rico, but very few have been explored thoroughly (Monroe, 1976, p. 50–54). The most extensive caves are within belts of bedded limestone. Both the Río Camuy and Río Tanamá have long underground courses, both mostly in the Lares Limestone. The Camuy underground course is

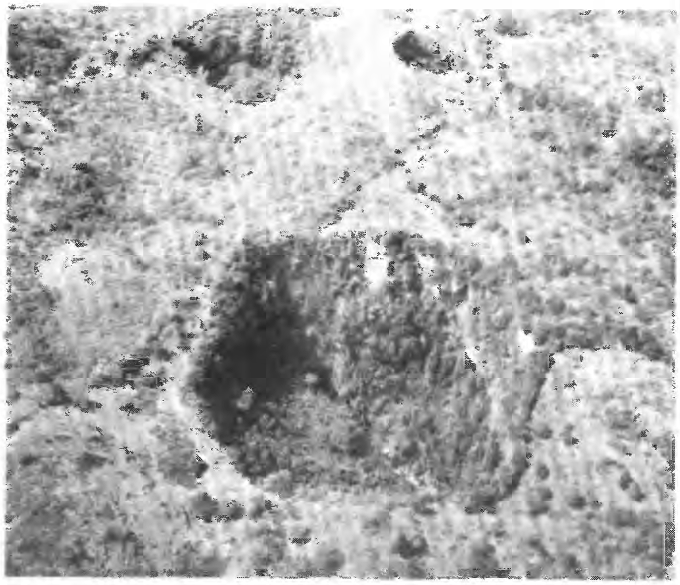

FIGURE 16.—Tres Pueblos sink viewed from the north. The sink is about 140 m wide and about 120 m deep from the top of the east wall to the Río Camuy below. The river enters the sink at the far side. Tres Pueblos sink is just west of highway 129 at the intersection of the municipios of Camuy, Hatillo, and Lares.

about 5 km long. The roof of this cave ranges from about 5 to 30 m above river level. Near the entrance to the underground course, the Lares Limestone is perforated by many caves and natural tunnels that are probably ancient courses of the river.

The Río Tanamá is mostly unroofed and now flows through nine natural tunnels, separated by steep-walled gorges (Gurnee, 1972). Many of the smaller streams in the same general region have partial underground courses.

In addition to river caves, the Karst province includes many small lens-shaped caves, which have apparently formed by solution at or near the water table. The river caves commonly include features associated with solution by running water, such as fluting and ceiling and wall notches, but the lens-shaped caves show no indication of ever having had running streams. The earth in the caves is commonly clay and includes sand and gravel only near the entrance, whereas the earth in the river caves is commonly a stream alluvium. In general, the smaller lens-shaped caves are much better decorated with speleothems than are the larger river caves.

Very similar in origin to caves are natural bridges. Two rather sizable natural bridges are present in the Aguada Limestone. One of these bridges, west of Río Guajataca, 3 km northwest of the dam at the north end of Lago Guajataca, is used as such (Monroe, 1976, p. 54). Just before the bridge, a trail branches. One branch goes beneath the bridge and is the main route to a series of connected sinks; the other goes over the bridge and up into the hills to provide access to the village of Ponce and the country farther north. The other bridge (fig. 17), 9 km south of Camuy, forms an archway between two sinks. About 2 km east of this bridge are the remains of a similar bridge, of which only the two buttresses remain. At both places, a strong bed of limestone rests on relatively friable crossbedded limestone; the friable limestone was dissolved and eroded away to form the opening below the arch.

FIGURE 17.—Natural bridge, 9.2 km south of mouth of Río Camuy.

MOGOTES

Mogotes are subconical steep-sided hills that rise out of a flat plain. They vary in height from a few meters to 50 m. Mogotes differ from the conical hills of cone karst in that they are separated by broad plains covered by sandy clay, whereas the cones are closely spaced and are separated by narrow sinuous valleys.

All mogotes have steep sides (fig. 18), and many have vertical cliffs or overhangs, especially on their western sides. All are capped by very dense limestone from a few centimeters to about 10 m thick that has dissolved into a badland of sharp spires a decimeter or so high, interspersed with solution pits. Deep roadcuts and quarries show, however, that the hard limestone is merely a shell over rather soft, chalklike limestone or over a rubble of solution cobbles in a matrix of the red clay known as terra rossa. On many mogotes, the soft interior has been partially removed and the capping has been left as a shell. The limestone cap rock has formed by alternating solution of pure limestone and almost immediate reprecipitation in place. Monroe (1976, p. 41–44)

FIGURE 18.—West side of a mogote 4.3 km west-southwest of Vega Baja.

described the process of solution and reprecipitation in detail and has ascribed asymmetry of the mogotes to differential solution by action of the trade winds (Thorp, 1934; Monroe, 1976, p. 44-45).

The surface plains surrounding the mogotes is covered by a mantle of sandy clay that appears to have subsided (Monroe, 1969; Miotke, 1973), and the mogotes are left as residual hills of limestone (fig. 19). Evidence for the subsidence of the plain is discussed in the next section, "Ramparts."

FIGURE 19.—View to the southeast of mogotes rising out of pineapple fields in a plain of sandy clay southeast of Manatí.

RAMPARTS

Closely related in origin to the mogotes are limestone ramparts that are found at the top of many river valleys and sea cliffs in northern Puerto Rico. The most prominent of these is on the west side of the Río Guajataca in western Puerto Rico (Kaye, 1957; Monroe, 1969). The walls rise very steeply 125 m from the river valley, forming a wall of hard limestone, mostly indurated on the surface by reprecipitation, as are the mogotes. On both sides of the river the surface descends from the top of the wall some 25 m to a plain covered by the common sandy clay (fig. 20). It is significant that the tops of the mogotes at the same latitude for several kilometers east and west of the river have about the same altitude as the top of the rampart and rise about 25 m above the plain. The sandy clay of the plain is similar in lithology on both sides of the river, whereas the underlying limestone contains no sand. It is apparently a part of a sheet of sand of about the same composition and the same altitude for many miles in each direction; therefore, the sandy clay was probably once a continuous sheet of alluvial material that extended very widely across northern Puerto Rico at an altitude equal to or higher than the tops of the ramparts and mogotes. Subsequently, sheet solution of the underlying limestone has lowered the sandy clay to its present position, about 25 m below the tops of the residual limestone ramparts and mogotes.

Similar ramparts slightly less prominent than those of the Río Guajataca parallel several other rivers in northern Puerto Rico, such as the Río Grande de Manatí. Ramparts about 5 m high have been noted at the top of sea cliffs in northwestern Puerto Rico between Camuy and Isabela (Monroe, 1976, p. 41).

ZANJONES

Zanjones, an uncommon kind of karst morphology, are present in Puerto Rico (Monroe, 1964b). These are vertical-walled trenches, many more than 1,000 m long, that range in width from a few centimeters to a few meters and in depth from about 1 to 4 m. They occur as parallel trenches oriented generally in one direction. The intervening ridges are from 5 to 10 m apart (fig. 21). Zanjones appear to be joints enlarged by solution (Monroe, 1976, p. 48–50).

THE COASTAL PLAINS PROVINCE

On all sides of Puerto Rico, lowlands near the sea are underlain by sedimentary deposits transported by rivers from the higher parts of the island and then deposited either in the sea or in alluvial plains at places where the gradient of the rivers is too low to transport the sediment. Some of these deposits have been extensively reworked by the sea and the wind.

NORTHERN COASTAL PLAINS

In northern Puerto Rico, the Coastal Plains deposits consist predominantly of sand and contain subordinate

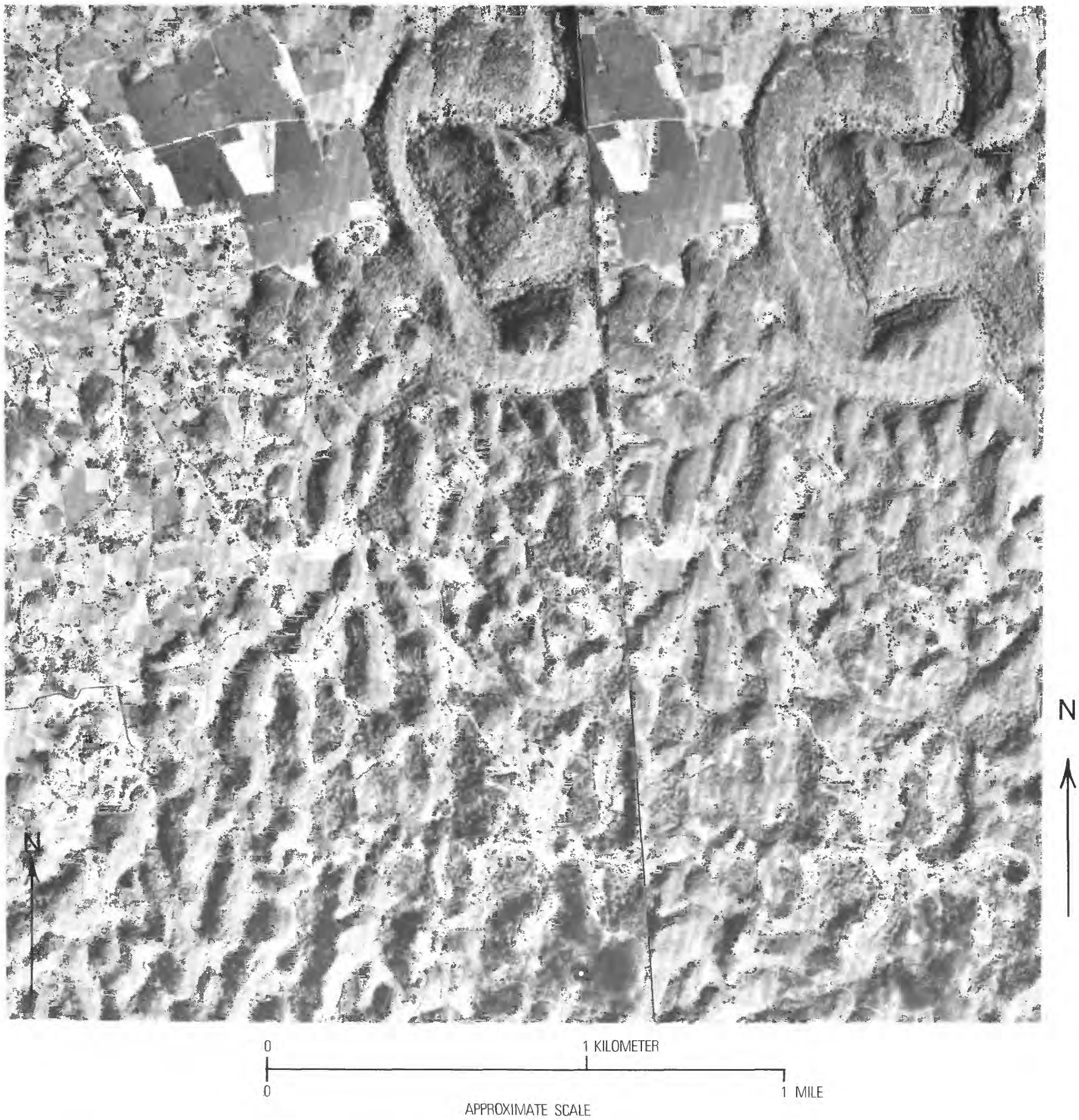

FIGURE 20. – Rampart of Aymamón Limestone on left bank of Río Guajataca, 4 km southwest of Quebradillas. Top of rampart is about 155 m above the river to the east and about 35 m above the plain of sandy clay to the west. The lower part of the photograph shows that the limestone has been dissolved into cone karst. Stereopair of aerial photographs from U.S. Soil Conservation Service, 1963.

amounts of clay. These deposits form playa plains (Hill, 1899b) that slope gently from the foothills of the Upland province or from the Northern Karst province to the Atlantic Ocean. Most of the deposits are in flood plains and ancient distributaries of the rivers that drain into the Atlantic Ocean from the Upland. Between the present and past mouths of the rivers are great lagoons, such as Laguna Tortuguero near Manatí and Laguna San José near San Juan, or former lagoons that have been filled with alluvium, such as Ciénaga or Caño Tiburones, east of Arecibo, and the great swamps of Sabana Seca between Dorado and Bayamón. Mangroves have invaded many of the lagoonal areas.

Most of the coast from Cabezas de San Juan to Camuy consists of beach deposits of various kinds of sand, except for a short stretch northwest of Laguna Tor-

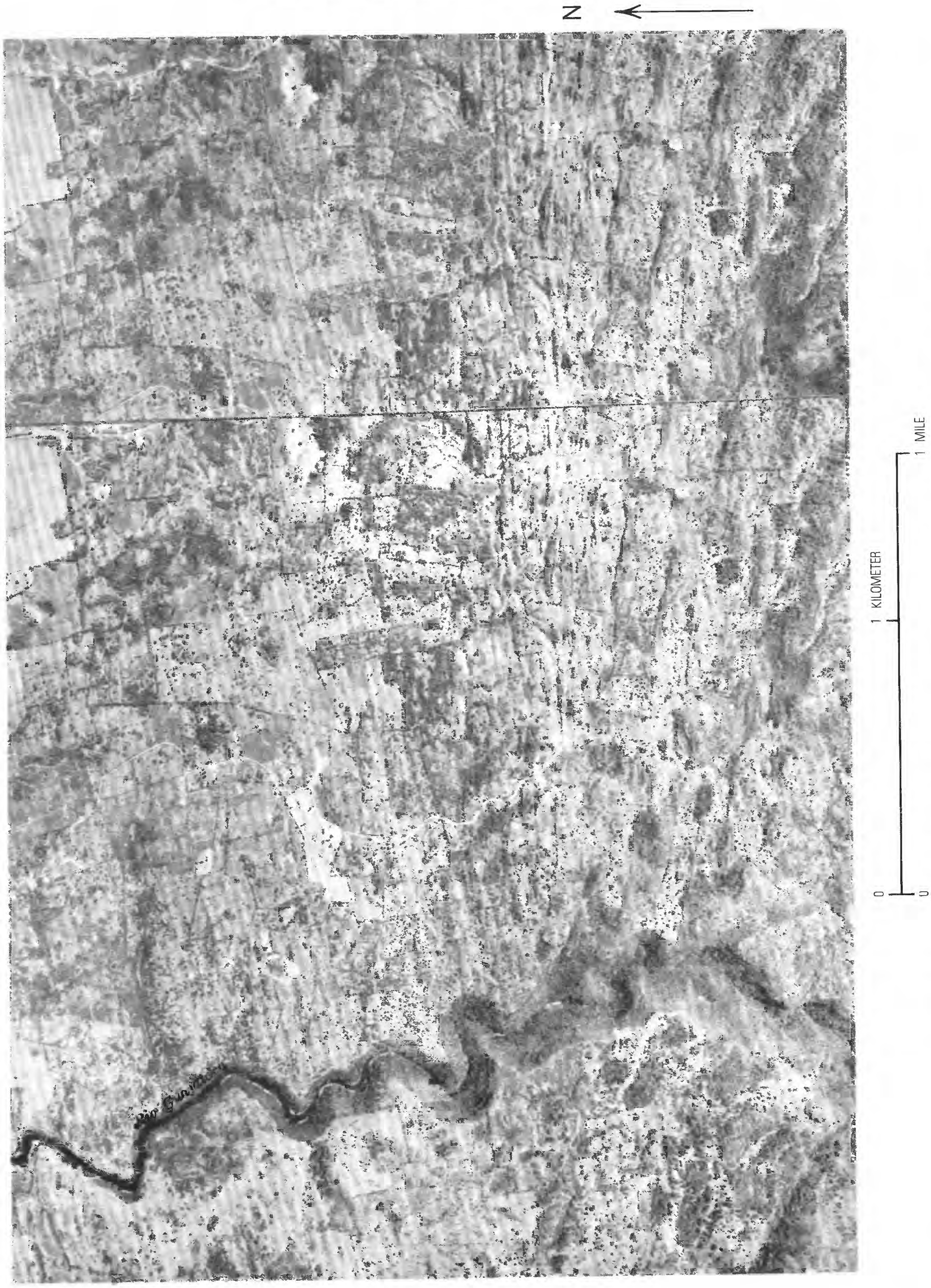

FIGURE 21. – Zanjones north of Lares. Stereopair of aerial photographs from U.S. Soil Conservation Service, 1964.

tuguero, where the coastline consists of cliffs of limestone. For long stretches these beaches are arcuate (Kaye, 1959a). West of Camuy, sea cliffs of limestone alternate with short stretches of sand beach. The type of material that forms these beaches is closely related to the sediments from rivers that flow from the central part of Puerto Rico. At the mouths of most of these rivers and for a short distance west of the mouth, the beach sands consist largely of grains of quartz and lava, and locally they contain a considerable content of magnetite (Briggs, 1965; Guillou and Glass, 1957). Such beaches are usually hard, and many of them are light to dark gray because of the content of dark grains of magnetite and volcanic rock. Such beaches extend west from the mouths of the rivers because of the effect of the long-shore ocean currents that tend to move river sediments west along the shore. A few kilometers west of the mouth of each river, however, the quartz sand is mixed with a sand made up of shell fragments, and a short distance still farther west, the beach sand is composed almost entirely of shell fragments.

Beaches of shell fragments are soft, but because of the abundance of calcium carbonate in the shell fragments, the sand at many places has been cemented into beachrock (Kaye, 1959b), which is forming today (fig. 22), for one can find such recent artifacts as bottle caps, reinforcing rods, and bricks cemented into the beachrock. The unconsolidated sand of the beach and the sand in the sandstone of the beachrock at any one locality are identical. At a few places, beachrock has formed where there is an abundance of magnetite in the shell sand–at such places the beachrock is black. Beachrock at present beach level occurs mainly between low and high tide and just above high tide in the zone of sea spray. It apparently forms only at places where the sand is subject to alternate wetting and drying, and it may be related in origin to the reprecipitation of calcium carbonate on the surface of the mogotes; that is, partial solution of the calcium carbonate is followed immediately by precipitation during evaporation.

Beach ridges roughly parallel to the present beach are present for a kilometer or more inland from the present coast at several places in northern Puerto Rico, especially west of Loíza Aldea and northwest of Bayamón. These indicate that the coastline has advanced seaward during relatively recent times.

At many places in the northern Coastal Plains the beaches are bordered by sand dunes that consist of grains of sand that have been blown from the beach by the wind. This process has been going on for a very long time (Kaye, 1959b), for many ridges of semiconsolidated dune sand, eolianite, now cap ridges far above the sea.

FIGURE 22.–Beachrock formed in a calcareous beach east of the mouth of Río Cibuco.

At least one is now partly submerged and forms the reef off the Condado section of San Juan, connecting parts of the ancient dune still above sea level at the forts of El Morro and San Cristóbal on the island of San Juan with the eolianite hills at Punta Maldonado farther east. As are the beaches, most of the eolianite is composed largely of shell fragments. The dissolving action of the salt spray of the ocean has carved the eolianite at places along the shore into an intricate topography of sharp spires and shallow basins (fig. 23) of a few centimeters relief (Kaye 1959a).

FIGURE 23 – Large solution pan dissolved in eolianite at Mar Chiquita, 5 km north of Manatí.

At several places in the northern Coastal Plains are extensive deposits of white sand composed almost exclusively of quartz. This sand was brought by rivers from areas of quartz-bearing intrusive rock to the coast where it was washed by the sea, and all clay, iron oxide, and other impurities were removed; then it was blown across the plain by the wind. Today it forms a surface of alternating low hills and depressions – low dunes and deflation hollows. The most extensive area of this white dune sand is north of Highway 2 between Manatí and Vega Baja, south of Laguna Tortuguero. This sand has been mined for use in making glass.

This is an appropriate place to mention the marine-cut terrace at the northwest corner of Puerto Rico on which an air force base was built, although the terrace is not part of the Coastal Plains province. This plain was apparently cut by the sea (Meyerhoff, 1938) at some time in the past (Monroe, 1968) when sea level was about 80 m higher than it is now. Similar wave-cut terraces in the Aguadilla area are found at several lower altitudes, especially at 40–50 m and at 10 m above sea level. All along the northern coast, traces of a fossil beach can be found 4 m above present sea level, marked at most places by eroded layers of ancient beach rock and at many places by ancient sea caves.

EASTERN COASTAL PLAINS

The eastern coast of Puerto Rico consists of rocky headlands where the mountains of the central Upland plunge into the sea, between coastal lowlands composed of sand and cobbles discharged by rivers from the uplands to the west brought to the coast by rivers. Because much of southeastern Puerto Rico consists of granodiorite and quartz diorite, rocks which weather to clay and quartz sand, the beaches along this coast are made up largely of quartz sand and hence are firm beaches, generally lacking beachrock.

The beaches are shaped by long-shore currents. This effect is especially well shown at El Morillo at the southwestern end of Puerto de Humacao; the beach is much wider south of the point at which a hill of volcanic rock has been partly buried by sand piled up by currents than it is to the north. This pattern is repeated at many places along the coast, such as Punta Fraile.

Beach ridges inland from the coast, especially near Humacao, indicate recent growth of the coastal plain into the sea. The larger rivers, such as Río Humacao and Río Guayanés, that enter the sea along the coast have filled their valleys with thick deposits of sandy alluvium that provide a nearly unlimited store of underground water.

SOUTHERN COASTAL PLAINS

Whereas the northern Coastal Plains are characterized by sand beaches that pass landward into broad playa plains of sand and clay, the southern Coastal Plains, particularly the part between Ponce and Guayama, consists of a series of great alluvial fans of poorly sorted clastic debris from the mountains to the north. Nearly every stream or arroyo that reaches the Coastal Plains ends in a fan, and the larger drainage basins end in fans that have a radius of as much as 5 km. All the fans have a noticeable though gentle slope from the apex in all southerly directions. The fan of the Río Salinas (whose upstream name is Río Majada) extends from Coqui to Salinas and has its apex nearly as far north as Sabana Llana. The large alluvial fan north of Bahía de Jobos, farther east, shows exceptionally well on the Central Aguirre Quadrangle (Berryhill, 1960) as a set of very regular convex topographic contours.

Gravel and cobbles are so common in the sediments of the alluvial fans that they become concentrated at the strand line when finer material is washed away by waves and currents. Hence, most of the beaches east of Ponce are composed of cobbles. Large lagoons are less common on the southern coast than on the northern, although Bahía de Jobos has almost been closed to form a lagoon, as has already happened at the nearby Laguna de las Mareas (Berryhill, 1960) farther east. Coral reefs are present all along the southern coast but are more abundant in the western part. Mangrove swamps line much of the coast, and at places they are gradually covering coral reefs and killing the coral.

West of Ponce, the coast is dominated by sea cliffs, largely of middle Tertiary limestone. These are interrupted, however, by several bays. At the eastern end of this stretch of coast is the Bahía de Tallaboa, which has a northern shoreline composed largely of sediment carried to the coast by the Río Tallaboa. Action of the currents has carried much of this sediment westward to form a long spit known as Punta Guayanilla. The east side of this spit is composed of the clastic debris brought to the sea by the Río Tallaboa; the west side is mostly mangrove swamp. This spit forms the east boundary of the nearly land-locked Bahía de Guayanilla, into which drain the Río Guayanilla and the Río Yauco. On the southwest side of the bay is the rocky Punta Verraco, but the northern and western shores of the bay are composed of clastic debris carried to the sea by the rivers and are bordered at most places by mangrove swamps or rocky headlands. West of the Punta Verraco is the rocky cliff into which Punta Ventana (fig. 24) has been dissolved.

FIGURE 24.–Punta Ventana, a natural window dissolved in Miocene limestone at edge of Caribbean Sea, 6 km south-southwest of Guayanilla.

West of Bahía de Guayanilla, rocky headlands alternate with small areas of coastal plain composed of clastic debris and mangrove swamps. At the southwest corner of Puerto Rico are the complex multiple tombolos of Cabo Rojo in which a series of sandy beaches have been shaped by currents from the east and the north, enclosing several lagoons and connecting two rocky islands with the mainland. North of Bahía Sucia are several lagoons that have been modified into salt pans in which seawater evaporates to form sea salt, sold commercially.

WESTERN COASTAL PLAINS

The west coast of Puerto Rico is much like the east coast in that it consists of rocky headlands, where the longitudinal mountain chains of Puerto Rico plunge into the sea, transecting wide coastal plains, where the major west-flowing rivers enter the sea. The alluvium brought in by these rivers has been shaped by long-shore currents into a number of cuspate beaches, some of which have been extended beyond the lowland areas to form narrow beaches at the foot of headlands. Mangrove swamps are common at the sides of and behind beach deposits.

The north wall of the Añasco Valley is apparently a faultline scarp that can be traced southeast to the Ponce area (Cox and Briggs, 1973), but the fault itself is concealed near Añasco by thick alluvial deposits of the Río Grande de Añasco. The beach of Bahía de Añasco has advanced seaward a few hundred meters, as shown by the beach ridges behind the present beach.

In contrast to the stony beaches of the south coast, those of the west coast are sandy, probably because the rivers feeding them are longer, less precipitous, and carry more sand and fewer cobbles to the sea.

LAJAS VALLEY

One of the most interesting geomorphologic features in Puerto Rico is the Lajas Valley. Until the Pleistocene Epoch this valley was a strait that separated Sierra Bermeja and other hilly areas of southwest Puerto Rico from the main island. The valley is nearly flat; formerly a number of lakes or lagoons were present, but all have been drained by canals except Laguna Cartagena. The highest divide in the valley is about 2 km east of Laguna Cartagena where Highway 303 crosses the valley at an altitude of 13 m.; from this divide the surface slopes irregularly both east toward the Río Loco and west toward Boquerón. The subsoil of the valley consists of a mass of alluvium, several hundred meters thick at some places.

Apparently the Lajas Valley was originally formed by block faulting when the Sierra Bermeja was faulted up from the main area of Puerto Rico and was tilted toward the south. This tectonic activity left a fault-block valley and a fault-line scarp on the south side and a gentler slope on the north side. This movement may have taken place as early as Eocene time, but there is good evidence that the valley existed as a strait during middle Tertiary time, for Oligocene and Miocene strata are present in the eastern part of the valley and Miocene strata, 7 km east of Boquerón in the west (Gordon, 1961). During early Pleistocene time the strait still existed, separating Sierra Bermeja from Puerto Rico, but the rising and falling of sea level, as the continental glaciers of Europe and North America lowered or raised sea level, resulted in several stages of low sea level in which the strait was an alluviated valley, as it is today, alternating with periods when it was a strait.

OFFSHORE ISLANDS

Several islands off the coast of Puerto Rico are basically part of the main island, but have been separated from it by late Tertiary structural movements or by fairly recent drowning of a part of the island during the melting of the late Pleistocene ice sheets of North America and Europe.

The Culebra group of islands east of Fajardo form a part of the partly drowned Upland province. Most of Culebra is volcanic rock, but on the north shore there is a small area of granitic intrusive rock (Briggs and Akers, 1965).

Farther south is the large Isla de Vieques (Briggs and Akers, 1965). Most of the west half of Vieques is composed of granitic rock and is apparently a continuation of the San Lorenzo batholith of southeastern Puerto Rico. The eastern half of the island includes large areas of volcanic rock, which probably is the rock intruded by the batholith. On the eastern tip, the volcanic rock is overlain by limestone of Miocene age, which indicates that a part of the Virgin Passage must have been in existence as early as Miocene time.

The largest island south of Puerto Rico is Isla Caja de Muertos, which is at least in part a fault block. The rocks exposed on it are Eocene volcanic rocks and Miocene limestone (Kaye, 1957).

The mountain range La Cadena San Francisco, which plunges into the sea near Rincón appears above sea level at Isla Desecheo, which consists entirely of volcanic rocks like those exposed in La Cadena San Francisco (Seiders and others, 1972). Of special interest on Desecheo are two marine wave-cut terraces at 2 and 6 m above sea level, observed by Hubbard (1923) and Meyerhoff (1933).

Isla Mona and Isla Monito, the western outposts of Puerto Rico, are composed entirely of limestone and dolomite of Miocene age (Kaye, 1959c; Briggs and Seiders, 1972). Isla Mona is a wave-eroded plateau 70–90 m above sea level, surrounded almost completely by a sea cliff that drops precipitously to sea level. Near the top of the sea cliff, the limestone is honeycombed by caves, many of which were explored and exploited more than 50 years ago as sources of guano and phosphate rock.

LANDFORMS ILLUSTRATED ON SOME TOPOGRAPHIC MAPS OF PUERTO RICO

Besides the small-scale (1:240,000) shaded-relief topographic map included as plate 1, Puerto Rico is covered by a series of 67 topographic quadrangle maps. The 67 maps of the quadrangles in the main island are at a scale of 1:20,000 and have contour intervals that range from 1 m near the coast to 10 m in areas of high relief. To facilitate the work of geomorphologists interested in tropical land forms, I have selected 15 of the maps that show either an exceptionally large number of features or that display especially well certain features not generally shown on other maps. The locations of these quadrangles are shown on figure 25.

The quadrangles are listed alphabetically. After the name of the quadrangle, the latitude and longitude of the southwest corner are given. This is followed by the indication of the contour interval of the quadrangle, in meters – some quadrangles have a smaller interval near the coast, so that two or three intervals are given. Reference is then given for the geologic map, if one has been published.

The landforms are listed and summarized by quadrangles and arranged alphabetically by categories for each quandrangle. Where an international term differs from an American term, both are given. The location of a feature is indicated, in parentheses, by dividing the quadrangle into nine rectangular blocks 2.5 minutes on a side. The letters A, B and C denote the blocks from north to south on the map, and the numbers 1, 2, and 3 are from west to east across the map. Accordingly, a feature that is in A3 is in the upper right-hand block, and one in C1 is in the lower left-hand block. Some landforms cover large areas of the map and may be located more generally, such as "northern third." Very small features otherwise hard to identify are also located by reference to some prominent point on the topographic map.

To facilitate the work of geomorphologists who are interested in specific landforms, a checklist is included that shows on which quadrangles the landform can be recognized and the specific quadrangle that best shows the landform. Those features that are exceptionally well displayed on a map are identified by an asterisk.

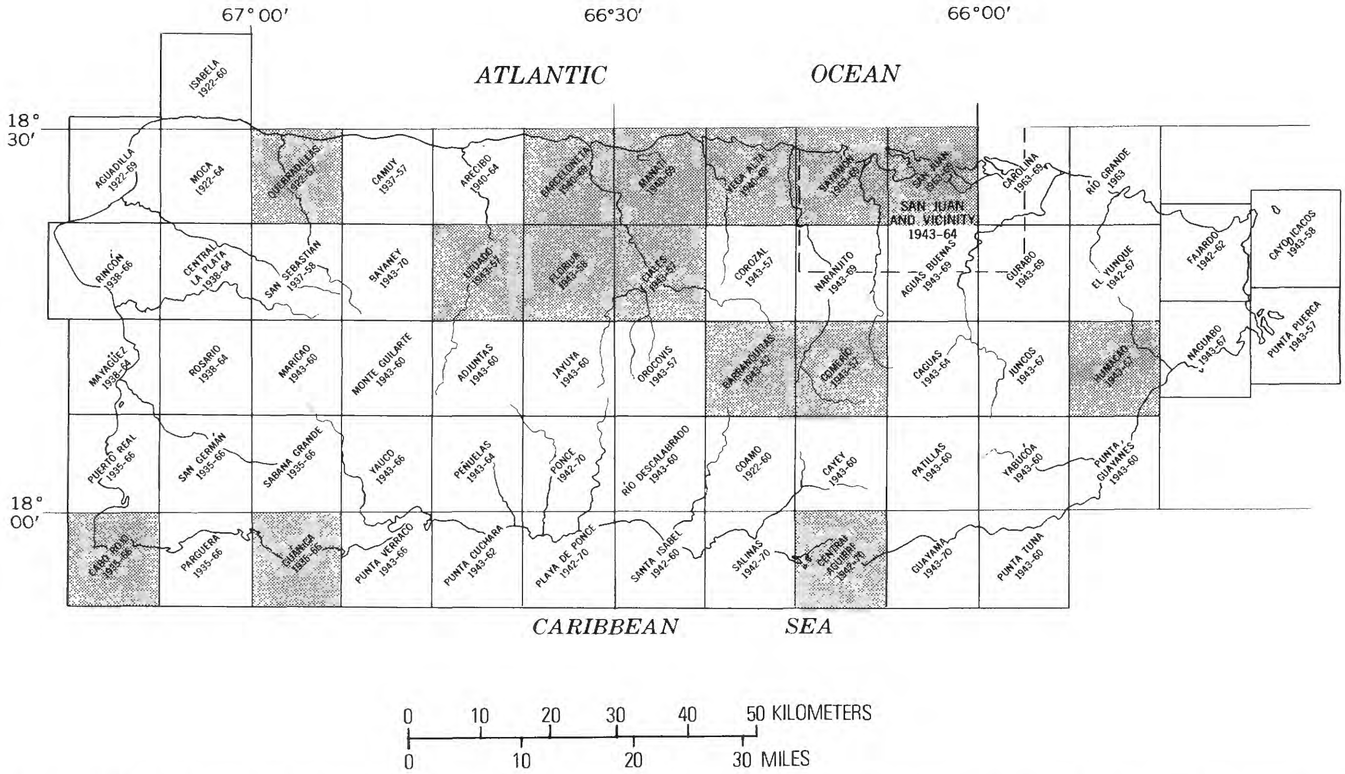

FIGURE 25.–Index map showing names of 7.5-minute quadrangles in Puerto Rico. The 15 quadrangles selected for study of landforms are indicated by shading.

LIST OF QUADRANGLES AND OF LANDFORMS SHOWN ON EACH MAP

Barceloneta.–18°22'30" N., 66°37'30" W.; 1, 5, and 10 m; Briggs (1965)

- Coastal features:
  - Beaches (northern third of map)
  - Beach, cuspate (A1–A2)
  - *Beachrock (A2, A3)
  - Cape or point (punta) (A2, A3)
  - Distributaries, some abandoned, (of Río Grande de Manatí) (A2, A3)
  - Lagoon, filled (now being drained) (A1, A2)
  - *Spit, river-mouth (A3)
  - Swamp, coastal (northern third)
  - Tombolo (A3)
- Submarine features:
  - Reef (A2)
  - *Ridge, submerged (A2)
  - Shelf, insular (northern third of map)
- Escarpment features:
  - Cliff (B3, C3)
  - Escarpments (several)
- Karst (solution) features:
  - Blind valleys (valleys in which stream disappears into sink or tunnel) (several in south third of map)
  - Disappearing stream (C1)
  - Emergence (C2)
  - Interior drainage (south half of map)
  - Karst valley (elongated solution valley) (B2, C1, C2)
  - Karst valley, alluviated (B2, C2)
  - Mogote (haystack hill) (B2)
  - Perched stream (C2, Quebrada Cimarrona, near BM 147.1)
  - Resurgence (C2)
  - Sink holes (dolines) (several in southern third of map)
  - *Sinks, compound (uvalas) (B2, B3, C2)
- Mountain and structural feature:
  - Parallel ridges (B1, B2)
- Stream erosional and depositional features:
  - *Flood plain (B3)
  - Levee, natural (A3)
  - *Meanders (B3)
  - Meander scar (B2, B3)
  - Oxbow lake (A3, B3)
- Wind features:
  - Deflation depressions, in wind-blown sand (B3, west of El Cantito)
  - Dunes, coastal (A1)
  - Eolianite ridges (some partly submerged) (A2, A3)
- Miscellaneous feature:
  - Canals, drainage (northern third of map)

Barranquitas.–18°07'30" N., 66°22'30" W.; 10 m; Briggs and Gelabert (1962)

- Mountain and structural features:
  - Asymmetric divide (C1, near Cerro Pulguillas)
  - *Dissected highland (entire map)
  - *Graben valley (A1, valley east of Botijas)
  - *Monadnock (B2, La Torrecilla)
  - *Structurally controlled drainage (B3, C2, Cañón de San Cristóbal)
- Stream erosional and depositional features:
  - Alluviated upland valley (C2, head of Río Usabón; C3, Aibonito and vicinity)
  - Box canyon (A3, Río Hondo valley)
  - Flood plain (A2, A3, Río Grande de Manatí and Río Hondo)
  - Gorge, V-shaped (A3, B3, Río Hondo and Río Usabon)

Barranquitas.–Continued
Stream erosional and depositional features–Continued
Gullies (C1)
Hanging valleys (C2, northeast corner of block on south side of Cañón de San Cristóbal)
Meanders (B2, valley of Río Grande de Manatí)
Meanders, entrenched (A3)
Youthful stage of erosion (A3, C1)
Miscellaneous features:
Dam and reservoir (C2)
Insular divide (B1, C1, C2)
Quarry (Cantera) (A1, A2)

Bayamon.–18°22'30" N., 66°15' W.; 1 and 5 m; Monroe (1973b)
Coastal features:
*Bar, river-mouth (A2)
Bay (bahía, ensenada) (A2, A3, B3)
Beaches (northern third of map)
Beach ridges (B2)
*Distributary (B1, A1, A2, Río Cocal, distributary of Río de la Plata–see also Vega Alta Quadrangle)
*Distributaries, abandoned (B1, Caño Campanero; B3, Caño Aguas Frías)
*Diverted river mouths (A2, A3, B3)
Prograded shore (B2)
Sea cliff (A2, north side of Punta Salinas)
Swamp, mangrove (A2, B3)
Swamp, coastal-marsh type (B2, B3)
*Tombolo (A2)
Submarine features:
Reefs (A3)
Shelf, insular (northern third of map)
Escarpment features:
Cliff (C1)
Cuesta (C1, south of Río Bucarabones)
Dip slope (C1)
Karst (solution) features:
Interior drainage (B1, B2)
Mogotes (B1, B2, C1)
Mountain and structural feature:
Strike ridges (B1, B2, C1, C2)
Stream erosional and depositional features:
Dendritic drainage (C2)
Flood plain (C1, C3)
Levee, natural (B3, B1, east slope from river in Vega Alta Quadrangle)
Meanders (C3)
Meander, abandoned (B3, 1 km south of Las Palmas)
Meander core, abandoned (C3, east northeast of Represa de Guaynabo)
Oxbow lakes, of drowned river (A1)
Piracy, stream (B2, Río Hondo south of Sabana Seca)
Terrace, river (C3, in and south of Bayamón)
Wind features:
Coastal dunes (A1, A2)
Eolianite hills (A2, A3, Punta Salinas and Isla de Cabras)
Miscellaneous features:
Canals, drainage (B1, B2, B3)
Causeway, containing trapped sand (A3)
Dam (represa) (C3)
Filled land (A3, south of Academia Policía)
Lighthouse (faro, range lights) (A3, B3)

Cabo Rojo.–17°52'30" N., 67°15' W.; 5 m; Mattson (1960)
Coastal features:
*Bar, bayhead (B2)
Bay (bahía) (B2)
Bay, reverberation (a bay whose beach conforms to diffracted wave front) (B2, 400 m northeast of the lighthouse (faro))
Beaches (A1, A2, B1, B2)
*Beach, barrier (A2)
Beach, cuspate (A1)
Cape (cabo) or point (punta) (B1, B2, B3)
Lagoons (A1, A2)
Sea cliffs (A1, B2)
*Sea stacks (B2, marked by *)
Swamp, mangrove (B2, B3)
Swamp, coastal-marsh type (A1)
*Tombolos (B2)
*Tombolo, incipient (B1, Punta Aguila)
Submarine features:
Coral reefs (B2, round sea mounts)
Drowned valleys (A1, C2, Canal de Guanajibo, "valley" 3 km south southeast of the lighthouse (faro))
Reefs (A1, B2)
Shelf, insular (south half of map)
Slope, insular (C1, C2)
Escarpment feature:
Dip slope (A3)
Mountain and structural feature:
Strike ridges (A2)
Stream erosional and depositional feature:
Fan, alluvial (A3)
Miscellaneous features:
Lighthouse (faro) (B2)
*Salinas (salt-evaporating pans) (B1, B2, B3)

Central Aguirre.–17°52'30" N., 66°15' W.; 1, 5, and 10 m; Berryhill (1960)
Coastal features:
Bay (bahía) (B1, B2)
Beaches (B2, B3)
Beach, barrier (B2, B3)
Beach ridges (B2, B3)
Cape (punta) (B3)
*Coastal plain (land between mountains and sea or bay)
*Keys (cayos) (B1, B2)
Lagoon (laguna) (B3)
Prograded shore (B2, B3)
Sea cliff, low (B1, B3)
*Swamp, mangrove (B1, B2, B3)
*Tidal islands (B1)
Submarine features:
*Coral reefs, fringing (B2, B3, at seaward edge of pattern of dots; also rock pattern at east edge)
Coral reefs, barrier (B1, B2, seaward edge of Cayos de Barca)
Sand bars (B1, B2)
Shelf, insular (south half of map)
Stream erosional and depositional features:
*Arroyos (A2, B3)
*Fans, alluvial (A1, A2, A3, B2, B3)
Flood plain, cut in alluvial fan (A3)
Flood plain, having especially steep slope (A3)
Gullies (A3)

Central Aguirre. – Continued
Miscellaneous features:
Canals, drainage (B2)
Canal, aqueduct (northern edge of map)
Channel, dredged (B1)
Dam and reservoir (A3)
Harbor (B1)
Irrigation ditches (northern third of map)
Irrigation ponds (northern third of map)
Lighthouse (faro, range light) (B1)

Ciales. – 18°15' N., 66°30' W.; 5 and 10 m; Berryhill (1965)
Escarpment features:
Cliffs (A1, A3)
Escarpment (A1, A2)
Karst (solution) features:
*Cone karst (cockpit karst) (A1, A2, hills 1-2 km east of Ciales)
Disappearing streams (A1, A2)
Interior drainage (northern third of map)
Karst valleys (valleys lined with sinks) (A1, several in southern part of barrio Hato Viejo)
Rampart, river (A1, A3)
Sinkholes (dolines) (A3)
*Zanjones (A2, Quebrada Torres and other subparallel valleys)
Mountain and structural features:
Fault-line valley (C1, southwest corner)
Maturely dissected mountainous highland (south half ofmap)
Stream erosional and depositional features:
Flood plains (A1, B1, B2, B3)
Gorge (A3, B2, B3)
Gullied granitic lowland (B2, B3, south of Morovis)
Hanging valleys (C3)
Meander, abandoned (A1, west side of river 1,000 m southwest of BM 98.4)
Meander, entrenched (A1, and many in southern two-thirds of map)
Meander core (A1)
Meander scar (A1, B2)
Parallel drainage (A2)
Piracy?, stream (B2, Quebrada Grande de San Lorenzo)
Slip-off slope (B1)
Terraces, river (A1, B2)
Undercut slope (B1)
Miscellaneous features:
Fine-textured topography (granitic area) (B2)
*Landslide topography (A3, western and southern sides of valley of Río Unibón)
Landslide topography (A1, B1, northwest of Río Cialitos and east of Río Grande de Manatí, both near Ciales)

Comerío. – 66°15' N., 18°07'30" W.; 10 m; Pease and Briggs (1960)
Mountain and structural features:
Asymmetric divide (C2, north end Quebrada Bocana)
Fault-line valley (B2, Río Arroyata)
Stream erosional and depositional features:
Box canyons (A1)
Falls (A1)
Flood plain (A1, C1, C3)
Gorge, V-shaped (B1)
*Hanging valleys (A1)
*Meander, abandoned (C1, La Plata; A1, southwest of Comerío)

Comerío – Continued
Stream erosional and depositional features – Continued
*Meander core (C1, hill northeast of La Plata)
*Meanders, entrenched (entire course of Rio de la Plata)
Slip-off slopes (B1, C1, C2, C3)
Terraces, river (many in southern two-thirds of map)
Miscellaneous feature:
Dam and reservoir (B3)

Florida. – 18°15' N., 66°37'30" W.; 10 m; Nelson and Monroe (1966)
Escarpment feature:
Escarpments (B1, B2, B3)
Karst (solution) features:
Disappearing stream (B2)
Hills in alluviated sinks (hums) (A1, A2)
Hill in center of sinkhole (B1, at west edge of map, 700 m south of Río Limón)
Interior drainage (northern third of map)
Karst valley, of coalesced sinks (A2, A3, Los Caños and Quebrada del Pozo Azul)
Sink holes (dolines) (northern third of map; also C3, west of Hacienda Flor de Alba)
Sinks, alluviated (A1, A2)
Sinks, compound (uvalas) (A3)
Mountain and structural features:
Dissected highland (southern half of map)
*Fault-line scarp (B1, B2, C2, C3)
*Fault-line valleys (B1, B2, C3)
*Outliers, of karst upland (B1, hills near Hacienda Piedra Gorda; also, west edge of map)
Structurally controlled drainage (B1, B2, C2, C3)
Stream erosional and depositional features:
Asymmetric valley (C3, near Hacienda Colom)
Flood plain (C3)
Gorge (C3)
Hanging valleys (B1, C1, C2)
Meanders, entrenched (southern third of map)
Slip-off and undercut slopes (C2)
Miscellaneous feature:
Contrasting topography (north half of map, karst; south half, structurally complex volcanic rocks)

Guánica. – 17°52'30" N., 67°00' W.; 1 and 5 m
Coastal features:
Bar, bayhead (B2)
Bay (bahía, ensenada) (A2, A3)
Beach (B3)
*Delta (A3)
Keys (cayos) (A1, B1)
Swamp, mangrove (A1, B1, B2, B3)
Submarine features:
Coral reefs (B3)
*Reef (arrecife), barrier (B2)
Reef, fringing (B3)
Shelf, insular (middle third)
Slope, insular (southern third)
Escarpment features:
Cliffs (B3)
*Cuesta (A2–A3, B2–B3)
*Dip slope (*see* cuesta)
Escarpment (A1, A2)
Mountain feature:
Cuchilla (knife-edged ridge) (A2, Cerro de Abra)
Stream erosional and depositional features:
Asymmetric valley (B2, valley of Escuela Las Salinas)
Fan, alluvial (A3)

Guánica.–Continued
Miscellaneous features:
Quarry (cantera) (A3)
Salinas (salt-evaporating pans) (A1, B1, B2)

Humacao.–18°07'30" N., 65°52'30" W.; 1 and 10 m; M'Gonigle (1978)
Coastal features:
Beaches (playas) (C3)
*Beach ridges (B3, C3)
Coastal plain (playa plain) (B3, C2, C3)
Distributaries (C2, C3)
Diverted river mouth (C3)
*Headland (C3, El Morillo)
*Prograded shore (B3, C3)
Swamp, mangrove (south half drained) (B3)
Submarine feature:
Shelf, insular (C3)
Mountain and structural features:
Cuchilla (knife-edge ridge) (A1, A2, A3, B1)
Differential erosion (hornblendite in ridge south of Escuela Regalado Rivera more resistant than adjacent granodiorite farther west) (C1-C2)
Fault-line valley (probable) (B1, C1, Rio Humacao, west northwest of Humacao)
Structurally controlled drainage (joints?) (C1)
Stream erosional and depositional features:
Fans, alluvial (A3, B1, B2, B3)
Flood plain (C1)
Flood plain having steep slope (A2, A3)
Gorge (B1, C1)
Gullies (B1, C1)
Hanging valley (B1–C1, Quebrada del Inglés)
Meanders (A3, B3)
Meanders, abandoned (C2)
Meanders, entrenched (C1)
Meander scar (C2, north of Miraflores)
*Piracy, stream, by headward erosion (A2, B2, Quebrada Mambiche and Quebrada Peña Pobre; B1, C1, Río Humacao)
Terraces, river (C2)
Miscellaneous features:
Canals, drainage (B3)
Contrasting topography, (fine dissection in granitic area in southewestern third of map; ridges of metavolcanic rock in northeastern two thirds)
*Fine textured topography (C1)
Mine (mina) (B1, an abandoned iron mine)
Quarry (cantera) (C1)

Manatí.–18°22'30" N., 66°30' W.; 1 and 5 m; Monroe (1971)
Coastal features:
*Bay, reverberation (beach shaped by advancing wave front) (A1)
Beaches (A1–A2, A3)
Beach, cuspate (A1–A2)
Diverted river mouth (A3)
*Lagoon (laguna) (A1-A2, A3)
Lagoon, filled (now swamp) (A2–A3)
Sea cliffs (A1, A2)
Swale (behind eolianite ridge) (now filled with beach sand) (A1)
Tombolo (A1, A3)
Submarine features:
Ridges, submerged (A3)
Shelf, insular (northern third of map)

Manatí.–Continued
Escarpment features:
Cliff (C1, especially at top of slope on east side Río Grande de Manatí)
Dip slope (C1, south of Iglesia Santos Apostoles)
Escarpment (C1)
Karst (solution) features:
*Blind valleys (C2, C3)
Cave (C3, Cueva Manahena)
*Disappearing streams (C2, C3)
Hills in alluviated sinks (B1, B2, B3)
*Interior drainage (southern two-thirds of map)
*Mogotes (haystack hills) (B1, B2, B3, especially near Combate)
Rampart, river (C1, top of slope east of Río Grande de Manatí)
Resurgence (C3, head of Quebrada Las Lajas)
Sink holes (abundant in southern third of map)
*Sinks, alluviated (C2, valley leading to El Salto and another 2 km farther east)
Sinks, compound (uvalas) (southern third of map)
Mountain features:
Outliers (C1, C2)
Parallel ridges (B1, B2, B3)
Stream erosional and depositional features:
Flood plains (B1-C1, B3)
Gorge (C3)
Levee, natural (C1)
Meanders (B1, B3, C1)
Terrace, river (C1)
Wind features:
*Deflation depressions (B2, in barrio Algarrobo)
Dunes (B2)
Eolianite ridge (A3, partly submerged)
Miscellaneous features:
Canals, drainage (A3)
Landslide topography (C1, east slope up from Río Grande de Manatí)
Quarries (canteras) (B1, B2, B3)

Quebradillas.–18°22'30" N., 67°00' W.; 5 and 10 m; Monroe (1967)
Coastal features:
Bar, river mouth (A1–A2)
Beach (A1)
Lagoon, filled (A1)
*Sea cliffs (A1, A2, A3)
Swamp, coastal-marsh type (A1)
*Terraces, marine (A1, A3)
Escarpment feature:
Escarpment (C1, C2)
Karst (solution) features:
Blind valleys (C2, C3)
Disappearing streams (C2, C3)
Interior drainage (southern half of map)
Mogotes (haystack hills) (B1, B2, B3)
*Rampart, ring, around doline (B1, 1 km south southwest of Iglesia Virgen del Carmen)
*Rampart, river (A1, B1, wall at top of west bank of gorge of Río Guajataca)
*Sink holes (dolines) (many deeper than 70 m) (B1, B2, C1, C2, C3)
Mountain and structural feature:
Strike ridges (A3, B3)

Quebradillas. – Continued
Stream depositional and erosional features:
Flood plain (A1–A2)
*Gorge, V-shaped, in limestone (A1, B1, B2, C2)
Meanders, entrenched (A1, A2, B1)
Wind feature:
Dunes, coastal (A1)
Miscellaneous features:
Canal, aqueduct (A1, B1, B2, C2)
Contrasting topography (northern third, nonkarst; southern third, karst)
Cultural contrast (no houses in west central part, in karst area)
Dam and reservoir (C2)
Landslide topography (C2, at and below dam of Lago de Guajataca)
Tunnels, aqueduct (A1, A2, B1, B2)

San Juan. – 18°22'30" N., 66°07'30" W.; 1 and 5 m; Kaye (1959a); Pense and Monroe (1977)
Coastal features:
*Bay (bahía) (A1–B2)
Beaches (B2, B3)
*Beach, cuspate (B2–B3)
Beachrock (A2, crosses west of Punta Piedrita)
Coastal plain (northern half of map)
Delta (B1, B2, of Río Piedras; now drained by Río Puerto Nuevo)
Distributary (B1, Río Puerto Nuevo; B2)
Lagoon (laguna) (B3)
Sea cliff (A1)
Swamp, mangrove (B1, B2, B3)
Tidal channel (B2, Caño de Martín Peña)
Submarine features:
*Canyon, submarine (A3)
*Reef (of submerged eolianite) (A2, A3)
Shelf, insular (northern third of map)
Slope, insular (northern third of map)
Escarpment feature:
Ecarpment (B3, south of highway 3)
Karst feature:
Mogotes (B1, peaks on Montes de Caneja)
Stream erosional and depositional features:
Flood plain (C2)
Meanders (C2)
Wind feature:
Eolianite ridge (A1, north end of San Juan Island)
Miscellaneous features:
*Channel, dredged (A1, B1)
*City wall (A1)
Dry dock (B1)
Filled land (A1, B1)
Forts, old Spanish (A1)
Harbor (A1-B1)
Lighthouse (faro) (A1)
Piers (A1, B1)
Quarry (cantera) (B1, C3)

Utuado. – 18°15' N., 66°45' W.; 1, 5, and 10 m (shaded relief); Nelson (1967)
Escarpment feature:
Escarpment (B1, B2, B3)
Karst (solution) features:
Cone karst (Kegelkarst) (A2, barrio Carreras)
*Exhumed nonkarst hills in karst area (A1, A2, along Route 621)

Utuado – Continued
Karst (solution) features – Continued
Hills in alluviated sinks (A3)
Interior drainage (northern half of map)
Karst valley (A1, Tanamá valley)
Mogotes (B1)
Rampart, river (A2, top of cliff west of river valley; B2, top of cliff in barrio Río Abajo)
Sink holes (dolines) (A1, A3)
Sinks, alluviated (A3)
Sinks, compound (A2, A3)
*Tunnels, natural (A1; four in valley of Río Tanamá)
Mountain and structural features:
*Asymmetric divide (between C2 and C3)
Outlier (B2; outlier of limestone on peak between two branches of lake)
Structurally controlled drainage (B3)
Stream erosional and depositional features:
Falls (saltillo) (B2)
Flood plains (A2, C1, C2)
Gorge (A2)
Gullies, in granitic rocks (C2)
Hanging valley (B2, Saltillo Jobos)
Meanders (C1)
Meander scars (A2)
Piracy, imminent (C1, several places)
Terraces, river (C1)
Miscellaneous features:
*Contrasting topography: karst area (A3), hills of volcanic rock (B3), gullied area underlain by granitic rock (C2), and area underlain by clay (northern part of C1)
*Cultural contrast (few houses in northern half, many in southern half)
Dams and reservoirs
Hydroelectric plant (A2, at dam; B3, at end of tunnel)
Landslide topography (A2, 1-2 km north northwest of Dos Bocas)
*River development, for power
Tunnels, aqueduct (B3, C3)

Vega Alta. – 18°22'30" N., 66°22'30" W.; 1 and 10 m; Monroe (1963)
Coastal features:
Bar, bayhead (A2)
Bar, river-mouth (A3)
Beach, barrier (A2)
Beach, cuspate (A3)
Beach ridges (low) (A1, A2–A3)
Beaches (playas) (A1, A2, A3)
Cape or point (punta) (A2)
Distributary (B3, Río Cocal)
Diverted river mouth (A3)
Islands (islas, isletas) (A1, A2, A3)
Lagoon (laguna) (A2)
Lagoon, filled (A1-B1-A2, Cíenaga Prieta)
Sea cliff (A1–A2, A3, Punta Cerro Gordo and Alto Las Ovejas)
Swamp, coastal-marsh type (A2, A3)
Submarine feature:
Canyons, submarine, heads of (A2, A3)
Escarpment features:
Dip slope (C2, C3, south slope of Río Lajas)
Escarpment (C2, C3, north side of Río Lajas)
Karst (solution) features:
Blind valleys (C1, C2)

Vega Alta. – Continued

Karst (solution) features. – Continued

Disappearing stream (C2)
Interior drainage (B1, B2, C1, C2)
Karst topography, dissected (C1, C2)
Mogotes (haystack hills) (B1, B2)
Sink holes (dolines) (southern third of map)
Sinks, compound (uvalas) (C1)

Stream erosional and depositional features:

*Abandoned channels (of Río de la Plata) (B3, ancient valley at Higuillar and ancient channel via Rio Cocal – see adjacent Bayamon Quadrangle – on both sides of present river channel)
Flood plains (B1, C3)
Gorge (C1)

Vega Alta. – Continued

Stream erosional and depositional features. – Continued

*Levees, natural, (of Rio de La Plata) (B3, C3)
Meanders (B3, C3)
Meanders, abandoned (B3)
*Meander scar (B1)
Oxbow lake (B3)
Terraces, river (C3, San José)
*Wind gap (B3, ancient valley of Río de La Plata at Higuillar)

Wind features:

Deflation depressions (small) (B2, just south of marsh)
Eolianite ridges (A1, A3, on coast)

Miscellaneous features:

Canals, drainage (A1, B1)
Landslide topography (C1, north of Capilla Fátima on both sides of Río Cibuco)

CHECKLIST OF LANDFORMS

Abbreviations of quadrangle names:

Ba, Barceloneta	Ci, Ciales	Ma, Manatí
Br, Barranquitas	Co, Comerío	Qu, Quebradillas
By, Bayamón	Fl, Florida	SJ, San Juan
Ca, Cabo Rojo	Gu, Guánica	Ut, Utuado
Ce, Central Aguirre	Hu, Humacao	Ve, Vega Alta

Landforms	*Quadrangles*
Coastal features:	
Bar, bayhead	*Ca, Gu, Ve
Bar, river-mouth	*By, Qu, Ve
Bay	By, Ca, Ce, Gu, *SJ
Bay, reverberation	Ca, *Ma
Beach (playa)	Ba, By, Ca, Ce, Gu, Hu, Ma, Qu, SJ, Ve
Beach, barrier	*Ca, Ce, Ve
Beach, cuspate	Ba, Ca, Ma, *SJ, Ve
Beach ridges	By, Ce, *Hu, Ve
Beachrock	*Ba, SJ
Cape or point	Ba, Ca, Ce, Ve
Coastal plain (playa plain)	*Ce, Hu, SJ
Delta	*Gu, SJ
Distributary,	Ba, *By, Hu, SJ, Ve
Distributary, abandoned	Ba, *By, Hu
Diverted river mouth	Ba, *By, Hu, Ma, Ve
Headland	*Hu
Islands	Ve
Key (cayo)	*Ce, Gu
Lagoon	Ca, Ce, *Ma, SJ, Ve
Lagoon, filled	Ba, Ma, Qu, Ve
Prograded shore	By, Ce, *Hu
Sand bar	Ce
Sea cliff	By, Ca, Ce, Ma, *Qu, SJ, Ve
Sea stack	*Ca
Spit, river-mouth	*Ba
Swale (behind eolianite ridge)	Ma
Swamp, mangrove or coastal-marsh type.	Ba, By, Ca, *Ce, Gu, Hu, Ma, Qu, Sj, Ve
Terrace, marine	*Qu
Tidal islands	*Ce
Tidal channel	SJ
Tombolo	Ba, *By, *Ca, Ma

*The landform is especially well displayed on topographic map indicated.

Landforms	*Quadrangles*
Coastal features – Continued	
Tombolo, incipient	*Ca
Submarine features:	
Canyon, submarine	*SJ, Ve
Coral reef	Ca?, *Ce, Gu
Drowned valleys	Ca
Reef (arrecife)	Ba, By, Ca, Gu, *SJ
Reef, barrier	Ce, *Gu
Reef, fringing	*Ce, Gu
Ridge, submerged	*Ba, Ma, SJ
Sand Bars	Ce
Shelf, insular	Ba, By, Ca, Ce, Gu, Hu, Ma,SJ
Slope, insular	Ca, Gu, SJ
Escarpment features:	
Cliff	Ba, By, Ci, Gu, Ma, Ut
Cuesta	By, *Gu
Dip slope	By, Ca, *Gu, Ma, Ve
Escarpment	Ba, Ci, Fl, Gu, Ma, Qu, SJ, Ut, Ve
Karst (solution) features:	
Blind valley	Ba, *Ma, Qu, Ve
Cave (cueva)	Ma
Cone karst	*Ci, Ut
Disappearing stream	Ba, Ci, Fl, *Ma, Qu, Ve
Exhumed nonkarst hill in karst area	*Ut
Hill in alluviated sink	Fl, Ma, Ut
Hill in center of sinkhole	Fl
Interior drainage	Ba, By, Ci, Fl, *Ma, Qu, Ut,Ve
Karst valley	Ba, Ci, Fl, Ut
Karst topography, dissected	Ve

Landforms	*Quadrangles*
Karst (solution) features – Continued	
Mogote (haystack hill)	Ba, By, *Ma, Qu, SJ, Ut, Ve
Perched stream	Ba
Rampart, river	Ci, Ma, *Qu, Ut
Rampart, ring	*Qu
Resurgence	Ba, Ma
Sink hole (doline)	Ba, Ci, Fl, Ma, *Qu, Ut, Ve
Sink, alluviated	Fl, *Ma, Ut
Sink, compound (uvala)	*Ba, Fl, Ma, Ut, Ve
Tunnel, natural	Ma, *Ut
Zanjones	*Ci
Mountain and structural features:	
Asymmetric divide	Br, Co, *Ut
Cuchilla (knife edge ridge)	Gu, Hu
Differential erosion	Hu
Dissected highland	*Br, Ci, Fl
Fault-line scarp	Br, *Fl
Fault-line valley	Ci, Co, *Fl, Hu
Graben valley	*Br
Monadnock	*Br
Outlier	*Fl, Ma, Ut
Parellel ridges	Ba, Ma
Strike ridges	By, Ca, Qu, SJ
Structurally controlled drainage.	*Br, Fl, Hu, Ut
Stream erosional and depositional features:	
Abandoned channel	*Ve
Arroyos	*Ce
Asymmetric valley	Fl, Gu
Box canyons	Br, Co
Dendritic drainage	By
Falls	Co, Ut
Fan, alluvial	Ca, *Ce, Gu, Hu
Flood plain	*Ba, Br, By, Ce, Ci, Co, Fl, Hu, Ma, Qu, SJ, Ut, Ve
Gorge	Br, Ci, Co, Fl, Hu, Ma, *Qu, Ut, Ve
Gullies	Br, Ce, Ci, Hu, Ut
Hanging valley	Br, Ci, *Co, Fl, Hu, Ut
Levee, natural	Ba, By, Ma, *Ve
Meanders	*Ba, Br, By, Hu, Ma, SJ, Ut, Ve
Meander, abandoned	By, Ci, *Co, Hu, Ve
Meander, entrenched	Br, Ci, *Co, Fl, Hu, Qu
Meander core	By, Ci, *Co
Meander scar	Ba, Ci, Hu, Ut, *Ve
Oxbow lake	Ba, By, Ve
Parallel drainage	Ci
Piracy, stream	By, Ci, *Hu
Piracy, imminent	Ut
Slip-off slope	Ci, Co, Fl
Terrace, river	By, Ci, Co, Hu, Ma, Ut, Ve
Undercut slope	Ci, Fl
Wind gap	*Ve
Youthful stage of erosion	Br
Wind features:	
Deflation depression	Ba, *Ma, Ve
Dunes	Ba, By, Ma, Qu
Eolianite ridges and hills	Ba, By, Ma, SJ, Ve

Landforms	*Quadrangles*
Miscellaneous features:	
Canal, aqueduct	Ce, Qu
Canals, drainage	Ba, By, Ce, Hu, Ma, Ve
Causeway	By
Channel, dredged	Ce, *SJ
City wall	*SJ
Contrasting topography	Fl, Hu, Qu, *Ut
Cultural contrast	Qu, *Ut
Dam	Br, By, Ce, Co, Qu, Ut
Drydock	SJ
Filled land	By, SJ
Fine-textured topography	Ci, *Hu
Forts, old Spanish	SJ
Harbor	Ce, SJ
Hydroelectric plant	Ut
Insular divide	Br
Irrigation ditch	Ce
Irrigation ponds	Ce
Landslide topography	*Ci, Ma, Qu, Ut, Ve
Lighthouse (faro, range lights)	By, Ca, Ce, SJ
Mine (mina)	Hu
Piers	SJ
Quarry (cantera)	Br, By, Gu, Hu, Ma, SJ
Reservoir	Br, Ce, Co, Qu, Ut
River development	*Ut
Salina (salt-evaporating pan)	*Ca, Gu
Tunnels, aqueduct	Qu, Ut

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☆ U.S. GOVERNMENT PRINTING OFFICE: 1980 O—311-344/76