The Karst Landforms of Puerto Rico

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A discussion of a solution landscape formed in a tropical climate of moderately high rainfall

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By Watson H. Monroe

ABSTRACT

Puerto Rico has a great variety of landforms developed by solution of limestone under tropical climatic conditions. Karst topography is present in most parts of Puerto Rico where limestone crops out, but it is more highly developed in the northern and northwestern parts, which are underlain by thick limestone formations of Oligocene and Miocene age.

Puerto Rico has a warm climate dominated by nearly constant easterly trade winds and by rainfall generally scattered throughout the year but characterized by sudden short showers. The warm humid air of the trade wind belt promotes the rapid and intense weathering of all intrusive and volcanic rocks, producing thick soils. The torrential rains cause rapid erosion of the soil, and when the soil contains abrasive mineral grains, the erosion rapidly deepens valleys. The rains also lead to the casehardening of limestone, for when the water enters porous limestone it immediately dissolves the surfaces of the grains and crystals of calcite. As these rains usually last only a short time and are followed by brilliant sunshine, the wet rock is warmed, carbon dioxide is driven off, and calcium carbonate is reprecipitated essentially in place. The streams containing sand, gravel, and cobbles derived from soil on igneous rocks have eroded deep canyons through the limestone and have greatly enlarged the passages of the river caves of Puerto Rico. The nearly constant wind direction has resulted in asymmetry of many of the limestone hills at places where the hills are sufficiently isolated to allow full play of the wind.

The karst features of Puerto Rico have been formed entirely in carbonate rocks and mostly in limestone. The limestone ranges in age from Early Cretaceous to Quaternary, but the main karst development has been in limestone of Oligocene and Miocene age in northern Puerto Rico. This middle Tertiary limestone terrane is crossed by several large cuestas with south-facing scarps which constitute notable barriers to travel, except at those places where rivers from the interior cross the belt on the way to the coast. The back slopes of the cuestas have been dissolved into a wilderness of karst forms including dry valleys, closed depressions, some of which are more than 70 m deep, towers, conical hills, and caves.

Some of the dry valleys are apparently relicts of surface drainage on a nonkarst surface, but others appear to be determined by joint control. The closed depressions are chiefly of the irregular kind generally known in tropical karst studies as cockpits, but some are regular as the dolines of the classical karst terrane of the Mediterranean region. Hill features include mogotes or towers, cone karst, and many river and coastal ramparts or walls of limestone, which rise high above deep canyons and on the opposite side drop down lesser distances to flat plains of the detrital material known as blanket sand. Solution of the limestone beneath the blanket sand has left the mogotes of northern Puerto Rico projecting through the sand as residual hills. The isolation of these hills by the surrounding plains of blanket sand has permitted the trade winds to shape the hills asymmetrically, gentle on the windward side and steep on the lee.

In several places, relatively thin-bedded limestone in beds a few centimetres thick has been dissolved into long narrow trenches known as zanjones. Zanjones are found only in the lower part of the sequence of middle Tertiary rocks.

The karst areas of Puerto Rico contain hundreds of caves, some of which contain rooms more than 30 m high and several kilometres long, traversed by through-flowing rivers that head in volcanic and intrusive rocks. The locations of more than 100 caves are shown on the map accompanying the report.

INTRODUCTION

Puerto Rico, the easternmost of the Greater Antillean Islands north of the Caribbean Sea, has a wide variety of karst features formed in a tropical climate, which is humid on the north side of the island and semiarid on the south side. Although the areas of karst terrane are not large, they have aroused the interest of karst specialists, especially from Europe, because of the excellent examples of cone karst, tower karst, well-developed cuestas, and many features not known elsewhere.

Exact locations in this report are given in metres referred to the Puerto Rico rectangular-grid coordinate system, marked by tics on the borders of the karst map accompanying this report (pl. 1) and on the border of all U.S. Geological Survey topographic maps of Puerto Rico. The numbers show the metres east and north of an arbitrary reference point south of Isla de Mona southwest of Puerto Rico. For greater convenience to the reader, the name of the quadrangle in which the feature is located is also referred to. Figure 1 is an index map showing names of quadrangles in Puerto Rico.

SCOPE OF PRESENT REPORT

This report attempts to describe and classify the karst landforms of Puerto Rico, especially those formed in the northern karst belt in the outcrop area of limestones of Oligocene and Miocene age. Isolated observations of karst phenomena in other areas are made where possible. Only very general observations, mostly quoted from the literature, will

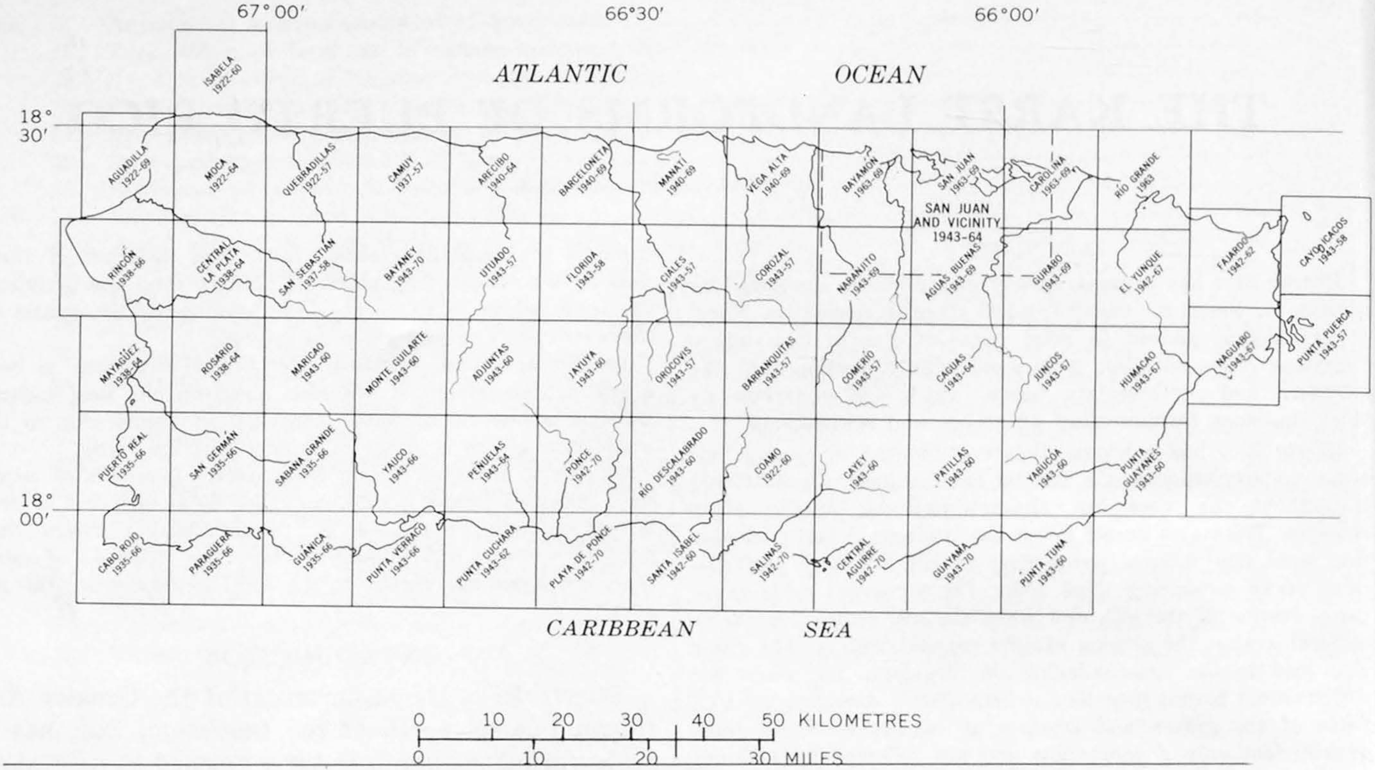

FIGURE 1.—Index map showing names of 7½-minute quadrangles in Puerto Rico.

be made on the phenomena of karst hydrology and the rate of karst denudation; such studies are being conducted by specialists from Europe and from the U.S. Geological Survey. The extensively developed karst features of Isla de Mona, a dependency of Puerto Rico about 40 miles farther west, are not described in this report; the reader is referred to works by Kaye (1959b) and Briggs and Seiders (1972).

PREVIOUS INVESTIGATIONS

Puerto Rico has such a wide variety of karst features—landforms and underground drainage phenomena—that it has become an area of great interest to karst specialists, especially from Europe. It is noted for its cone karst (Kegelkarst), its tower karst, the high cuesta scarps held up by limestone, and many minor features not reported from other areas.

The first scientific papers referring to karst areas of Puerto Rico were by Hill (1899a, p. 100, 101; 1899b, p. 9, 10), who merely noted the limestone hills near Lares and San Sebastián. He called them cockpits (erroneously) and pepinos (cucumber-shaped hills) and considered them to be remnants of a dissected cuesta.

Berkey (1915, p. 52) coined the term "haystack hill" for these features, which he ascribed to differential erosion. He believed that the purer parts of the limestone are dissolved into many large caves which collapsed to leave sinkholes. These then enlarged and merged, smaller caves collapsed to form notches between the hills, and finally the hills were left standing surrounded by the residuum from solution. Less pure, more clayey limestone was not subject to solution and formed the floor on which the residue from solution accumulated.

In his study of the physiography of Puerto Rico, Lobeck (1922, p. 329–336) called attention to the cuesta scarp between Morovis and Lares, pointing out that it cuts the conical hills, which he believed were remnants of a former continuous surface left by collapse of underground cavities. He also noted the Los Puertos cuesta scarp (formed by the Aguada Limestone) which he traced from Moca to the Río Grande de Arecibo. He considered the apparent wave-cut bench west of the Río Guajataca to be the result of planation on a bedding plane and to be similar to the benches formed on limestone layers in the Cibao Formation on the sides of the Río Grande de Manatí. He also concluded that the rivers from the interior, such as the Río Camuy and the Río Tanamá, flow along courses carved before deposition of the limestone; recent studies reported in the present paper do not support this idea.

The first detailed study of the karst features of northern Puerto Rico was made by Hubbard (1923). He considered that the entire karst belt is a plateau dissected largely by solution. The southern edge is marked by the Lares cuesta scarp, which is the highest part of his plateau. North of the cuesta he divided the country into four topographic belts: from south to north, the Lares Pepino Belt, the Cibao Prairie Belt, the Los Puertos Pepino Belt, and the Quebradillas Plateau Belt. The Los Puertos Belt includes the area characterized now by abundant sinks in the Aguada Limestone and the mogotes of the Aymamón Limestone, and the Quebradillas belt is the outcrop area of the upper chalky part of the Aymamón Limestone and the Camuy Formation (Zapp and others, 1948). Hubbard also called attention to the underground course of the Río Camuy and suggested that the Río Guajataca may be a deroofed cave stream. He noted the asymmetric shape of the hills, steeper on the western side. He explained this by pointing out that showers usually occur in the afternoon when the sun has been shining on the hills from the west, so that the rock on the west side is hotter than that on the east or shaded sides. He believed that this difference increased the rate of solution and resulted in a more cavernous structure on the west sides. He believed that linearity of arrangements of the hills is due to collapse of underground linear drainage lines.

James Thorp (1934), while engaged in soil studies in Puerto Rico, suggested that the asymmetry of the mogotes in northwestern Puerto Rico is due to the beating of rain on the eastern sides of the hills because of the trade winds. This results in more solution on the windward slopes. He also believed that the valleys between the hills resulted from collapse of caves.

The first study devoted to karst features alone was written by Meyerhoff (1938), who related karst development to the relative solubility of the various limestone formations. He ascribed the coarseness of the texture, that is, the relative distance between limestone residual hills, to the vertical interval between the old peneplained surface above the tops of the mogotes and the top of the water table. He also ascribed the plateau in northwestern Puerto Rico to planation by marine erosion.

The next studies of consequence were made by Lehmann (1954), who classified much of the karst area of Puerto Rico as cone karst or Kegelkarst and who ascribed the lineation found between hills to solution along joints. He believed that the mogotes of northern Puerto Rico are the result of lateral planation by streams, and he concluded that the formation of cone karst ceases near the sea and that the depressions grow in a horizontal direction to eventual evenness. He coined the term "directed karst" (gerichtete Karst), which he explained by solution along joints. The pioneering work of Lehmann was followed by more detailed studies in the Florida area (Barceloneta and Florida quadrangles) by Gerstenhauer (1964).

Detailed geologic mapping of the quadrangles in northern Puerto Rico by Briggs (1965, 1968), Monroe (1962, 1963a, b, 1967, 1969a, b, 1971, 1973b), Berryhill (1965), Nelson (1967a, b), Nelson and Monroe (1966), Nelson and Tobisch (1968), and Tobisch and Turner (1971) has added a great deal of information about distribution and lithology of the limestone formations and has provided most of the geomorphic information incorporated in the present report. Specific contributions of essentially new concepts were made by Briggs (1966) in his descriptions of the blanket sands and by Monroe in his description of the zanjón (1964b) and his discussion of the casehardening and asymmetry of mogotes (1966b), of subsoil solution (1969c), and of evidence of a former clastic cover of some of the Lares Limestone that resulted in superposed drainage (1974).

Studies of the Camuy caves and their geology by Gurnee, Thrailkill, and Nicholas (1967) and Thrailkill (1967), of the Río Tanamá Canyon by Gurnee (1972), and of several river cave systems by Nelson (1970?) showed for the first time how very large and extensive are some of the caves in northern Puerto Rico.

Blume (1968, 1970) described in detail the cuestas and cuesta scarps made by the Lares and Aguada Limestones, giving much more specific information than Hubbard. He noted that some scarps are scalloped and others are straight.

Moussa (1969) discussed stream capture of a small drainage system in southern Puerto Rico by headward development of a cave system.

Miotke spent a month in Puerto Rico in 1969 making fundamental studies on the rate of solution of Aguada and Aymamón Limestones and the composition of the karst water on the surface and underground. He also observed subsidence of the blanket sand plains by collapse of underground cavities (Miotke, 1973).

Birot, Corbel, and Muxart (1968) made reconnaissance studies of the hydrology of the karst region of northern Puerto Rico and compared Puerto Rico with Jamaica.

More complete studies of the hydrology of the karst area of northern Puerto Rico have been carried out by Ennio Guisti and Ferdinand Quiñones (unpub. data, 1974) of the U.S. Geological Survey.

Data on the hydrology of the karst area, including volume and quality of surface and subsurface water, are included in the compilation of water records of Puerto Rico, 1958–63 (Kipple and others, 1968). A study of the chemical quality of the water in Cienaga Tiburones east of Arecibo gives the location of several of the large karst springs and analyses of their water (Díaz, 1973).

TERMINOLOGY

Most of the karst terms used in this report are familiar to geomorphologists, but for the benefit of those persons who do not have a background in geomorphology or physical geography, definitions of selected karst terms are given below.

The karst terms defined here include only those used in the present paper. The definitions have been taken mainly from "A Glossary of Karst Terminology" (Monroe, 1970) and from a multilingual glossary of karst and speleological terminology (Commission for Documentation, International Speleological Union, unpub. data, 1974). The reader is also referred to the terms published by Sweeting (1972, p. 332–335) and Jennings (1971).

aggressive water: Water having the ability to dissolve rocks. In the context of limestone and dolomite, this term refers especially to water containing dissolved carbon dioxide.

beachrock: A friable to indurated rock consisting of sand grains of various minerals cemented by calcium carbonate; naturally cemented beach sand.

bicarbonate: A salt containing the radical HCO_3^{-1}, such as $Ca(HCO_3)_2$.

blind valley: A valley that ends suddenly downstream at an upward slope or rock face; any stream in the valley that disappears underground in swallow holes or in a cave.

bogaz: A solution-enlarged joint 2–4 m wide and extending linearly for some tens of metres.

breakdown: See cave breakdown.

casehardening: In the context of karst terminology, the induration of the surface of limestone by solution and reprecipitation of calcium carbonate.

cave: A natural underground room or passage large enough to be entered by man.

cave breakdown: (a) Enlargement of parts of a cave system by fall of rock masses from walls and ceiling. (b) Rock that has collapsed from the walls and ceiling of a cave.

cave system: An underground network of connected cavities that can be penetrated by man.

cliffed cone karst: Cone karst in which each cone is surmounted by a vertically walled tower.

cliff-foot cave: A cave formed at the foot of a cliff by solution by standing water in a lake or a swamp; cliff-foot caves are also common at sea level or former stillstands of sea level. Commonly called Fusshöhl in international terminology.

closed depression: A general term for any enclosed topographic basin having no external drainage, regardless of origin or size.

cockpit: (a) Any closed depression having steep sides. (b) More exactly, the irregularly shaped depressions surrounding conical hills in cone karst.

collapse doline, collapse sink: A closed depression formed by the collapse of the roof of a cave.

cone karst: A type of karst topography, common in the tropics, characterized by many steep-sided cone-shaped hills surrounded by more or less star-shaped depressions; equivalent to Kegelkarst.

corridor: Open or closed valley, commonly straight, cut in soluble rock, having steep or overhanging side walls. Mostly located on joints or zones of weakness.

cuesta: A hill or ridge with a gentle slope on one side and a steep slope on the other; the gentle slope generally conforms with the dip of resistant beds that form it, and the steep slope or scarp is formed by the outcrop of the resistant strata.

cuesta karst: A type of karst formed on a cuesta, characterized by a steep slope or scarp at one side of an area and sinks and towers on the gentle slope.

doline: A simple closed karst depression with subterranean drainage, having a shape like a dish, a funnel, or a cauldron. Its diameter normally exceeds its depth. Dolines may have asymmetric longitudinal or cross sections. They are subdivided according to their shapes or supposed origin.

doline karst: A type of karst topography characterized mainly by dolines.

dome pit: A vertical overhead cavity in a cave, generally with an arched ceiling and underlain by a vertical shaft.

drip line: A line at the entrance to a cave that is directly below the top of the entrance.

dripstone: Hanging or standing concretion of calcium carbonate formed by dripping water; collective term for such features as stalactites, stalagmites, columns, drapery, and so forth.

dry valley: A valley that at present lacks a surface stream or river because of underground drainage.

eccentric: European term for a speleothem having an abnormal shape; in the United States eccentrics are generally called helictites.

emergence: Karst spring generally flowing with a large quantity of water. These springs are classified, where possible, into exsurgences and resurgences.

exsurgence: An emergence with no known surface headwaters.

Fusshöhl: A cliff-foot cave.

guano: Deposit of excrement of bats and swallows; used as fertilizer.

haystack hill: Early Puerto Rican English term for mogote.

helictite: A curved or angular twiglike projection from the side or bottom of a stalactite.

impermeable confining bed: A nearly impervious stratum above or below an aquifer; formerly called aquaclude.

impounded karst: A karstified body of limestone of limited area completely surrounded by rocks of low permeability. A term proposed by Jennings (1971) for the French karst barré.

karren: The surface and subterranean minor solution features of the karst landscape, consisting of channels, furrows, or basins dissolved on surfaces of limestone.

karst, karst landscape: A terrain in which subterranean drainage follows cavities in readily soluble rocks (karstifiable rocks) and in which characteristic surface and underground features appear (karst phenomena). Readily soluble rocks are chiefly limestone, but include dolomite, other carbonate rocks, gypsum, salt, and so forth.

karst barré: Impounded karst.

karst denudation: The removal of carbonate rocks by solution. The term is generally used in determining the rate of lowering of the surface by solution.

karst hydrology: Science of the behavior of waters in karst areas.

karstifiable rocks: Collective term for all those rocks in which, owing to their solubility in water, karst phenomena can develop.

karstification: The evolutionary process of forming a type of terrain in soluble rocks with surface and subterranean phenomena that are the result of solution.

karstify: To form karst phenomena by solution.

karst landscape: See karst.

karst phenomena: General term applied to the entire group of surface and subterranean features and the hydrologic regime of the karst landscape.

karst spring: Any overflow or point of escape of karst water to the surface or into a cave.

karst type: A karst landscape whose surface is characterized by the occurrence of a single dominant karst feature or a group of features. The names of the types of karst landscape depend on dominant geographical, geological, hydrological, climatic, and genetic aspects. Examples are tropical karst, doline karst, and tower karst.

Kegelkarst: German term for cone karst.

lapiés: French term for karren; commonly also used in English-speaking areas.

mogote: A steep-sided hill of limestone generally surrounded by nearly flat alluviated plains; karst inselberg.

natural arch: A rock arch or very short natural tunnel.

natural bridge: A rock bridge spanning a ravine and not yet eroded away.

natural tunnel: A nearly horizontal cave open at both ends, generally fairly straight in direction and fairly uniform in cross section.

pepino: Name used by Hill (1899a) and Hubbard (1923) for mogote.

polje: Extensive depression in karst terrain closed on all sides, having a flat bottom and steep walls. In many places the walls form a sharp angle with the floor. There is no outflowing surface stream. A polje may be completely dry, have a surface stream originating and ending within it, or be inundated all the year round or temporarily.

resurgence: Reemergence of a stream that has earlier sunk underground; the term is also commonly but incorrectly used for any emergence.

Rillenkarren: Shallow channels eroded by solution in limestone, separated by sharp ridges 2–3 cm apart.

Rinnenkarren: Flat-bottomed grooves several centimetres apart separated by sharp ridges.

river cave: A cave in which a stream flows. The stream may be perennial or intermittent.

rock shelter: A natural shallow cave, generally under an overhanging ledge and having a more or less flat bottom.

shaft: American term for a vertical cave on the surface or a vertical passage in a cave.

shelter cave: A small cave in which the maximum horizontal extension seldom exceeds the width of its mouth.

sink, sinkhole: An American term used generally for closed depressions, especially referring to dolines, vertical caves, and swallow holes.

sinter: Calcareous concretionary material, generally crystalline, deposited from flowing water both on the surface and in caves.

siphon: Place where the ceiling of a cave dips beneath either quiet or running water; this immersion separates parts of the cave which otherwise belong together.

solution: The change in matter from a solid or gaseous state to a liquid state by combination with a liquid. In the scientific study of karst phenomena, the erosion of karstifiable rocks by chemical means with the aid of acids, especially carbon dioxide in water.

solution pan: Shallow solution basin formed on bare limestone, generally characterized by flat bottom and overhanging sides. Synonyms: Kamenitza, Opferkessel, panhole, tinajita.

speleologist: A scientist engaged in the study and exploration of caves, their environment, and their biota.

speleothem: A secondary mineral deposit formed in caves, such as stalactite or stalagmite.

Spitzkarren: Vertical spearlike or steeplelike spikes of limestone left by solution; from a few centimetres to more than 1 m long.

stalactite: A cylindrical or conical deposit of minerals, generally calcite, formed by dripping water, and hanging from the roof of a cave or at the bottom of a cliff. Most stalactites have a hollow tube at the center.

stalagmite: A deposit of mineral matter, commonly calcite, rising from the floor of a cave, formed by precipitation of minerals from solutions dropping from above.

stream sink: Point at which a surface stream sinks into the ground; swallow hole.

struga: A corridor or trench formed by solution along a bedding plane in steeply inclined strata of limestone.

subsidence: Gradual sinking or settling to a lower level, as the slow descent of the roof of a cave or of the surface of the ground above a cavity.

swallow hole: The place where a surface stream disappears underground; a stream sink.

tower: A steep-sided hill in a karst terrain.

tower karst: General term for a karst terrain dominated by steep-sided hills, such as cone karst and mogote karst.

travertine: Limestone precipitated from a flowing stream, generally more tightly cemented and stronger than calcareous tufa.

uvala: A large, dish-shaped or elongate karst depression having an uneven bottom, commonly containing scattered dolines.

vertical cave: A natural cavity that is vertical, or nearly so, on the surface or in a cave, in which the depth exceeds the width. Also known as a shaft or natural well and in Great Britain as a pit or pothole.

zanjón: A solutional trench in limestone, generally ranging from a few centimetres to several metres in width, from about 1 to 4 m deep, and from a few tens to more than a thousand metres long. Generally several zanjones occur parallel to each other only a few metres apart. Puerto Rican term for corridor.

zanjón karst: A karst terrain dominated by zanjones.

ACKNOWLEDGMENTS

Many landowners, geologists, geographers, and speleologists have contributed information incorporated in this report. Where possible, these sources are acknowledged in the text. Special thanks are due to Russell H. Gurnee, of the Explorers Club, for information about the Camuy and Tanamá Rivers and for maps of several caves; José Martínez Oquendo, of the Puerto Rico Department of Natural Resources, who also located on maps many of the caves shown on the limestone map and listed only by name in the list of karst features; Pedro A. Gelabert and Ramón Alonzo, consulting geologists, who showed me several caves in the field; and Donald G. Jordan, District Hydrologist, U.S. Geological Survey, who contributed unpublished information on karst hydrology.

PHYSIOGRAPHIC AND GEOLOGIC SETTING

PRINCIPAL GEOGRAPHIC REGIONS OF PUERTO RICO

Puerto Rico can be divided into three main geographic regions (fig. 2): a mountainous area that constitutes most of the southern two-thirds of the island, a belt of rugged karst topography in the north-central and northwestern parts of the island,

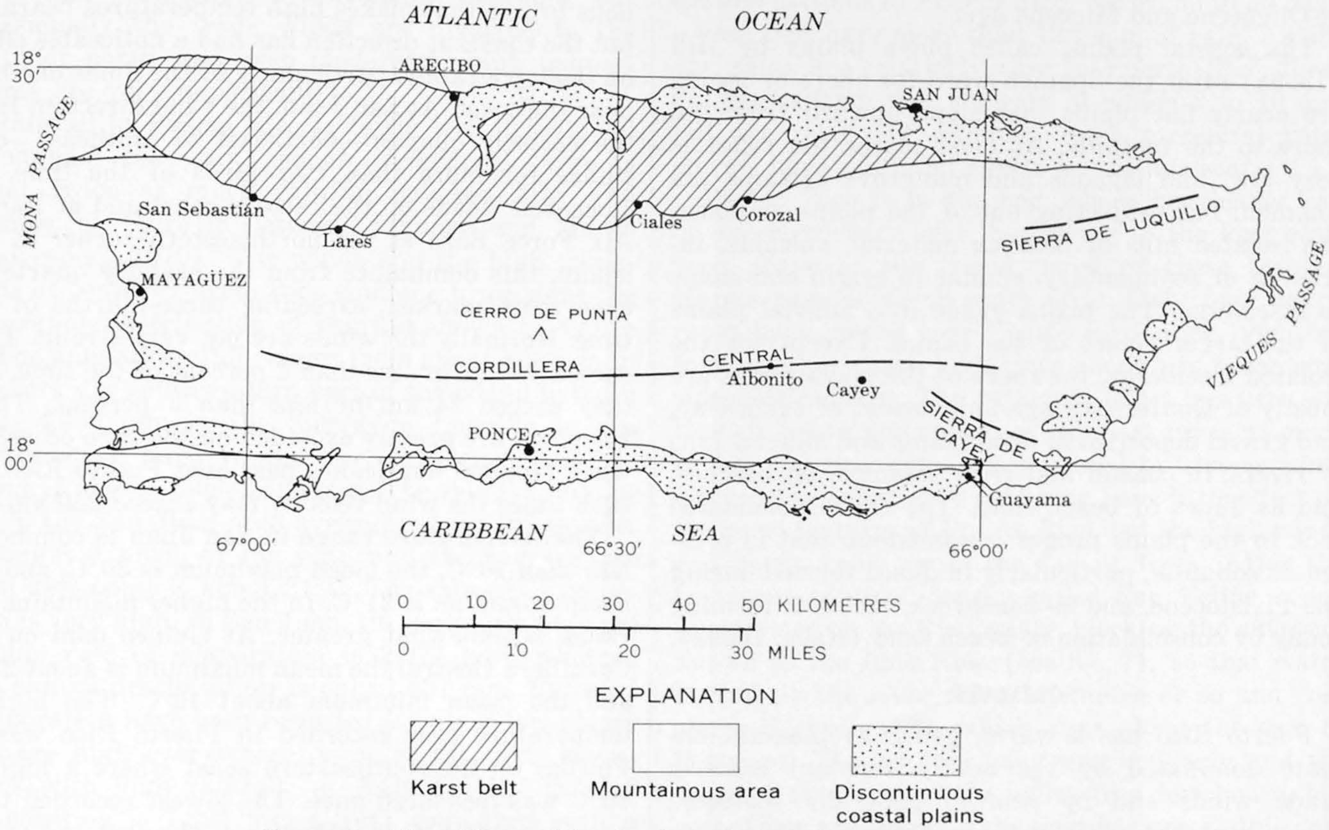

FIGURE 2.—Map of Puerto Rico showing principal physiographic divisions.

and a discontinuous fringe of relatively flat coastal plains.

The mountainous area extends from the Mona Passage on the west to the Vieques Passage on the east and occupies the southern two-thirds of the island, except for a wide coastal plain between Guayama and Ponce. The relief is dominated by the Cordillera Central from Mayagüez to Aibonito and farther east by the Sierra de Cayey near the southern coast and by the Sierra de Luquillo in the northeastern part of the island. The Cordillera Central is only 15 to 20 km from the south coast through much of its length, and it includes the highest peaks in Puerto Rico, of which the highest, Cerro de Punta, is 1,338 m above sea level. The mountainous area has been deeply eroded by streams into valleys several hundred metres deep; valley sides are steep, with slopes of 30° to 45° not uncommon.

The rocks in the mountainous area are predominantly volcanic, including lava and tuff, sedimentary rocks derived from volcanic rocks, intrusive rocks, and discontinuous beds of limestone (Briggs and Akers, 1965). These rocks range in age from Early Cretaceous to middle Eocene. In the south-central and southwestern parts of the island the mountainous area extends to the Caribbean Sea at some places and includes clastic sediments in part derived from volcanic rocks and limestone of Oligocene and Miocene age.

The karst region in north-central and northwestern Puerto Rico is an area underlain mostly by limestone, in which the topography is chiefly formed by solution. The topography varies in relief from extremely rugged karst terrain, in which vertical cliffs are common, to rather gentle rolling hills having a relief of only a few tens of metres. Most of the drainage is underground except along the courses of those rivers that flow across the belt from the mountainous area to the Atlantic Ocean, and parts of two of these are underground. The highest altitudes within the karst region are along an escarpment at its southern edge, commonly higher than 400 m; the highest point is 530 m. A large part of the present report will describe this karst area. The rocks cropping out in the karst are principally limestone and secondarily subordinate amounts of chalk and dolomite and of gravel, sand, and clay derived from the volcanic rocks of the mountains. Within the karst region are a few inliers of volcanic rock—exhumed hills of the surface on which the sediments were deposited. The rocks of the karst region are of Oligocene and Miocene age.

The coastal plains, called playa plains by Hill (1899a) after the Spanish word for shore or beach, are nearly flat plains that slope upward from the shore to the foothills. At most places the relief is very low, and lagoons and mangrove swamps are common, but projecting out of the plains at places are isolated hills of bedrock material, volcanic, intrusive, or sedimentary, similar in origin and shape to inselbergs. The plains grade into alluvial plains of the larger rivers of the island. Except for the isolated inselbergs, the rocks of the playa plains are mostly of Quaternary age and consist of sand, clay, and gravel deposited in flood plains and alluvial fans of rivers, in coastal and river swamps, on beaches, and as dunes of beach sand. The only consolidated rock in the plains proper is sandstone that is present as eolianite, particularly in dunes formed during the Pleistocene, and as beachrock, which is forming today by consolidation of beach sand (Kaye, 1959a).

CLIMATE

Puerto Rico has a warm, generally pleasant climate dominated by the nearly constant easterly trade winds and by rainfall generally scattered throughout the year, but characterized by sudden showers. (fig. 3)

The trade winds not only provide a nearly continuous breeze that makes high temperatures bearable, but the constant direction has had a noticeable effect on the topography, particularly of the limestone hills near the coast. At San Juan, the wind direction from the easterly quarter—northeast to southeast—continues for more than two-thirds of the time. At Roosevelt Roads on the eastern coast and at Ramey Air Force Base at the northwestern corner of the island, this dominance from the easterly quarter is even more marked, exceeding three-fourths of the time. Normally the winds are not very strong. They exceed 38 km/hr less than 1 percent of the time, and they exceed 24 km/hr less than 5 percent. These velocities are greatly exceeded on the rare occasions when tropical hurricanes pass over Puerto Rico. At such times the wind velocity may exceed 250 km/hr.

The temperature range in 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 on the Cordillera Central 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 on the southeastern coast where a high of 40°C was measured once. The lowest recorded temperature was 6°C at Aibonito at the east end of the Cordillera Central. The constant trade winds make

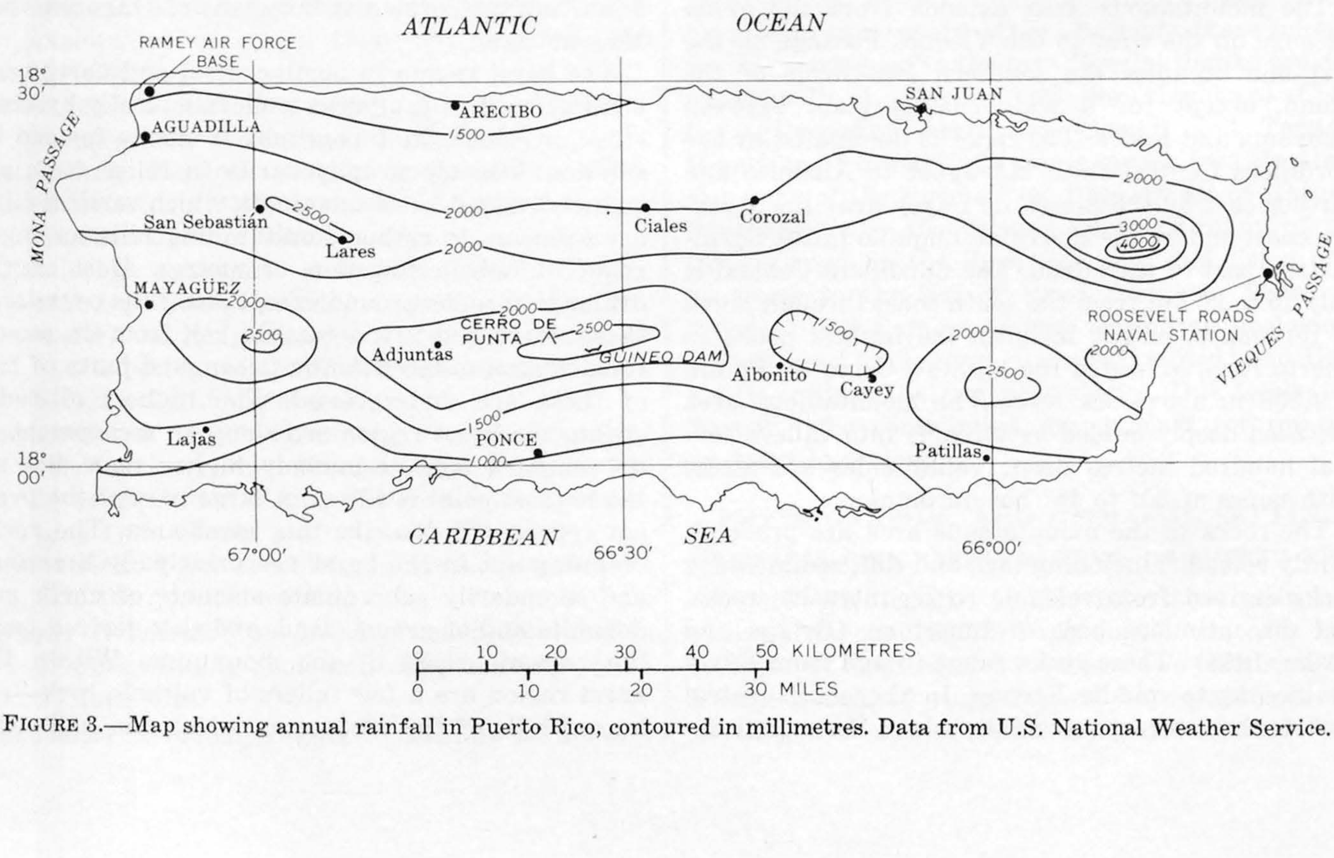

FIGURE 3.—Map showing annual rainfall in Puerto Rico, contoured in millimetres. Data from U.S. National Weather Service.

even high temperatures reasonably bearable, but occasionally the trade winds are diverted to the south or north, and even moderately high temperatures are very unpleasant.

Rainfall in Puerto Rico is fairly well distributed throughout the year, though in general there is about twice as much rainfall between May and October as there is between January and March (Calvesbert, 1970). The winds and the high mountains of central Puerto Rico combine to produce the orographic distribution of rainfall shown by figure 3. The annual rainfall ranges from about 860 mm in the very dry southwestern part of the island to more than 4,000 mm in the Sierra de Luquillo in the northeastern part. In the northern karst belt the range is about 1,300–2,500 mm. The relative humidity in the San Juan area averages about 80 percent throughout much of the year, and the average annual dew point 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, whereas the annual precipitation is only 1,631 mm. Rates of evaporation have been recorded at only a few places but are high everywhere, even in the high mountains with high rainfall; at Adjuntas the rate of evaporation is 1,294 mm a year compared with a rainfall of 2,146 mm.

The combination of high temperature, constant wind direction, high evaporative rate, and orographic rainfall have produced very strong rain shadows in the lee of most of the mountain ranges in Puerto Rico. This is most pronounced in southwestern Puerto Rico in the lee of the Cordillera Central, where at several stations the rainfall is less than 1,000 mm, and at Lajas the evaporative rate is more than 2,000 mm. This results in a semiarid or steppe climate. The orographic precipitation and the accompanying rain shadow are even noticeable in the relatively high rainfall in the higher parts of the northern karst belt, which reaches about 2,500 mm in the western part, accompanied by a shadow having only about 1,900 mm immediately south of the karst area.

Most showers in Puerto Rico are sudden and have sharp boundaries, so that the path of a shower is plainly marked. The showers tend to be torrential, but are estimated to last usually only from 15 min to half an hour. The U.S. National Weather Service records only the mean number of days per year with precipitation of 12.7 mm or more. Although one cannot say that all such rain will be in one shower, the frequency of such days indicates an abundance of hard showers. More than 40 stations, nearly half of the 100 stations in Puerto Rico, record 30 to 50 days a year that have more than 12.7 mm of rain. As all-day rains are relatively rare in Puerto Rico, these figures indicate that showers in which 2 to 10 mm fall are relatively common. Such torrential rainstorms have profound effects on the landscape.

Puerto Rico is in the belt where hurricanes can be expected every year, but owing to the long east-west shape of the island, most of these tropical storms pass north or south of it. Only four hurricanes have passed over Puerto Rico since 1900, but several others have been close enough to cause considerable damage. The principal effect has been extremely heavy downpours of rain—at times as much as 400 mm in a day—accompanied by strong wind. Hurricanes are so rare that they have little effect on the karst features of Puerto Rico, but the high winds and heavy rains cause the fall of trees. After the hurricane of 1928, locally called San Felipe, a log jam formed on the Río Camuy, blocking the entrance known as the Blue Hole (see fig. 7), so that water backed up the river for a kilometre or so and rose above Highway 129, which runs along the side of the river. The log jam gave way suddenly and the water drained out of the valley in a few hours, but rotten logs are found in the Camuy caves to this day, and the entrance at the Blue Hole is still so blocked by logs that it cannot be entered.

THE LIMESTONE FORMATIONS

Most of the karst features described in this report are formed in the extensive karst region in north-central and northern Puerto Rico. For completeness, the limestone and accompanying karst features in the mountainous region are described briefly. The known limestone deposits are shown on plate 1.

LIMESTONE OF CRETACEOUS AGE

The oldest limestone known in Puerto Rico is exposed in the eastern part of the island and is of Early Cretaceous age, probably Albian or Aptian. It crops out in an arcuate belt from quarries west of Caguas, through Cidra, to Cayey. This limestone, the Aguas Buenas Limestone Member of the Torrecilla Breccia (Briggs, 1969), contains the Aguas Buenas (Cg–1)[1], probably the best known cave system in Puerto Rico. The limestone is lenticular and is present at several places at the base of the Torrecilla Breccia, ranging in thickness from 0 to 60 m. It consists of light- to dark-gray thick-bedded (30–100 cm) to very thick-bedded (>100 cm) finely crystalline

[1] These numbers refer to locations shown on plate 1 and listed by quadrangles on p. 59–66.

limestone, bearing an extensive rudist and gastropod fauna. The limestone apparently was deposited as a reef formed on the flanks of volcanic islands. Other limestone beds of Early Cretaceous age, but slightly younger, have been mapped in the Cayey (Berryhill and Glover, 1960), Comerío (Pease and Briggs, 1960), and Barranquitas (Briggs and Gelabert, 1962) quadrangles (fig. 1). All are similar to the Aguas Buenas.

Limestone is more common in the Upper Cretaceous than in the Lower Cretaceous rocks, but in eastern and central Puerto Rico it is present only locally, and commonly in relatively thin units. Upper Cretaceous limestone is most extensive in southwestern Puerto Rico, where it is present at several horizons, in units as thick as several hundred metres. The most extensive and thickest limestone is the Parguera Limestone of Almy (1965), which is present in typical form from Guánica west to the coast. The Parguera consists largely of medium-bedded to massive glauconitic calcarenite and light-gray massive limestone. It varies in thickness very greatly along strike, reaching a maximum thickness of more than 300 m. The other Upper Cretaceous limestone formations are similar to the Parguera but are generally thinner. Caves are present in some of them, and in southwestern Puerto Rico, karren are well developed on many.

LIMESTONE OF EARLY TERTIARY AGE

Limestone formations of Paleocene and Eocene age are present in several parts of Puerto Rico, but the most conspicuous is the Cuevas Limestone (Glover, 1971), which crops out over a wide belt in southern Puerto Rico between Salinas and Villalba. The width is deceptive, as the formation is only about 35 m thick, but the outcrop pattern is wide because of repeated faulting. Several caves are known in this limestone, and many more are probably present.

LIMESTONE OF OLIGOCENE AND MIOCENE AGE

NORTHERN PUERTO RICO

By far the most important limestone units in the karst terrain of Puerto Rico are the formations of Oligocene and Miocene age in northern and southern Puerto Rico. Deposits of chalk and calcareous clay are shown on the map because they contain enough thin beds of limestone to provide subterranean drainage in some places, although other karst phenomena are not common. Karst phenomena are best developed in the broad limestone belt in northern Puerto Rico that extends west from the Río Grande de Loíza to Aguadilla, a distance of about 140 km. The belt reaches its maximum width near Arecibo where it is about 22 km wide.

The strata have been divided into six formations (Monroe, 1973a), ranging in age from late Oligocene to middle Miocene (see table 1 and fig. 4); four of the formations consist principally of limestone, and the other two contain limestone locally. In ascending order the formations are: the Lares Limestone, the Cibao Formation, the Aguada Limestone, the Aymamón Limestone, and the Camuy Formation, each of which has distinctively different solution properties (Meyerhoff, 1938), which give rise to karst phenomena characteristic of each formation. A sixth unit, the Mucarabones Sand, is the eastern lateral clastic equivalent of the Lares Limestone and the lower two thirds of the Cibao Formation, and it consists of sandy limestone only in its western extremity; near Morovis, however, it contains a small lens of fairly pure limestone which has been dissolved into a combination of cone karst, closed depressions, and a few small caves. For further details on the Mucarabones Sand, the reader is referred to the stratigraphic report by Monroe (1973a). The karst-prone parts of the other formations will be described below to provide a framework for the geomorphologic discussions to follow.

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

Age	*Unit and description*	*Thickness (metres)*
Miocene	Camuy Formation; sandstone, limestone and sandy, ferruginous chalk.	0–170
	Unconformity.	
	Aymamon 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:	250–280
	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.	0–160
	Miranda Sand Member; (in eastern area only) sand and gravel, sand and sandy clay.	0–15
	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
	Río Indío 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
Oligocene	San Sebastián; mostly thin-bedded sand and clay, some sandy limestone, locally, especially in west, sand and gravel.	0–155
	Unconformity (angular).	
Cretaceous to Eocene	Volcanic, sedimentary, and intrusive rocks.	

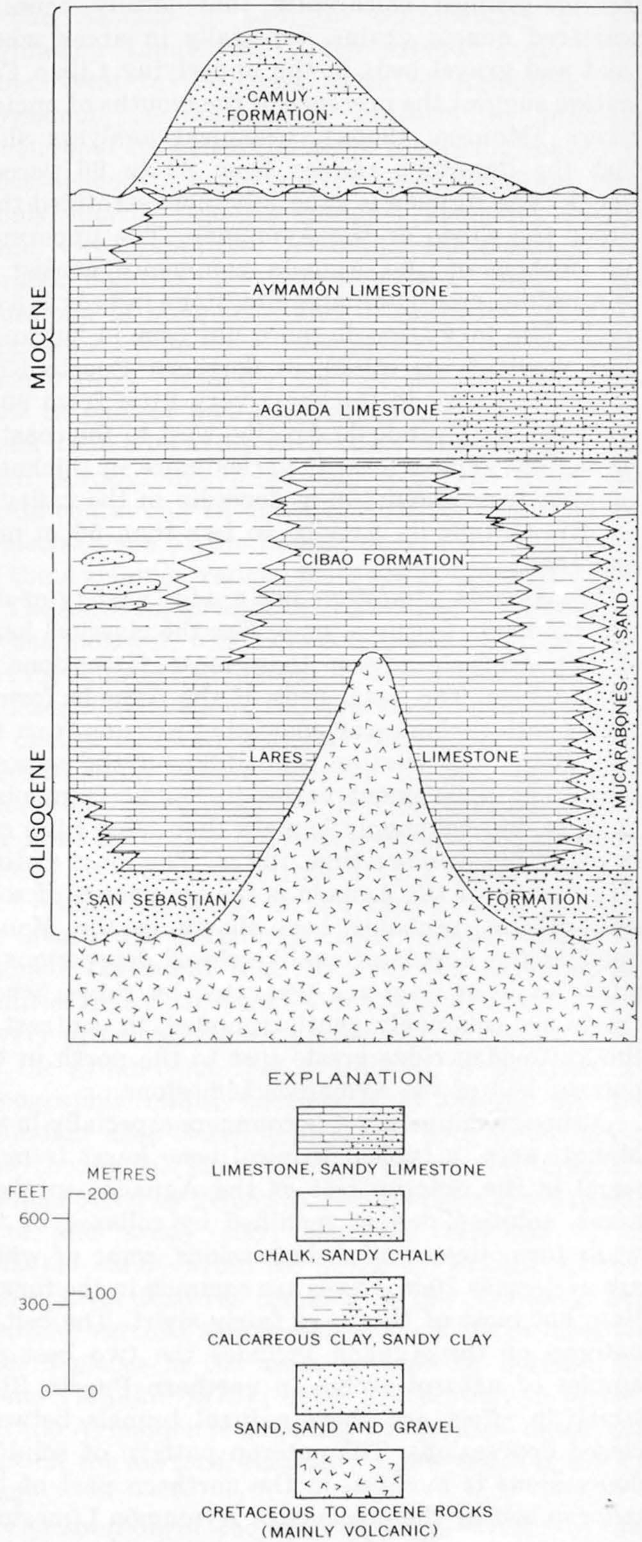

FIGURE 4.—Columnar section of middle Tertiary rocks in northern Puerto Rico.

The lowest and oldest of the limestone units in northern Puerto Rico, the Lares Limestone, crops out in a belt that extends from Corozal westward to Moca. The Lares rests on the late Oligocene San Sebastián Formation, which consists of clastic strata of clay, sand, gravel, and locally of very sandy limestone. Although the San Sebastián shows no karst features, it forms an impermeable confining bed below the Lares Limestone and conceivably could form the floor of cavernous water passages in the limestone. The San Sebastián was not deposited at several places where high hills formed islands in the sea during deposition of the formation, and at such places the Lares rests directly on a basement that consists in various places of sandstone, volcanic rock, intrusive rock, or hydrothermally altered metamorphic rock. The Lares consists of limestone, generally very pure calcium carbonate, mostly calcarenite, that contains many fossils. The abundance of calcareous algae and corals indicates that much of the formation accumulated as organic reefs. Chemical analyses of Lares Limestone (W. H. Monroe, unpub. data, 1974) range from 85 to 99 percent $CaCO_3$. Along the outcrop, the limestone varies in thickness from a maximum of about 310 m to a featheredge at the eastern and western ends where it intertongues with clastic units. At most places it is about 270 m thick. From Corozal nearly to Moca the Lares Limestone rises in a high, generally south-facing escarpment, as its basal limestone is indurated and is much more resistant to erosion and further weathering than is the San Sebastián Formation or the deeply weathered volcanic and tuffaceous rocks of early Tertiary and Cretaceous age (Blume, 1970). The Lares Limestone gives rise to a distinctive cone karst, characteristically consisting of round pointed cones and, at places where jointing has affected the cone development, of rather jagged sawtooth cones and ridges. Cone karst is formed only at those places where the limestone is very thick bedded to massive. At places along strike where the thick-bedded limestone merges laterally into thinner bedded rock, a striking change from cone karst to zanjón karst takes place. The Lares is also one of the formations in which large caves have formed. It is noteworthy that caves, such as the Río Camuy system (see fig. 7), that start in the Lares as high-ceilinged open-river caves become impassible when they pass beneath the less competent softer limestone of the overlying Cibao Formation.

The Lares Limestone is overlain sharply by the Cibao Formation of late Oligocene to early Miocene age. The Cibao is the most heterogeneous formation of the middle Tertiary sequence in northern Puerto Rico. It is a lenticular formation consisting in its type area and at many places elsewhere of calcareous clay and slightly clayey chalk, but it contains very extensive members of quartz sand, sand and gravel derived from volcanic rock, and of calcarenite of nearly pure calcium carbonate. Chemical analyses of the chalky beds (W. H. Monroe, unpub. data, 1974) range from 76 to 85 percent $CaCO_3$, and of the various limestone members from 91 to 98 percent $CaCO_3$. Furthermore the typical argillaceous facies contains many thin beds and tongues of limestone, some of which is so fine grained that it may be termed calcilutite. As is common in northern Puerto Rico, the layers of limestone form ridges and hence cuesta scarps at those places where they are thick enough to affect the topography. The most notable of these escarpments are as follows: the scarp in the northern part of the Ciales quadrangle (Berryhill, 1965) and the Corozal quadrangle (Nelson, 1967a) held up by the Quebrada Arenas Limestone Member; the cap of Montebello Limestone Member that forms steep cliffs at the top of the cones of Lares cone karst in the Florida quadrangle (Nelson and Monroe, 1966) and the Utuado quadrangle (Nelson, 1967b); and the relatively discontinuous scarps produced by thin beds of limestone in the upper part of the Cibao in the southern part of the Camuy quadrangle (Monroe, 1963b). The other principal karst features within the Cibao Formation are the cliffed cone karst best seen in the Florida quadrangle (Nelson and Monroe, 1966); zanjones that are prominent in the northeastern part of the San Sebastián quadrangle and in adjacent areas; and numerous swallow holes at the northern ends of blind valleys in the upper part of the Cibao. Large caves are rare in the Cibao except in part of the Río Camuy cave system; even there many of the caves cannot be traced very far because of blockage of passages by cave breakdown resulting from the incompetence of the limestone.

The Aguada Limestone rests conformably on the Cibao Formation, and in many places it is difficult to distinguish between the two formations, especially where the upper part of the Cibao contains beds of limestone. The Aguada is present from the eastern end of the basin of deposition of the middle Tertiary rocks to the west coast of Puerto Rico at Aguadilla. As pointed out by Zapp, Bergquist, and Thomas (1948), the Aguada Limestone is transitional between the Cibao Formation and the Aymamón Limestone. It consists almost entirely of limestone, containing many chalky beds in the lower part, resembling the Cibao, and predominantly indurated limestone in the upper part, resembling Aymamón. The limestone is commonly fine- to medium-grained calcarenite that locally contains scattered quartz grains, especially in areas where sand and gravel beds in the underlying Cibao Formation suggest the presence of the mouths of ancient rivers (Monroe, 1966a). Chemical analyses show that the limestone ranges from 89 to 96 percent $CaCO_3$. The Aguada is generally more stratified than either the Cibao or the Aymamón. The uppermost few metres of the Aguada commonly consist of thin-bedded crosslaminated limestone in beds 1–3 cm thick. The formation is more uniform in thickness than most of the others in northern Puerto Rico. It seems to vary in thickness very little from 90 m from the Río Grande de Arecibo west to the coast at Aguadilla; farther east it varies more in thickness, ranging from about 150 m downdip in the valley of the Río Grande de Arecibo to less than 50 m near San Juan.

The Aguada Limestone has a wide variety of distinctive karst features, more like the classical karst of the Adriatic region than most formations in Puerto Rico. The basal beds of the Aguada form a high, south-facing escarpment that extends from the San Juan area west to Aguadilla on the western coast. The escarpment varies in height from place to place, but commonly is more than 50 m high and in many places more than 100 m. The most distinctive feature of the Aguada is the abundance of solution dolines, probably best shown in the Manatí quadrangle; dozens of cuplike closed depressions as much as 30 m deep are separated by ridges whose crests are commonly gently rounded, in contrast to the knife-edge ridge crests just to the north in the outcrop belt of the Aymamón Limestone.

Although doline karst is common, especially in the Manatí area, a typical tropical cone karst is more usual in the outcrop belt of the Aguada; in those areas, solution dolines modified by collapse of the walls form steep-walled depressions, some of which are as deep as 70 m. Caves are common in the formation, but most of them are fairly short. The belt of outcrop of the Aguada includes the two best examples of natural arches in northern Puerto Rico, which in effect are short natural tunnels between closed depressions. The outcrop pattern of solution depressions is modified in the northern part of the outcrop belt by the presence of Aymamón Limestone on the crest of the ridges between the depressions, which changes the ridges from smoothly rounded slopes to a succession of steep-walled towers connected by knife-edged ridges. Finally, most of the small polje-like depressions in Puerto Rico have formed in the outcrop belt of the Aguada.

The Aguada is overlain conformably by the Aymamón Limestone, which extends from Loíza Aldea west to the coast north of Aguadilla. The Aymamón is remarkably uniform in lithology throughout its belt of outcrop, consisting mainly of thick-bedded to massive very pure limestone, commonly quartz free. It contains abundant fossils, mainly recrystallized, including calcareous algae, corals, mollusks, and Foraminifera. Most of the limestone is biomicrite and intrasparite. Chemical analyses show 98–99 percent $CaCO_3$. In northwestern Puerto Rico, the upper part of the formation consists in part of pale grayish-orange unconsolidated chalk that alternates with thick beds of recrystallized porcelainlike limestone. Near the coast, dolomite containing as much as 18.6 percent MgO has replaced some of the limestone. The total thickness of the Aymamón ranges from about 190 to 200 m.

The karst features of the Aymamón are dominated by the mogotes, which form a tower karst throughout its outcrop belt, except in the northwestern part of Puerto Rico, where the Aymamón consists mainly of chalky material that has been eroded into low west-trending ridges, possibly in part by marine planation (Meyerhoff, 1938). The relatively unconsolidated Aymamón has been recrystallized (Monroe, 1966b) on the surface into a very hard limestone, which caps the mogotes and causes them to stand up above the relatively easily eroded ridges of Aguada Limestone that form the boundaries of the dolines. Hence, the basal beds of the Aymamón form a very pronounced cuesta scarp that is readily noted on the ground but that is difficult to delineate on topographic maps, because it is masked by the abundant deep closed depressions both to the north and the south. The mogotes rise out of irregular plains floored by generally red to brown argillaceous sand and sandy clay, generally referred to as "blanket sand" after the work by Briggs (1966). Other karst features common in the Aymamón are well-like vertical shafts seen at the sides of mogotes and in places in the areas covered by blanket deposits (Miotke, 1973); caves are present in places, but the Aymamón is generally so unconsolidated, except on the surface, that only a few caves are very long.

The solution of the recrystallized surface of the limestone on the tops of the mogotes and the long mogotelike ridges has produced a labyrinth of sharp-pointed spikes as high as 30 cm, rather like low spitzkarren. These make walking very difficult, but most spikes eventually get broken off, perhaps by cattle, so they are a temporary feature. Similar spikes are common on the coast, where they are accompanied by solution pans, exactly like those dissolved in the calcarenite of the eolianite ridges (Kaye, 1959a).

The youngest formation of middle Tertiary age in northern Puerto Rico is the Camuy Formation, which forms a discontinuous belt from the Río de la Plata west to Isabela. The Camuy rests unconformably on the Aymamón Limestone. In contrast with the underlying massive limestone of the Aymamón, the basal beds of the Camuy are markedly stratified in beds a few centimetres thick, and at many places these thin beds are crosslaminated; furthermore, the basal Camuy is commonly pink or red in contrast to the very pale orange to white of the Aymamón. Although the Camuy is predominantly calcareous, most of it contains appreciable quantities of quartz sand, and the upper part contains thin-bedded, slightly crossbedded calcareous quartz sandstone. Chemical analyses show that the limestone parts of the formation contain as much as 95 percent $CaCO_3$. The maximum thickness of the formation is near Arecibo where about 170 m was penetrated in a test well.

The upper and lower, predominantly sandy members of the Camuy Formation (Monroe, 1963b) contain few karst features, and weathering has proceeded as in any calcareous sand or sandstone, except that the upper member contains many cylindrical shafts as deep as 30 m. The middle member consists of hard limestone that contains abundant medium to coarse grains of quartz sand. The induration of the middle member has given rise to a cuesta scarp that rises about 25 m above the lower lying Aymamón to the south; the lower sandy and marly member of the Camuy crops out on the cuesta scarp and rises toward the south to form a capping on many of the northernmost mogotes of the Aymamón. No large caves have been recorded from the middle member, but it has been dissolved into a network of solution holes as much as 20 cm in diameter.

SOUTHERN PUERTO RICO

The middle Tertiary rocks in southern Puerto Rico consist of the Juana Díaz Formation of Oligocene and Miocene age and the Ponce Limestone of Miocene age. The Juana Díaz consists of lenticular and intertonguing beds of sand, gravel, clay, mudstone, chalk, and limestone. Most of the limestone, however, is very chalky, except for a thick organic reef complex 8–14 km west-northwest of Ponce. The reef limestone contains abundant corals and algae, and analyses show that it contains 97–98 percent

$CaCO_3$. The formation also contains other lenses of less pure limestone and chalk that are 75–91 percent $CaCO_3$.

The only part of the Juana Díaz that shows any karst phenomena is the reef complex south and southwest of Peñuelas, which contains several rather large caves. The surface in this area, especially in the southwestern part of the Peñuelas quadrangle, contains the only large closed depressions shown on the topographic maps of the middle Tertiary limestone belt in southern Puerto Rico.

The Juana Díaz Formation is overlain unconformably by the Ponce Limestone, which consists of very hard, generally light grayish-orange calcarenite containing abundant molds of mollusks, solitary corals, echinoids, and Foraminifera. The Ponce was deposited as a fringing reef of fairly pure limestone, containing at most places about 96 percent $CaCO_3$, but in some places near the coast it has been slightly dolomitized and contains as much as 7 percent MgO.

The Ponce is a karstifiable limestone and would have many more karst features if it were in a more humid climate, for lithologically it somewhat resembles both the Aymamón and the Aguada Limestones. Rock shelters are common on the nearly vertical cliffs formed by the Ponce and a few caves have been reported from the formation, although I have personally seen only two. Karren have been dissolved in the limestone near the coast, much more than in any limestone in northern Puerto Rico, but this may be a function of the climate.

A secondary karst feature dependent on the climate is the large amount of caliche that has formed on the surface in southern Puerto Rico, especially in areas underlain by limestone of the Ponce and Juana Díaz and, to a lesser extent, over limestones of Cretaceous and early Tertiary age. The caliche consists of as much as 4 m of soft chalk to indurated chalky limestone, apparently formed in the soil and above the soil overlying limestone beds, presumably by evaporation of water containing calcium bicarbonate that has been drawn to the surface by capillary attraction. In some places it resembles travertine or sinter, except that it contains neither plant nor animal remains. An analysis shows 95 percent $CaCO_3$. I have never seen any karst features in or on the caliche.

OTHER AREAS

Limestone of middle Tertiary age is also present on Isla de Mona (Kaye, 1959b; Briggs and Seiders, 1972) and on Isla de Vieques (Briggs and Akers, 1965), but these areas will not be discussed in the present paper. The limestone on Isla de Mona contains many caves, which have been exploited for guano.

CENOZOIC DEPOSITS RESTING ON THE LIMESTONE FORMATIONS

The limestone formations described above are overlain in different parts of the island by coastal deposits, alluvial deposits, or blanket deposits. Most of these surficial units are composed of noncalcareous material and show no karst phenomena, but water percolating through some of them is acidified, so that solution takes place in the underlying limestone. This solution results in subsidence in some places.

BLANKET SANDS

The blanket sands fill in the depressions between mogotes and the ridges of mogotes in the northern karst belt between Bayamón and Aguadilla, especially in the northern part of the belt in the outcrop area of the Aymamón Limestone and the Camuy Formation. The detailed outcrop pattern is not shown on the map accompanying the present report (pl. 1) but is shown at a scale of 1:100,000 on the geologic map in a general report on the stratigraphy of the middle Tertiary rocks of Puerto Rico (W. H. Monroe, unpub. data, 1974) and in all the detailed geologic maps of the northern coastal area. A somewhat more generalized outcrop pattern is shown on the geologic map at a scale of 1:240,000 by Briggs and Akers (1965).

The blanket sands were named and described in 1962 by Briggs (1966, p. 62), and the reader is referred to his paper for details. Briggs described them as composed of quartz sand, clayey sand, sandy clay, and clay, "the dominant constituents of which are angular, subangular, and subround, medium to fine grains of clear quartz, and reddish-brown to moderate-brown, dark yellowish orange, light-gray, and white, commonly ferruginous kaolinitic clay. Quartz and clay together make up almost all of the blanket sands at most outcrops, but their relative proportions vary greatly."

The soil survey of Puerto Rico (Roberts and others, 1942) recognized the blanket sand deposits in a generalized way, but considered most of them residual from limestone, which, as Briggs points out, is impossible, as most of the limestone associated with the sands contains little quartz or other noncalcareous material. The soil survey divided the soils involved into four general groups: (1) compact, generally clayey soil, medium depth, red or yellow, resting on limestone; (2) friable, clayey and loamy soil, medium depth to deep, red or yellow, resting on limestone; (3) very friable loamy sand and sand, medium depth to deep, red or yellow, resting on limestone; and (4) loose, medium depth, light-colored sand. The first group contains about 11.5 percent of the material classified now as blanket sand and is present mostly in the area near the village of Florida, where the blanket sand is present mainly in the valleys between hills of the Montebello Limestone Member of the Cibao Formation; a few samples of this material show that it includes fairly acid soils with pH 4.6–6.2 and that the percentage of clay is mostly more than 90. The second group of soils is present near the inner part of the blanket-sand belt, mostly between ridges of Aymamón Limestone; it includes about 40.5 percent of the blanket sands. It, too, is predominantly clay, ranging from 74 to 93 percent, and is also acid, having a pH of 5.1–6.5. The third group of looser material, constituting 28 percent of the blanket sands, is also mostly between hills of Aymamón Limestone, but in part is associated with the Camuy Formation and may be partly residual from the Camuy, which locally contains considerable quartz sand; it consists of relatively little clay but is 76–92 percent sand; the pH ranges from 4.7 to 5.4. The fourth group of soils, some 20 percent of the total, consists mostly of loose sand; the pH is 6.0–6.8, probably reflecting the great permeability of the material which contains so little clay that carbon-dioxide producing plants do not grow on it readily. This group of soils is present mainly in the northern coastal strips of blanket sand east of the Río Camuy.

Using mainly the data given in the preceding paragraph, Briggs (1966, p. 62) stated that quartz ranges from less than 5 to more than 90 percent and clay ranges from less than 1 to more than 95 percent of the deposits. He said, "The great mass of the blanket sands exhibits quartz-clay ratios between 80:20 and 30:70; the overall proportion of quartz and clay in the blanket sands is probably about 65:35."

Briggs (1966) believed that the parent material of the blanket sands, debris from the volcanic interior, was carried to the coastal area by rivers during the long period between deposition of the limestone and its gradual uplift to its present altitude above sea level, probably beginning shortly after deposition of the Aymamón Limestone was completed. He believed that karstification of the limestone had already started at that time, and that longshore currents of the sea distributed the river-transported material over the partly karstified surface, so that the alluvium was trapped in solution depressions that had formed in the limestone surface. After deposition, the volcanic-derived debris was weathered to lateritic earth. This theory is supported by the greater abundance of sand over clay in the eastern part of the belt where through-flowing rivers are more abundant, and by the relative scarcity of sand west of the Arecibo area. Briggs's ideas are also supported by the fact that the higher areas of blanket sand farthest from the coast, presumably the older parts, contain much more clay than the lower seaward parts, which indicates greater laterization of these presumably older deposits.

Briggs's studies showed that the present coastal sediments include, besides quartz and calcite, small iron oxide concretions, feldspar, some organic material, magnetite, rare volcanic and plutonic rock fragments, and epidote. Farther inland, the blanket sand deposits show little more than quartz grains, iron oxide concretions, and clay, which he believes is derived from the volcanic fragments and other materials by the process of laterization. Hildebrand (1960) examined by X-ray diffraction 42 samples of the more clayey deposits, mostly from near the town of Florida, and reported quartz, kaolinite, halloysite, and anatase. In some of the samples he found boehmite. Common minor constitutents were goethite, hematite, oligoclase, sanidine, unidentified feldspar, and organic matter.

Briggs reported that the thickness may exceed 30 m at some places; he believes that a conservative estimate of the average thickness is 4–10 m.

The blanket sands have had a profound influence on the karstification of the limestone by providing reservoirs of acidified water that have acted on the underlying limestone (Monroe, 1969c; Miotke, 1973). Presumably the more sandy clays in groups 2 and 3 of the soils in the soil survey (Roberts and others, 1942) are the most effective agents for acting on the limestone, as the more clayey parts tend to plug the underlying solution channels, as shown by the large number of ponds that have formed in the blanket sands near Florida. The extremely loose sand of group 4 is very permeable so that rainwater passes through it very readily and leaches out such mineral matter as clay and iron oxide, other than quartz. In the largest outcrop belt of this sand between the Río Cibuco and the Río Grande de Manatí, the sand has been so leached that the remaining material at the surface is 98–99 percent SiO_2 and is used as a glass sand; in the area of outcrop of this pure quartz sand, the wind has blown the sand from depression blowouts into many low sand dunes.

ALLUVIAL DEPOSITS

Very thick masses of alluvium fill valleys in both northern and southern Puerto Rico; some of these valleys may contain more than 100 m of alluvium. In some places the valley fills may have buried karst topography, and in places they may have filled fairly large caves, but the deposits are so thick that this cannot be determined. In the general area of San Juan, coalescing alluvial plains have buried nearly all the limestone, so that only isolated hills project through sandy clay, forming small inselbergs. So far as I know, there have been no collapses in this alluvial cover because of solution of underlying limestone. This cover is even greater in the southern part of Puerto Rico, especially east of Ponce, where broad coalescing alluvial fans have buried all but a small part of the Juana Díaz Formation and Ponce Limestone. The alluvial cover is very thick near the southern coast, reaching a thickness of nearly 900 m at Santa Isabel.

In many places cliff-foot caves have been eroded in limestone at the edges of the alluvial plains. These show up especially well where the Río Grande de Arecibo cuts the limestone wall at the side of its valley. These caves, however, appear to be at least as much due to mechanical corrasion as to solution; they are certainly not the Fusshöhle (cliff-foot caves) looked for by Gerstenhauer (1964).

COASTAL DEPOSITS

Much of the beach sand in Puerto Rico contains many shell fragments; this sand is cemented in many places, particularly in the intertidal zone, into beach rock, which is a coarse calcarenite. The cementation itself is probably related, in some manner not yet fully understood (see also Russell, 1959, 1962), to the reprecipitation of calcium carbonate that forms the crusts on the mogotes. In places, a combination of solution and marine erosion has left low arches and pedestals in exposed beach rock.

Karstification has taken place at many places in the calcarenite formed by induration of sand dunes that accumulated during Quaternary time near the Atlantic coast of Puerto Rico. Kaye (1959a) has described ridges of indurated sand dunes at various altitudes above and below sea level, and he has also described the solution pans and small karren spikes that have formed on the crests and sides by solution. Similar minor karst features are found on the surface of Aymamón Limestone where it is exposed along the coast between Camuy and Aguadilla. Kaye (1957a) also called attention to solutional sea-level notches and discussed their origin. At places I have seen broad, low natural arches at sea level dissolved by the same mechanism in both the eolianite and the Ponce Limestone. In addition to the minor karst features, fairly large caves occur in the eolianite, especially north of Manatí. These were formed partly by wave erosion and partly by solution. In the same area, small dolines on the crest of the coastal ridge suggest that the eolianite may contain fairly large caves, some of which have collapsed; these sinks may, however, be merely solution basins, as no way is known of differentiating gentle collapse or subsidence features from lowering of the surface by direct solution.

Such coastal features as modern sand dunes, noncalcareous beaches, and coastal swamps have had no noticeable karst effect, although it seems likely that the peaty water associated with mangrove swamps may be sufficiently acid in places to dissolve limestone. Most of these features are at or slightly below sea level, however, so that any effect on the underlying limestone has not been observed. It is entirely possible that the large springs found in the Ciénaga Tiburones, southeast of Arecibo, and in Laguna Tortuguero, northeast of Manatí, may come from caves enlarged by solution by the swamp acids, but it seems more likely that these springs are the result of interception of water-bearing caves by erosion during lower stages of sea level in the Pleistocene.

FACTORS AFFECTING KARSTIFICATION OF LIMESTONE

All the karst phenomena in Puerto Rico have been formed on and in limestone; the small amounts of salt, gypsum, and dolomite present in places have had no noticeable solutional effect. Limestone is composed principally of calcium carbonate ($CaCO_3$) but may contain a considerable quantity of sand or clay. It is readily soluble in the presence of acidic water. It is only slightly soluble in pure water, ionizing to Ca^{+2} and $(CO_3)^{-2}$, but in the presence of carbonic acid, $H^+(HCO_3)^-$, formed by the solution of carbon dioxide in water, the free H^+ ion of the acid combines with the $(CO_3)^{-2}$ ion of the calcium carbonate to form the bicarbonate ion $(HCO_3)^-$, which is readily soluble. Thus, in effect,

$$CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca\,(HCO_3)_2.$$

As shown, the reaction is reversible. Slight increases in temperature, decrease in vapor pressure of CO_2, or loss of water will cause the solution to lose CO_2; this breaks up the calcium bicarbonate and restores the relatively insoluble $CaCO_3$, which tends to be precipitated.

The atmosphere and dry soil both contain 0.03–0.08 percent CO_2. Wet soil on the other hand has been observed (Harrison and Subramania Aiyer, 1913, 1916) to contain as much as 20 percent CO_2. Miotke (1973) found that the ground air on the sides of mogotes contained 0.9–1.3 percent CO_2 and that the blanket sand soil contained 1.5–7.0 percent during the normally drier Puerto Rican winter season; his experiments were not extended to wetter seasons. Thus, water draining through wet soil rich in organic matter is likely to contain a much greater concentration of carbonic acid than does rainwater. The pH of the various clayey soils on limestone, as shown by studies of the blanket sands, ranges from about 4.7 to 6.2 (Roberts and others, 1942).

Other acids present in soil that may have some effect on the solution of limestone include HNO_3, derived from atmospheric nitrogen that has been fixed by bacterial action, and various organic acids such as humic acid. Most of the acids, however, are acted on by bacteria almost as soon as they are formed and are transformed to CO_2.

Investigators generally agree that carbonic acid is the most active agent in the solution of limestone and that most of the CO_2 is formed in the soil itself. The carbonic acid, of course, first dissolves any $CaCO_3$ in the soil—an action so thorough that most soils derived from underlying limestone are acid. The acid waters in the soil percolate downward through the soil until they reach the soil-limestone interface, where solution is most active.

Most of the closed depressions in Puerto Rico, even some of the very deep ones, appear to be the end product of simple solution: An original small closed depression became deepened by solution of the bottom by water acidified by percolation through soil that contained carbon dioxide derived from respiration of the roots of plants and from decay of plant matter by action of bacteria.

In areas underlain by highly jointed limestone, the acidic waters may run rapidly down open joints and slightly acidify the water at depth; under such conditions the joints are enlarged by solution, and a network of small solution cavities may be formed at and below the water table. Under these conditions, most of the drainage is underground, and as a result karst areas contain few surface streams. Solution of the limestone produces a ground surface containing many stream sinks or swallow holes, many closed depressions, and, where limestone is at the surface, a network of minor features such as low solutional spikes and ridges.

Although readily soluble in acidic water, limestone is also consistently a ridgemaker in Puerto Rico and is generally so in many other tropical areas such as Jamaica (Sweeting, 1958, 1972), Cuba (Panos and Stelcl, 1968), Sarawak (Wilford and Wall, 1965), and New Guinea (Williams, 1971). The influence of a relatively thin bed of limestone in holding up a high ridge is well shown in Cerro de las Cuevas (Río Descalabrado quadrangle), northeast of Juana Díaz in southern Puerto Rico. The limestone there is nearly pure algal limestone, somewhat chalky in fresh outcrops. Although it is only about 35 m thick (Glover, 1971, p. 61), it forms a dip slope on the south side of the mountain from an altitude of about 200 m at the foot to 638 m at the crest. The north side of the mountain is composed of hard volcanic rocks, but they are more easily weathered and hence more easily eroded than the limestone.

Even those limestones that are relatively unconsolidated, as are most of the limestones of middle Tertiary age, are resistant to erosion, although subject to solution. Under tropical conditions limestone tends to accumulate a firm generally thick crust of reprecipitated calcium carbonate (Monroe, 1966b) which offers protection to less well consolidated limestone below. Any soil on the surface of ridges is likely to be washed off by torrential rains, leaving a bare surface of hard rock. Solution of limestone is most rapid under a cover of plant-bearing soil because of the greater abundance of carbon dioxide. When the soil is eroded, solution of the bare limestone is relatively slow. This accentuates the differential growth of limestone hills, so that over the years they tend to stand relatively much higher than soil-covered valleys. As a consequence, the bare limestone of the Lares escarpment at the southern edge of the northern karst region stands high above the valleys to the south, which are incised into the relatively more easily weathered and eroded volcanic rocks.

In Puerto Rico, the first stage of karstification appears to be the partial replacement of the original limestone, which is composed mostly of marine organisms, by limestone that has been dissolved and reprecipitated by action of underground water. The original marine limestone has been seen (1) in a core of Lares Limestone taken at depths of 3,704 to 3,726 feet below the ground surface from the CPR

No. 4 well drilled by Kewanee Interamerican Oil Company (Briggs, 1961) between Arecibo and Barceloneta and (2) in several outcrops of chalk in the Juana Díaz Formation near Ponce. These samples show few crystals of calcite visible with hand lens. The samples contain essentially unaltered foraminifers and algal fragments. In contrast to these rocks, most of the middle Tertiary limestone show, in hand specimen, abundant very fine crystals of calcite, and most fossil shells have been dissolved away, leaving casts of the interior and exterior. Commonly these casts have been filled with crystals of calcite. Almost certainly this alteration of the limestone has been caused by percolating or even circulating fresh ground water containing plant-derived carbon dioxide.

The stable isotopes of oxygen and carbon of several specimens of limestone from Puerto Rico have been determined, and these studies show that the carbon in the altered limestone is appreciably lighter than that in the unaltered rock; that is, that C^{12} is more abundant relative to C^{13}. This suggests that a part of the normal C^{13} present in marine limestone has been replaced by C^{12} derived from land plants (Friedman and others, 1969). The C^{13}-C^{12} ratio relative to PDB [2] for some of the samples from Puerto Rico are very significant. The samples from CPR No. 4 well show $+1.0\ ^0/_{00}$, which is within the range of $+1.0\ ^0/_{00}$ to $-1.8\ ^0/_{00}$ of normal marine limestone from the tropics. The samples of chalk from the Juana Díaz range from $+0.4\ ^0/_{00}$ to $-1.8\ ^0/_{00}$, showing essentially no substitution of C^{12} for C^{13}. Other samples of exposed rocks show various ratios from $-2.5\ ^0/_{00}$ for Lares Limestone at the bottom of a deep quarry to $-8.6\ ^0/_{00}$ for the very crystalline chalk that crops out in an outcrop of Aymamón Limestone. In the Aymamón, all mollusks are represented by calcite replacements, and the rock is perforated by abundant large solution channels formed when the limestone was under the water table (locality V–6 on pl. 1; fig. 25).

After the alteration by circulating ground water, karstification proceeds by both solution and reprecipitation, as described above. It is perhaps significant that karst phenomena have not been seen in limestone that has a C^{13}-C^{12} ratio greater than $-2.0\ ^0/_{00}$.

In Puerto Rico, most of the slopes in the karstified limestone tend to be nearly vertical. This is especially true in those units on which a crust of reprecipitated limestone has formed. Most of the

[2] Accepted abbreviation for University of Chicago standard belemnite from the Peedee Formation.

FIGURE 5.—Visor of reprecipitated limestone projecting from top of west side of a mogote, 400 m southeast of Coto Sur, 3.7 km east-southeast of Manatí.

mogotes are asymmetric, having a steep slope on the western side and a gentler slope on the eastern side. The steep slope almost invariably has an overhanging cap rock or visor (fig. 5) of very hard reprecipitated limestone which overlies a weaker, more or less solution-perforated cliff face in which at most places a rock shelter has formed by collapse of the incompetent chalky limestone (see fig. 28). Many of the karst valleys and deeper closed depressions have at the side a concave slope that steepens to nearly vertical at the top. At many places this steep slope is much like the western sides of the mogotes, consisting of a protruding visor of indurated limestone over relatively softer chalky limestone. This is a collapse feature, but the depressions themselves may show no evidence of cave collapse, so the steep cliff seems to be merely a phenomenon of collapse by oversteepening. Such frequent vertical cliffs at the sides of valleys and depressions increase the difficulties of traversing the more rugged karst terranes, especially as the material of the cliffs below the visor is entirely incompetent, tending to crumble and fall when weight is placed on it.

PHYSICAL GEOGRAPHY OF THE KARST AREA

The northern karst belt extends from Loíza Aldea on the northeast to Aguadilla on the west coast of Puerto Rico—a distance of about 135 km. South of Arecibo, the belt reaches its maximum width of about 23 km. 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 alluvial deposits of several rivers, but from San Juan west, the belt is interrupted only by the relatively wide alluvial valleys of rivers that have their headwaters in the central mountainous area of Puerto Rico and that pass through the belt to the Atlantic Ocean. The main rivers are, from east to west, the Río Bayamón; the Río de la Plata, which is the longest river in Puerto Rico; the Río Cibuco, which flows through the belt in a narrow gorge before it enters a broad flood plain; the Río Indio, a through-flowing tributary of the Río Cibuco; the Río Grande de Manatí; and the Río Grande de Arecibo. These rivers appear to have longer histories as subaerial streams than the rivers farther west that pass across the belt. The western streams are the Río Tanamá, which passes through nine tunnels on its way across the belt; the Río Camuy, which flows in an underground channel as it crosses the belt of outcrop of the Lares and Cibao Formations; and the Río Guajataca, which flows in deep, narrow gorges in crossing the limestone belts, gorges so narrow and deep that they may very well be deroofed caves.

Aside from these through-flowing rivers and some rather 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 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 centimetres in diameter. In many of the closed depressions in the karst belt, small streams originate at springs, flow across the depression, and then disappear in holes in the soil less than 1 m in diameter. At some places, fairly rapidly flowing streams disappear underground and can be heard flowing over rapids and falls for a short distance, and then are lost to knowledge, 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 north from about 5° along their southern border to less than 1° near the Atlantic Ocean. The combination of alternation in resistance to erosion and a constant northerly dip has resulted in 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 prominent single feature of the karst area is the Lares cuesta scarp (see pl. 1), which 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 Sebastían Formation and volcanic rocks below and to the south and the much more resistant limestone above and to the north (Blume, 1970); secondarily, it is the result of great landslides (Monroe, 1964a) which have created a steep cliff by the breaking away of blocks of limestone by diminishing support below as the underlying material is eroded by gullying and sheetwash, and as the clay of the San Sebastián Formation becomes water soaked and forms a gliding surface. The altitude above sea level of the top of the scarp ranges from a maximum of about 530 m near Caguana 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 the part 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, where the San Sebastián Formation crops out on an only slightly eroded flat at an altitude of about 430 m, the top of the scarp rises to only 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. The only other similar place is a relatively small upland of San Sebastián Formation about 8 km southwest of Ciales. Here the upper surface of the San Sebastián slopes gently north from about 380 m to about 350 m where it is overlain by the Lares Limestone, which rises to ridge crests of about 400 m, again about a 50-m difference in altitude. Even in this area, the tendency of a border stream to flow at the foot of the scarp is shown by the small unnamed stream which originates in the San Sebastián Formation, flows west and west-northwest, cutting its valley down into highly weathered tuff breccia and volcanic sandstone, and eventually flows into a cave in the Lares Limestone.

As pointed out by Blume (1970), the scarp varies in ground plan from scalloped to straight, and where it is straight, it is usually accentuated by large landslides. He also points out that in places where it is straight it cuts through the mogotes along the crest, as is especially well shown on the map of the Utuado quadrangle along the scarp at the top of the cliff above Lago Dos Bocas. Blume (1970) called attention to excellent examples of the scalloped plan of the scarp between San Sebastián and Lares; he considers this the normal form.

West of San Sebastián, the Lares Limestone intertongues with sand, clay, and gravel of the San Sebastián Formation. In that area, the cuesta scarp breaks up into a few isolated promontories, which are shown on the map (pl. 1) merely as remnants of the scarp.

North of the Lares cuesta scarp, on the back slope, the limestone has been dissolved into a variety of karst forms. The most usual form is cone karst which has been described as Kegelkarst in considerable detail by Lehmann (1954). Between San Sebastián and Lares, the back slope has been cut into zanjones in an area that extends upward into the outcrop belt of the Montebello Limestone Member of the Cibao Formation.

From the valley of the Río Tanamá nearly to the Río Grande de Manatí, and especially on both sides of the Río Grande de Arecibo, the cone karst formed on the Lares Limestone is bordered on the north and in some places replaced by cliffed cone karst; this consists of cones that have a cap or rim rock of a nearly vertical cliff of white limestone. The change in slope from steep cone upward to vertical cliffs is very noticeable. The area of cliffed cone karst is the area in which the coarsely granular Montebello Limestone Member of the Cibao Formation is present at the crest of the hills overlying the less granular Lares Limestone. Although the fresh limestone is relatively soft, on exposure it becomes casehardened into a very resistant rock. As the Montebello Member overlaps the Lares in the vicinity of the Río Grande de Arecibo, cliffed cone karst extends nearly to the Lares escarpment in that area. North of the area of cliffed cone karst, the Montebello Member gives rise to a kind of tower karst consisting of generally steep slopes, in many places cliffs, which rise to rounded hilltops.

Eastward from the longitude of Florida to a dividing line about 2 km east of the Río Grande de Manatí, the back slope of the cuesta is made up of typical cone karst, which contains some long dry valleys. An area of typical zanjón karst containing no high hills extends from the dividing line east of the Río Grande de Manatí to the longitude of Morovis; this area is separated by another sharp dividing line from an area of typical cone karst, which continues to the vicinity of Corozal. Still farther east, the back slope is dominated by the overlying Cibao Formation, which in that area contains another cuesta scarp. The Lares scarp dies out completely east of the Río de La Plata where the Lares grades laterally into the Mucarabones Sand.

In northwestern Puerto Rico and in the vicinity of the Río Grande de Manatí, the area of outcrop of the Lares Limestone grades northward into an area of very different topography underlain by the Cibao Formation. In its typical outcrop area, the Cibao erodes to low rolling hills covered by clay loam, but the Cibao is such a heterogeneous formation that the topography of its belt of outcrop does not maintain the regularity of the other belts of northern Puerto Rico. Between the type area in the valley of the Río Guajataca and the vicinity of Moca, the belt consists of low rolling hills of clay loam interrupted by a steep cuesta scarp held up by the Guajataca Member of the Cibao, which contains abundant beds of sand and gravel. This cuesta scarp dies out a few kilometres east of Lago Guajataca. Still farther east, the belt of low clay hills narrows rapidly as the belt of cliffed cone karst developed on the Montebello Limestone Member of the Cibao Formation expands. The typical clay-hill topography of the Cibao dies out between the Río Tanamá and the Río Grande de Arecibo, where the thickness of clay marl of the Cibao thins to about 10 m. The marly facies of the Cibao recurs east of Florida and continues with several interruptions to the eastern edge of karst belt near the Río Grande de Loíza. This facies gives rise to low rolling hills between the Río Grande de Manatí and the Río Indio, where it is in marked contrast with the cone karst and zanjón karst developed on the Lares Limestone farther south. It is interrupted throughout most of this area, however, by a steep scarp held up by the thin Quebrada Arenas Limestone Member of the Cibao (Monroe, 1962; Berryhill, 1965).

North of that scarp, the low rolling hills typical of the Cibao lowland continue northward to the major scarp of the Aguada cuesta. Although in general the Cibao lowland consists of low rolling hills, shallow dolines are present from place to place where surface water drains into slightly cavernous limestone beds in the Cibao. The lowland above the Quebrada Arenas scarp continues eastward, interrupted only by the wide areas of alluvium of the Río de La Plata and alluvial fans in the Bayamón and San Juan areas.

Short surface streams are fairly common in the areas of low rolling hills underlain by the calcareous clay and earthy chalk of the Cibao lowland. South of the cuesta scarp held up by the Guajataca and Quebrada Arenas members, these streams flow south to master streams, which then flow east or west to a through-cutting river, or, as in the case of a stream in the northeastern part of the Bayaney quadrangle, to a blind valley that ends in a swallow hole, known there as Hoya Caña. North of the cuesta scarps within the Cibao, the surface streams commonly flow northward into blind valleys ending in swallow holes near or within the Aguada cuesta. Although most of these short streams are intermittent, a few rise from springs in the Cibao and are perennial.

The most extensive scarp in the karst belt of northern Puerto Rico is that of the Aguada cuesta, which extends continuously, except for breaks at river valleys, from the western part of the city of San Juan to the west coast at Aguadilla. Remnants of the scarp can also be seen east of San Juan on both sides of the Río Grande de Loíza. Although it is still present, the scarp is masked between the Río Tanamá and the vicinity of Florida by the high hills just to the south held up by the Montebello Limestone Member of the Cibao Formation.

Although the Aguada scarp is a very impressive landscape feature, it is especially prominent in the southern part of the Camuy quadrangle, where it forms a wall about 50 m high on the upland both east and west of the valley of the Río Camuy. Outliers of the limestone are present south of the scarp as high steep-sided isolated hills. The scarp is a notable wall crossing the southern part of the Manatí quadrangle, but here its impact is somewhat obscured by the large number of outliers south of the main scarp, which rise as much as 100 m above the clay-marl plains of the upper part of the Cibao Formation. The main trend of the scarp, however, is impressive, as it forms a ragged wall 25–50 m above the rolling lowland to the south. In both the Camuy and Manatí quadrangles, the scarp is indented by many alluviated blind valleys along which surface streams flow until they disappear in swallow holes, some of which are caves that pass through ridges into collapse dolines farther north, where the streams again are subaerial for short distances.

North of the scarp, the cuesta is an extremely rugged karst topography characterized by a variety of karst types, especially doline karst in the Manatí quadrangle and by abundant small polje-like valleys and uvalas in other areas. In a few areas, the karst is cone karst, much like that formed on the Lares Limestone, but more characteristically the surface is pitted by deep solution dolines separated by rounded ridges, which form a rough irregular slope northward to the broken wall of the Aymamón scarp. The northern part of the area, which is characterized by very deep solution and collapse dolines in the Aguada Limestone separated by high towers capped by the Aymamón Limestone, is the roughest area in the entire karst belt; in the Quebradillas quadrangle, many of the dolines are more than 70 m deeper than the lowest point on their rims, and the adjacent towers capped by Aymamón Limestone rise some 50 m higher. This area is traversed by sparse horse trails and footpaths, but nearly vertical cliffs make it extremely difficult to pass through. The through highways in the past have followed the larger stream valleys, but the Puerto Rican Highway Authority is now beginning to build winding highways through the roughest parts of the karst, generally following the larger horse trails.

The Aguada doline belt is so rugged that the scarp marked by the outcrop of the basal part of the Aymamón Limestone is very difficult to detect on topographic maps. It shows up very plainly on the ground in the Manatí quadrangle as a topographic wall, but it may be difficult to identify as one approaches it, for it consists entirely of an irregular line of mogotes separated by very deep dolines. The scarp shows up very plainly on aerial photographs from which the trace of the scarp shown on the map (pl. 1) was plotted. As the Aymamón scarp is formed by an outcrop of limestone that is more completely recrystallized by reprecipitation (Monroe, 1966b) than is the underlying Aguada, it does not form such a contrast in topographic form as the beds of limestone that rest on softer chalk and clay and form the more notable scarps of the Aguada and Lares Limestones. The scarp can be recognized with difficulty from Bayamón west to Aguadilla, interrupted by the large river valleys, and is the northernmost of the scarps that are continuous for long distances.

One other scarp, recognizable only between Quebradillas and Arecibo, is marked by the outcrop of the middle limestone member of the Camuy Formation. This scarp is in the area of the blanket sands, which fill depressions on both sides; the depressions are generally deeper just south of the scarp. The scarp is best developed in the area of the Camuy and Quebradillas topographic quadrangles.

North of the Aymamón scarp, the doline karst characteristic of the Aguada Limestone gives way to an area characterized by mogotes. The belt of mogotes is continuous from San Juan west to Aguadilla, corresponding to the entire outcrop belt of the Aymamón in the east, but to only the lower part of the Aymamón west of the longitude of Isabela. In the eastern area, the entire Aymamón Limestone is composed of porous chalk that forms a reprecipitated crust, but west of Isabela the upper part of the Aymamón consists of yellow soft chalk that apparently is more nearly impermeable and that does not recrystallize as readily as does the purer chalk farther east. Furthermore, the deposits of blanket sand are very widely spaced west of the Río Guajataca, so that the subsand solution and collapse structures common farther east do not lower the surface to leave the residual mogotes.

The northwestern part of Puerto Rico is a gently rolling plateau or shelf that has been variously described as a wave-cut bench (Meyerhoff, 1938) and as a bedding-plane surface (Lobeck, 1922). It is so different in topography from areas farther east characterized by mogotes that many writers (Picó, 1950; and others) have considered it evidence that Puerto Rico has been tilted down toward the east, because the northwestern coast of Puerto Rico is a sea cliff, whereas the eastern coast is generally a drowned topography. This is disproved, I believe, because the structure contours drawn on the base of the Aymamón do not show any such regional tilting.

Between Quebradillas and Manatí, the mogote belt grades northward into a belt of fairly low west-trending ridges underlain by the Camuy Formation. These ridges form a topography somewhat similar to that of the plateau in northwestern Puerto Rico, and it is entirely possible that both areas have been modified by marine planation during Pliocene or Pleistocene time.

East of Arecibo, much of the coastal part of the karst belt is covered by wide alluvial plains, deltaic deposits of rivers, swamp deposits derived from filled lagoons, and such coastal features as beach deposits and dunes. Any karst features once present are now completely buried and perhaps filled by these alluvial and strand deposits. Springs, probably related to karst drainage, however, appear at a few places.

Along the coast is a discontinuous line of hills of calcarenite that represents the indurated remnants of a line of dunes formed during the Pleistocene. These eolianite hills, described by Kaye (1959a), contain many karst features, such as solution pans, small solution spikes, and in a few places closed depressions and caves.

VALLEY FEATURES

As is common in karst areas, the northern karst area contains little surface drainage, but it contains many valleylike features, some of which are very unusual.

THROUGH-FLOWING STREAMS

First should be mentioned the rivers that cross the karst belt. All these rivers have their headwaters in the volcanic and intrusive rocks of the central mountainous section of Puerto Rico and flow through the karst belt to the Atlantic Ocean. All the rivers change in volume as they cross the karst belt, but records are not sufficiently complete to determine how much loss and (or) gain of water takes place. Dye tests have shown conclusively that some of the water of the Río Tanamá passes underground to emerge at the San Pedro Springs (Ar–3) at the side of the valley of the Río Grande de Arecibo, but this loss may be from the lake impounded by a dam to provide water supply to the city of Arecibo. Furthermore, part of the water of the Río Grande de Arecibo is lost underground and emerges in springs at the south side of the Ciénaga Tiburones, southeast of Arecibo. Arnow (Ted Arnow, oral commun., 1960) believed that the Río Grande de Manatí loses some water as it crosses the belt of outcrop of the Lares and Aguada Limestones.

The three eastern rivers that cross the karst belt, the Río Grande de Loíza, the Río Piedras, and the Río Bayamón, flow in wide valleys now so choked with alluvium that it is difficult to detect what if any effect drainage to or from the limestone has had on their courses. The Río Grande de Loíza in the fairly recent past flowed in a series of meanders through the ranges of limestone hills northeast of Carolina and finally entered the Atlantic Ocean at Boca de Cangrejos, 12 km west of its present mouth, but most of the area once occupied by the river is now buried by thick alluvial-fan deposits; furthermore, most of the surface is now drained by artificial canals, finally erasing the last traces of the old river course. The Río Piedras is a short stream that passes from the volcanic terrain south of San Juan into a great alluvial plain with only a few inselbergs of limestone penetrating it. The Río Bayamón flows from the interior into a very broad alluvial valley at Bayamón—a valley too large to be accounted for by the present relatively small river. After passing the limestone ridges of the Aguada and Aymamón Limestones, the river flows into a large deltalike deposit which is now surrounded by swamp deposits which apparently fill the basin of an ancient lagoon.

The next river to the west is the Río de La Plata—the longest river in Puerto Rico, which has its headwaters in the Sierra de Cayey, only a few kilometres from the south coast of Puerto Rico. It flows through the karst belt in a heavily alluviated valley 800–1,400 m wide. The lower reaches of the river have had a complex history, involving flow toward the west-northwest south of the Cerros de Higuillar west of Toa Baja and then a course toward the northeast down the present valley of the Río Cocal to the Atlantic 6 km east of its present mouth. So far as can be determined at present, the valley of the river through the karst belt is so thickly alluviated that any cavernous condition in the limestone has no effect on the flow.

The next through-flowing river to the west is the Río Cibuco, which flows through a narrow gorge through much of the karst belt. The Río Cibuco and its principal tributary, the Río Mavilla, both have headwaters in the northern foothills of the mountainous interior of Puerto Rico, but both streams appear to have been beheaded by the Río Grande de Manatí and by tributaries of the Río de La Plata. This stream piracy took place so long ago that the course through the southern part of the karst belt is well adjusted to the present volume of the Cibuco. In the northern part of the karst belt, the Río Cibuco flows through a wide, deeply alluviated flood plain and eventually debouches into deltaic deposits that apparently fill an old lagoon, north and northeast of Vega Baja. The Río Mavilla flows at the foot of a cuesta scarp formed by the hard limestone, some 60 m thick, of the Quebrada Arenas Limestone Member of the Cibao Formation. Both streams have cut into karst aquifers, as shown by scattered springs.

Much like the Río Cibuco is its tributary the Río Indio, which enters the Cibuco about 2 km east of Vega Baja. Both streams flow through large landslide areas (Monroe, 1964a) at the contact of the Lares Limestone and the San Sebastián Formation; both flow through narrow valleys that contain narrow flood plains of alluvium derived from the outcrops of volcanic rocks; and both have low alluvial terraces on their banks. Both streams flow through valleys that seem to have been formed primarily by corrasion by alluvial materials rather than by solution, although the very narrow gorge of the Río Cibuco just below the mouth of the Río Mavilla is so steep sided that it could be a collapsed cave, like much of the valley of the Río Tanamá farther west.

The next river to the west is the Río Grande de Manatí, whose headwaters include a large area of the upland near Barranquitas and the Cordillera Central. For such a large river, the flood plain through the limestone belt is very narrow, at places less than 200 m wide, but in the narrow area 3–4 km northwest of Ciales, the river has had a long history of forming meanders (fig. 6) and then abandoning them. Many of the abandoned meanders are shown on the limestone map (pl. 1) as dry valleys. At one place on the east side of the valley, about 3 km due south of Manatí, a thick terrace deposit of sand and cobbles of volcanic rocks is plastered on the side of the valley about 20 m above the present flood plain, and high terraces are fairly common at other places. The evidence is that the river valley was formed nearly entirely as the result of corrasion by sand and gravel carried down from the interior of Puerto Rico. Below Manatí, in the northern part of the Barceloneta quadrangle, the river sweeps back and forth across its flood plain in large meanders, probably the best developed in Puerto Rico. The mouth of the river has changed many times, former mouths having been identified 3.5 km both east and west of the present mouth.

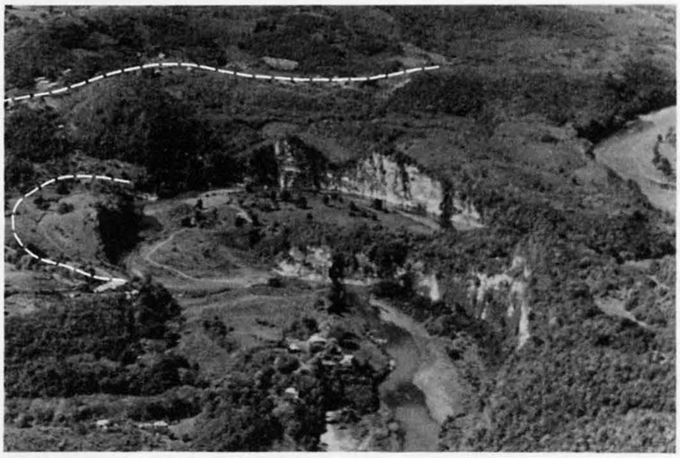

FIGURE 6.—Meanders of Río Grande de Manatí cut in Lares Limestone, 3 km north of Ciales. Abandoned meander is above cliff on left side of photograph and another one is near the top of photograph. Axis of meanders shown by dashed line.

The next river to the west, the Río Grande de Arecibo, cuts through the karst belt in a spectacular gorge 800–1,200 m wide, with nearly vertical walls as much as 200 m high. As most of the Cibao Formation in this area is represented by the Montebello Limestone Member, the walls are mostly bare limestone, at many places nearly vertical rockfall scars. The date of the beginning of the erosion of this valley can be determined almost exactly, as all the formations in the middle Tertiary sequence in the area 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 Formation contains a high proportion of quartz sand, which 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 Arecibo was drained by streams that flowed west, possibly entering the sea at some place west of Aguadilla. In the middle Miocene, however, the Utuado batholith, composed of quartz diorite and granodiorite (Weaver, 1958; Nelson, 1967b), began to be eroded by the young Río Grande de Arecibo, and the flood of quartz-loaded water was able to cut rapidly down through the relatively soft Tertiary limestone formations. The batholith now crops out between Lares and Jayuya in an area about 35 km long and 8 km wide. 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, 1967b) 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. 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. A third 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, another area of karst is characterized by low hills having an altitude of 50–60 m, about the same altitude as the tops of the hills on a small outlier in the valley, 2 km still farther north near Bajadero. These hills are all about 35 m above the present flood plain, which is nearly flat in this 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 4 m/km in the 5-km stretch between the highest terrace remnants and San Pedro.

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, for hard limestone was found beneath alluvium at a depth of 70 m in a well drilled 1.6 km east of Central Cambalache. Other wells drilled in its valley did not reach limestone. As the flood plain is less than 10 m above sea level, this proves that sea level was at least 60 m lower in the past, presumably in a low stage of the sea during the Pleistocene. Water is added to the river by limestone springs along its course, such as Los Chorros (U–2) 2.4 km north-northwest of Dos Bocas Dam and the San Pedro Springs (Ar–3) at San Pedro, 7 km south-southeast of Arecibo. The water budget for large springs on the south side of the Ciénega Tiburones (Giusti and Bennett, in press) east of Arecibo can be satisfied only by addition of water from the Río Grande de Arecibo. This water probably goes into the Aymamón Limestone near Bajadero, 6 km southeast of Arecibo. The limestone probably contains solution cavities formed during lower sea level of the Pleistocene, but the only evidence known at present for such cavities is the presence of springs in the Ciénega Tiburones and the large flow of water from an aquifer near Barceloneta at depths of about 300 m below sea level.

The Río Tanamá, a tributary of the Río Grande de Arecibo, has its headwaters in volcanic and intrusive rock less than 10 km south of the limestone belt. The Río Tanamá flows throughout the karst belt in a deep narrow canyon. At nine places it flows through long tunnels or short arches, four of which consist entirely of travertine (Gurnee, 1972). Almost certainly, much of the course of the river is following the route of a long river cave, much like the Río Camuy farther west.

Like the Río Tanamá, the Río Camuy heads in volcanic rocks a few kilometres south of the limestone belt and flows northward into the outcrop belt of the Lares Limestone in a gorge about 100 m deep. At the Blue Hole or Hoyo Prieto (B–14), the river flows into a cave at the foot of a high bluff and then follows a complex course underground until it emerges (Cm–19) 6 km almost due north (fig. 7).

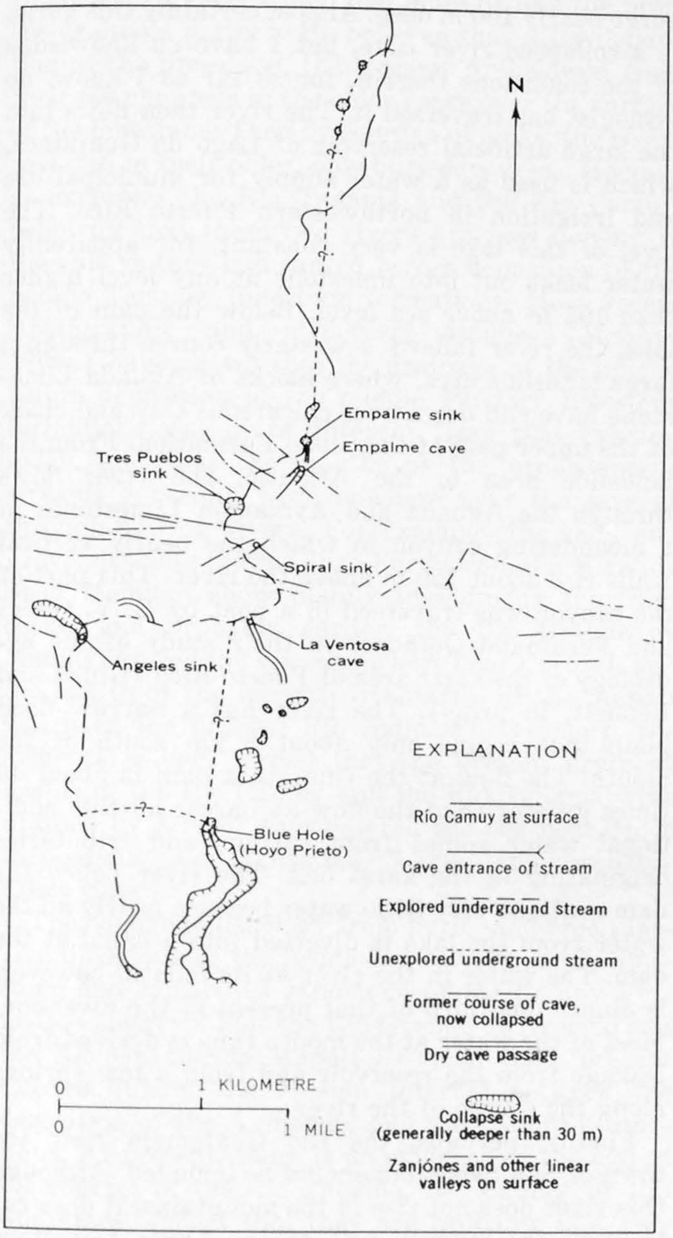

FIGURE 7.—Map of surface and underground features of the Río Camuy Cave system. Taken from published maps (Gurnee and others, 1967; McKinney and Miller, 1972).

The underground route of the Río Camuy is marked by several very deep collapse dolines. The first of these is the Angeles Sink (B–11) where the river crosses the southeast end of an elongated collapse sink. At the entrance to the Angeles Cave through which the river flows into the sink, I found in the alluvium many cobbles of porphyritic rock that had been transported to the site from one of the intrusive bodies that the river cuts through farther south. Cobbles of this kind have never been found in the Lares Limestone and only rarely in the lower part of the underlying San Sebastián Formation, so as the river enters the cave in the Lares Limestone, the cobbles can have been carried to their present position only by the fast-flowing water of the main Río Camuy.

It has not proved possible to enter the cave at Blue Hole because it is choked by rotten logs, and between Blue Hole and the Angeles Sink the river seems to flow in part through very thick masses of cave breakdown. Several explorations led by Norman Veve, Graham J. Nelson, Brother Nicholas Sullivan, David and Shirley St. Pierre, and Emily Davis (St. Pierre and St. Pierre, 1972; McKinney and Miller, 1972) have shown that the Angeles Cave is continuous with Cueva del Humo (B–20) and that the Río Camuy is present in the part of the cave beginning about 500 m north of Cueva del Humo, but apparently in less volume than enters Blue Hole. Directly below the Angeles resurgence, the water in the cave disappears into an impenetrable siphon but reappears a short distance farther east. Cave surveys of the underground river by Gurnee and his colleagues (1967) could be extended only a short distance downstream from the siphon below Angeles Sink; the area between the siphon and the Gurnee survey is impassible because of cave breakdown. Additional water enters the main cave at a point northwest of La Ventosa (B–12); this water probably comes more directly from Blue Hole.

The river course is marked farther north by the steeply pitching shaft of Spiral Sink (B–7); by the very large collapse doline, Tres Pueblos (B–6), 140 m in diameter and about 120 m deep (fig. 8); and by the bottle-shaped vertical shaft, Empalme Sink (B–3) 50 m wide and 125 m deep. Alluvium collected at the bottom of Empalme Sink consists mainly of subangular pebbles of andesite and silicified volcanic siltstone; the average grain size is about 1 cm. The river cave can be penetrated only 100 m or so north of Empalme Sink (Norman Veve, oral commun., 1969), beyond which it flows to the vicinity of the resurgence of the river (Cm–20) in underground passages that have not been explored except near the resurgence.

It is significant that the Camuy is flowing through relatively strong and competent Lares Limestone between the Blue Hole and Empalme Sink, but north of Empalme, the thickness of the Lares above the river level becomes progressively less, and within half the distance to the resurgence the river is flowing entirely in the relatively weak Montebello Limestone Member of the Cibao Formation, which is not strong enough to support the roof of a large cave.

FIGURE 8.—Aerial view from north of Tres Pueblos Sink. The sink is about 140 m wide and is about 120 m deep from top of wall on the east to Río Camuy, which enters the sink on the south side. For location see figure 7.

North of the resurgence, the Río Camuy flows through a narrow meandering vertical-walled gorge nearly to its mouth. The walls of the gorge are commonly more than 100 m high. Much of this part of the river course may very well be a collapsed cavern, but there is no conclusive evidence of this. About 4.5 km south of the mouth of the river, the canyon widens somewhat and has a narrow alluvial plain, mostly only 100 m wide, across which the river channel meanders back and forth. The water records (Kipple and others, 1968) show that the amount of water flow increases very greatly as the river flows across the limestone belt. The flow averages 4.5 times greater at La Cuesta, 8 km above the mouth, than it is at a point just south of the place the river enters the limestone. In contrast, the flow increases only about 10 percent between La Cuesta and the mouth.

The westernmost through-flowing stream is the Río Guajataca, which has its headwaters in the hills of volcanic rocks within a few kilometres of the town of Lares. The river enters the Lares Limestone at Lares and then flows west-northwest for about 5 km along a valley, which is apparently controlled by joints or zanjones, to a point where it reverses its flow to about east-northeast and then generally north. In that northerly reach, the river apparently follows a meandering course that has no noticeable relationship to the joint system that is well shown by the belt of zanjones on the surface. In this reach, the river flows through a nearly vertical-walled gorge nearly 100 m deep. Almost certainly this gorge is a collapsed river cave, but I have no knowledge of the conditions therein, for so far as I know, no geologist has traversed it. The river then flows into the large artificial reservoir of Lago de Guajataca, which is used as a water supply for municipal use and irrigation in northwestern Puerto Rico. The level of this lake is very constant, for apparently water leaks out into limestone at any level higher than 193 m above sea level. Below the dam of the lake, the river follows a westerly course through a large landslide area, where blocks of Aguada Limestone have slid down over calcareous clay and chalk of the upper part of the Cibao Formation. From the landslide area to the Atlantic, the river flows through the Aguada and Aymamón Limestones in a meandering canyon in which the nearly vertical walls rise about 150 m above the river. This part of the canyon was traversed in a boat by E. V. Giusti and Ferdinand Quiñones in their study of the hydrology of the karst area of Puerto Rico (Giusti and Bennett, in press). The river has a narrow flood plain that begins only about 3 km south of the mouth. The flow at the Guajataca dam is about 40 times greater than the flow at Lares; all this additional water comes from springs and tributaries originating in the karst belt. The river below the dam contains very little water because nearly all the water from the lake is diverted into a canal at the dam. The water in the river at its mouth, however, is almost one-third of that present at the diversion. Most of the water at the mouth thus is derived from leakage from the reservoir and from a few springs along the course of the river.

Finally, perhaps, the Río Guatemala near the town of San Sebastían should be included. Although this river does not rise in the mountains, it does cut through the outcrop belt of the Lares Limestone near San Sebastían. It has its headwaters in the Cibao Formation, from which it derives enough spring water to be perennial. It then flows west, cutting through the Lares Limestone in a narrow gorge, and then flows south across the San Sebastían Formation to the Río Culebrinas, which then flows west to the sea. Presumably a part of its deep gorge through the Lares Limestone has been excavated by sand and gravel derived from the Río Guajataca Member of the Cibao Formation. This initial corrasional erosion has probably been supplemented by solution of the Lares Limestone.

In his study of the physiography of Puerto Rico, Lobeck (1922, p. 329–336) came to the conclusion that the limestone had been deposited on a pre-Oligocene surface, which had more or less the present drainage pattern. He believed that after deposition of the limestone, the streams first flowed from their old channels in the older rocks over the surface of the limestone. Then by solution of sinks, the rivers reverted to their older, now buried, courses. He gave as examples the Río Tanamá and the Río Camuy, believing that these two rivers are now flowing in the valleys they had carved before deposition of the middle Tertiary limestone formations. More recent stratigraphic and structural studies (Monroe, 1966a) have shown that the drainage of the upland before deposition of the middle Tertiary limestone formations was quite different from that existing today, and that the mouths of the pre-Oligocene streams generally were nowhere near the present through-flowing rivers. For example, the sand and gravel deposits in the Cibao Formation, the Miranda Sand Member, show plainly that during the Oligocene, and probably earlier, the Río Grande de Manatí entered the sea somewhere near Corozal, and the mouth of the western tributaries of the Manatí was near the present Río Indio. Furthermore, the evidence is very strong that the present drainage basins of the Río Camuy and the Río Tanamá were drained by a river that entered the sea near Moca throughout San Sebastián, Lares, and probably Cibao time.

The change in lithology from pure, sand-free, clay-free limestone of the Aymamón to very sandy limestone and calcareous sandstone of the Camuy Formation suggests that the Río Grande de Arecibo and the Río Grande de Manatí assumed their present courses during the erosion interval between the deposition of the Aymamón and the Camuy Formations. At present, there is no evidence of the age of the courses of the Río Tanamá, Río Camuy, or Río Guajataca, except that they are probably late Tertiary.

DRY VALLEYS

Scattered through the karst area of northern Puerto Rico are many dry valleys, some of which contain intermittent streams that flow only during very rainy weather. A few of the valleys to be discussed here originate in the Cibao Formation and trend northward to end in blind valleys in the Aguada Limestone. Some of these contain small streams that may be perennial; although these valleys are not dry, they are included here because their morphology is similar to that of the dry valleys.

Probably the best known dry valley in northern Puerto Rico is Quebrada Cimarrona, which extends from the southern edge of the Barceloneta quadrangle (Briggs, 1965) northward and then eastward to the Río Grande de Manatí. Until some unknown date between 1960 and 1965, the valley had a small stream that originated in springs near the head of the valley. This flowing perennial stream was a hydrologic curiosity, for it flowed partly on bedrock and partly on an alluvial floor, far too wide for the stream, past several dolines, some of which were more than 5 m deep. The stream stopped flowing suddenly when the springs dried up; in 1972 the springs consisted only of a slightly marshy spot in the valley. Today (1973) the entire valley, 10 km long, is a dry valley.

The most puzzling dry valleys that I have seen are in the Lares Limestone northwest and west of Ciales. As can be seen on the limestone map (pl. 1), these valleys have a dendritic pattern and trend northeastward from the Lares scarp to abandoned meanders of the Río Grande de Manatí. The altitude at the head of the longest valley is about 285 m, but this has probably been lowered by solution because slightly farther north the bottom of the valley is at about 310 m (fig. 9). This valley ends in an abandoned meander of the Río Grande de Manatí at an altitude of about 85 m. The valley is interrupted in at least four places by closed depressions drained by swallow holes, so that any water now flowing down the valley during heavy rains soon passes underground. The abandoned meander at the end of the valley is itself also a dry valley, for it is at present only a line of closed depressions, all containing swallow holes. North of this main-trunk dry valley are several shorter old drainage systems, much like it, but apparently less complex.

This is the area that Lehmann (1954) designated as a type for his "gerichtete" karst or directed karst in Puerto Rico, in which he ascribed the alined depressions to joint control. Instead, apparently, the alinement must be explained by the lowering of a superposed drainage system into the limestone, first by mechanical erosion and then by solution. If these dry valleys have their courses determined by a drainage network eroded on clastic material that once covered the limestone, they must be older than the Río Cialitos, whose valley apparently beheads them. At the time the drainage network was formed, the Río Grande de Manatí had already carved its valley to a depth only about 60 m above its present level. The clastic material in which the side stream cut its original valley must have been a deposit younger than the Oligocene, for the possible cover

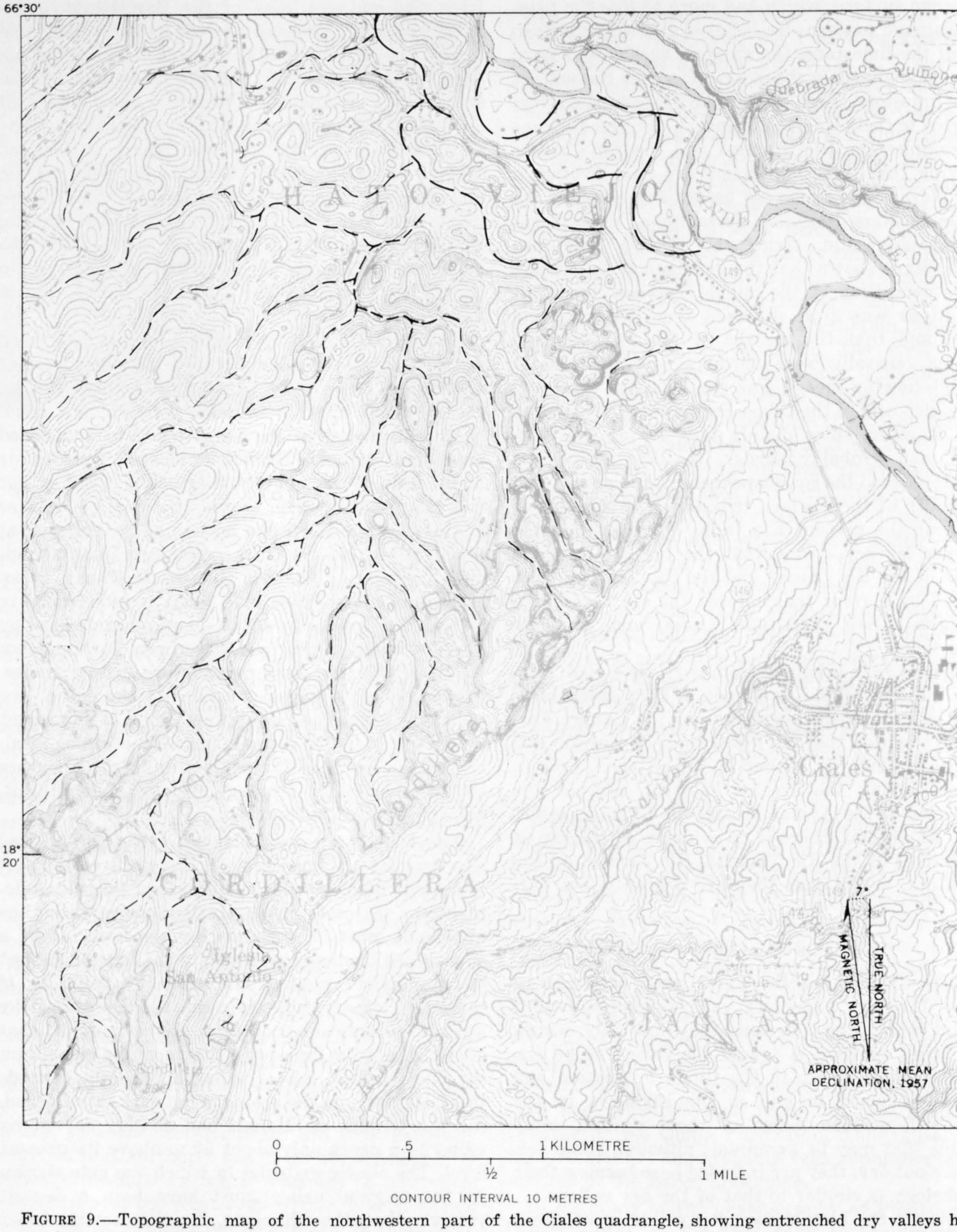

FIGURE 9.—Topographic map of the northwestern part of the Ciales quadrangle, showing entrenched dry valleys having a dendritic pattern. Long dashes show abandoned meanders of Río Grande de Manatí, short dashes. trace of dry valleys.

of clastic material of the Cibao Formation is exposed at much higher altitudes downdip to the north, and therefore could not have been the cover. The only tenable explanation seems to be that outcropping Lares Limestone had been planed down to a limestone pavement much like the one that exists today on the Aymamón Limestone 1 km south of Vega Baja, and that this plain had been covered by a flood of detrital material brought in by many streams flowing northward from the mountains of Puerto Rico. The streams that deposited the debris must then have been diverted, perhaps by capture by the Río Grande de Manatí, and the local dendritic drainage formed on the old pediment surface (Monroe, 1974).

An even more elaborate superposed stream is present to the west in the Florida quadrangle, where a part of it is known as Los Caños. This dry valley starts near the eastern edge of the quadrangle at the divide with the dendritic valleys in the Ciales quadrangle and then trends nearly due west for slightly more than 8 km. It receives many branching tributary valleys from the south, most of which trend northwest, but almost none from the north, for on the north side of Los Caños is the main scarp of the cuesta formed by the Montebello Limestone Member of the Cibao. At its west end, Los Caños seems to bend north, and the valley is lost in the plains of blanket sand at Florida.

The sides of Los Caños are so steep that the valley looks like a collapsed cave, but the dendritic pattern of the valleys entering it from the south suggests rather a superposed drainage system. Part of the valley to the north has walls that overhang in places, so that cliff stalactites have formed (fig. 10); this further suggests that the valley is a collapsed cave, but it is more likely that the valley was originally formed by a surface drainage system flowing on alluvial deposits. If one can assume that the area of Florida was once covered by a thin deposit of alluvial material, it is much easier to account for the extensive blanket-sand deposits east and west of Florida—deposits much farther south than those surrounding the hills of Aymamón Limestone. Deposits of alluvium could well have been eroded by the stream that carved the Los Caños valley and the much shorter streams that carved valleys that begin at the top of the cuesta on the north side of Los Caños and then trend north. None of these valleys contain active streams today, and most of them are lined with swallow holes (Monroe, 1974). Several much shorter dry valleys in the Lares Limestone are shown on the map (pl. 1).

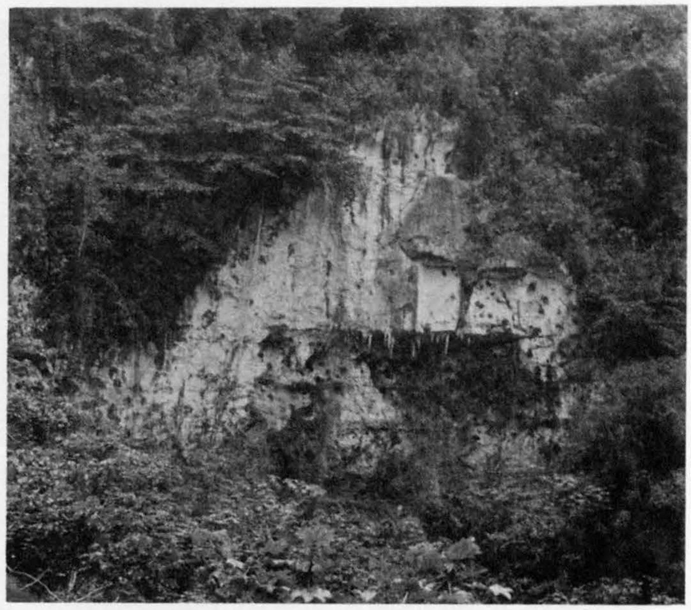

FIGURE 10.—Subaerial stalactites beneath overhang on cliff face, east side of dry valley at side of Highway 140, 2.4 km southwest of Florida.

Most of the dry valleys or nearly dry valleys in northern Puerto Rico originate at springs in the Cibao Formation. In their upper reaches they contain intermittent or even perennial streams, but as the streams flow north into the Aguada Limestone, most eventually lose their water, either in swallow holes in the bed of the valley or in caves at the northern end of the valley.

In the southern part of the Manatí quadrangle (Monroe, 1962, 1971) several such streams flow in a generally northerly direction across the clayey chalk of the upper member of the Cibao Formation and then become intermittent in generally dry valleys between walls of Aguada Limestone (fig. 11). The streams carry a heavy load of clay and sand eroded from the Cibao and probably contain considerable $Ca(HCO_3)_2$ in solution. They pass through nearly circular areas in the Aguada which are apparently closed depressions or sinks whose swallow holes have been plugged with clay and consequently have been filled to the brim with alluvium. The most accessible of these series of filled sinks ends in the intermittent lake known as El Salto (the waterfall), which is in the process of being filled (fig. 12). The altitude of the top of the waterfall at El Salto is about 160 m, and the valley to the east, about 165 m. When sufficient alluvium has been carried in by the stream so that the lake at El Salto is filled, additional alluvium will fill still more of the depressions upstream. The stream then will flow into a deep sink across a low

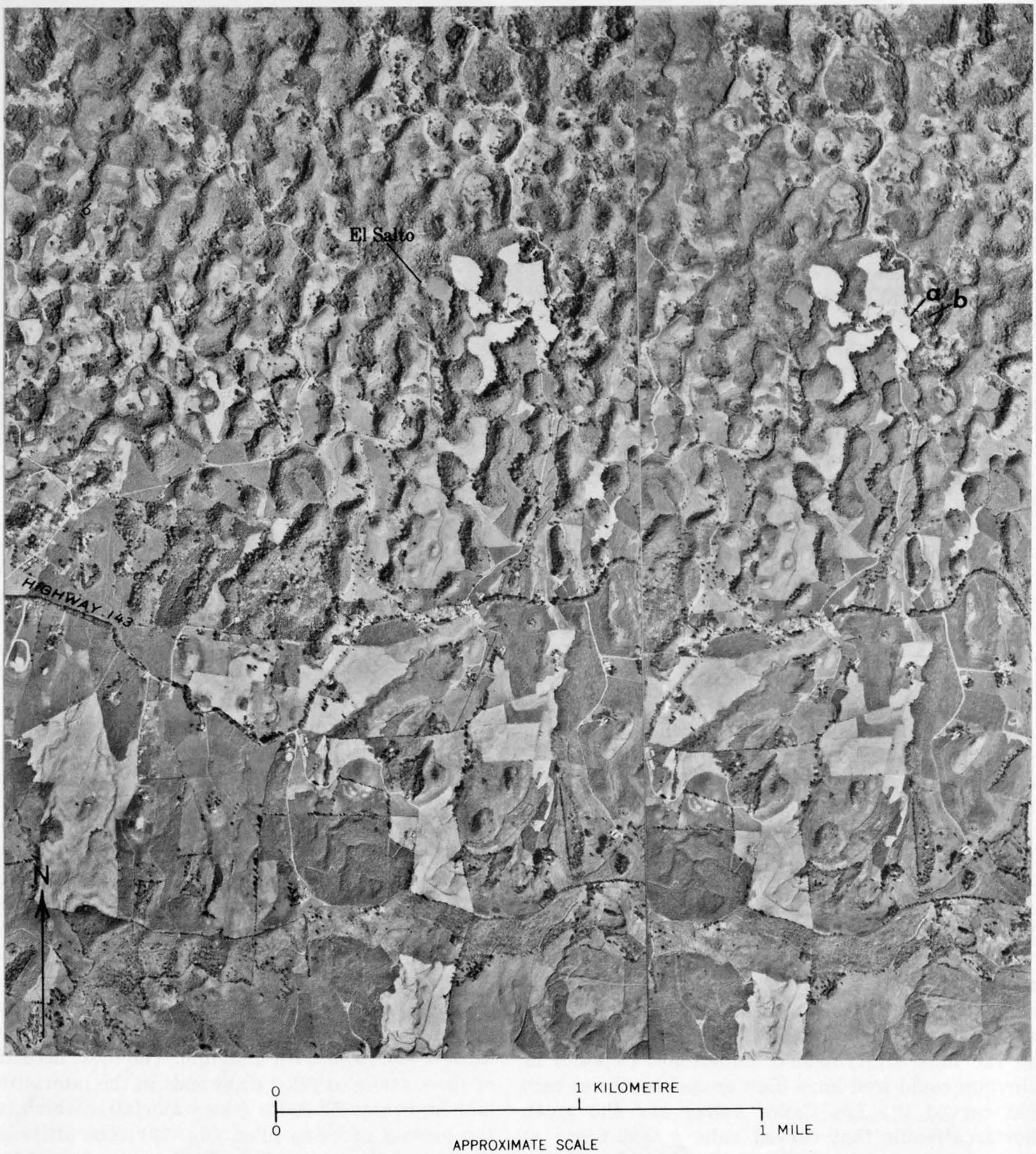

FIGURE 11.—Stereopair showing line of sinks filled with alluvium, leading to El Salto in the southern part of the Manatí quadrangle. *a* marks the low rock wall between the alluviated valley and the deep sinks; *b* marks the first of the family of deep sinks. To west and north is the typical doline karst of the Aguada Limestone. High hills in northern part of photograph capped by Aymamón Limestone. Aerial photographs from U.S. Soil Conservation Service, 1964.

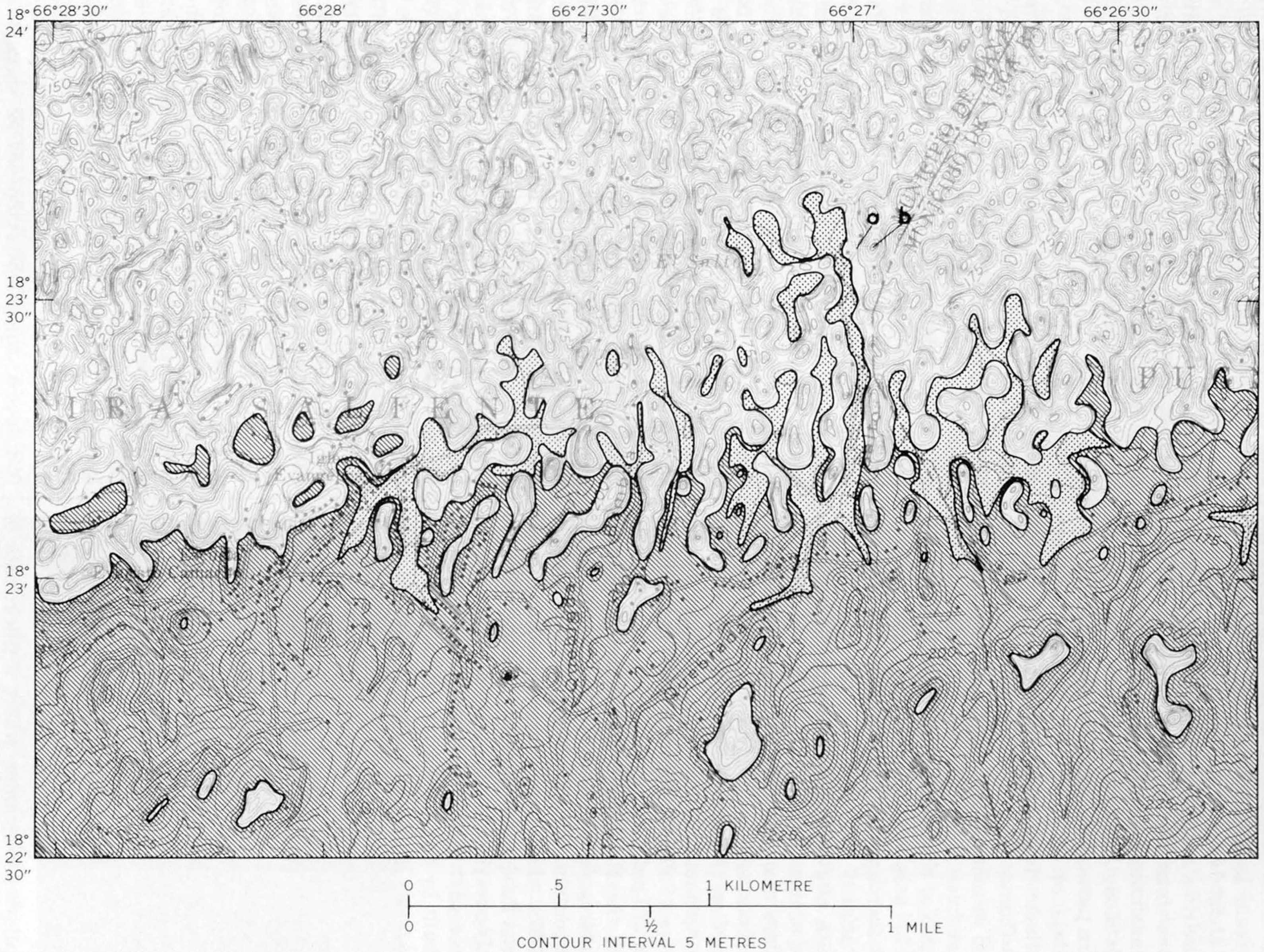

FIGURE 12.—Part of geologic map of the Manatí quadrangle showing doline karst in Aguada Limestone and lines of sinks filled with alluvium in both the Aguada and Cibao Formations. Cibao Formation shown by diagonal lines; alluvium shown by dots. *a* marks the low rock wall between alluviated valley and the deep sinks; *b* marks the first of the family of sinks.

rock wall which has an altitude of about 178 m, 350 m east of El Salto, only about 3 m above the present stream level. The sink has a floor whose altitude is about 145–150 m. It is one of a family of sinks, whose rims are below 175 m, and so the filling of successive sinks with alluvium can be expected to continue indefinitely. Similar series of filled sinks are present along the Aguada front entirely across the southern part of the Manatí quadrangle.

Dry valleys of an entirely different kind form short tributaries from 1 to 7 km south of the mouth of the Río Camuy (see pl. 1). Most of these tributaries trend in remarkably straight courses due east or due west from plains covered with blanket sand to the canyon of the Río Camuy. They appear to be controlled by a series of dominantly east-trending joints, but search of the canyon walls has failed to reveal any sign of the joints. Most of the valleys are covered with alluvium derived from blanket sand, and several of them are "beaded" with swallow holes.

Dry valleys that certainly have been eroded into less pure limestone are fairly common in the outcrop of the Camuy Formation and the upper member of the Aymamón Limestone in northern Puerto Rico. The most fully developed of these is the drainage system of Quebrada de los Cedros in the northern part of the Moca quadrangle and the adjacent Isabela quadrangle (Monroe, 1969a). Quebrada de los Cedros contains a concrete dam (Mo–1) built in the late 1940's which has never retained any water because even flood waters following heavy rains are immediately absorbed into the very porous limestone of the upper part of the Aymamón Limestone. The dam was built by the Isabela Irrigation Service, despite a warning by R. A. Laurence (written commun., July 31, 1947) that "the rock is quite porous, and is soluble in ground waters * * * It will probably require extensive grouting in the foundation, abutments and reservoir rims." Apparently any grouting that was done was unsuccessful. This well-developed valley with many tributaries must be superposed like those northeast of Ciales, for a dendritic drainage pattern would be most unlikely to form on such a porous limestone. The presence of blanket sand containing much quartz in the heads of the drainage system could provide the scouring material needed to deepen the channels by corrasion of the limestone to their present depth of more than 30 m.

Blind valleys are common where a thick mass of marly chalk of the upper member of the Cibao Formation is overlain by the Aguada Limestone. The largest valley is in the Vega Alta quadrangle at a point where an intermittent stream about 2.5 km long disappears in swallow holes in soil 1.7 km southeast of the plaza in Vega Alta.

In the northeastern part of the Corozal quadrangle, several unnamed intermittent and perennial streams flow into caves at the lower end of small dry valleys; these are shown on plate 1 and are listed with the numbered karst forms at the end of this paper.

The southwestern quarter of the Camuy quadrangle (Monroe, 1963b) contains several perennial and intermittent streams that have carved deep blind valleys, most of which end in caves. Several of these have been described by Nelson (1970), who calls them "Quebrada Caves." A perennial stream enters one of these caves (Cm–10, pl. 1) and can be heard roaring underground about 50 m farther northwest at the bottom of a nearly circular well about 4 m in diameter; this water has never been traced but may eventually appear at springs in either the Río Camuy to the northeast or the Río Guajataca to the northwest. About 1.8 km farther east-southeast, an intermittent stream passes from a dry valley into a short tunnel cave (Cm–15) less than 200 m long and then flows on the surface north and then east in a collapse valley. At the northeast corner of the valley the stream enters another cave (Cm–14) several hundred metres long, which has not been completely explored. It then emerges in a water-filled cave (Cm–12) and flows along another collapse valley into a low cave (Cm–8) in which it disappears in cave breakdown. This cave has not been traced because of the breakdown, but the water is believed to flow into the valley of the Río Camuy at the cave Boca del Infierno (Cm–9). These river caves contain no bats and very little other life and are exceptionally clean of mud and debris, for during rainy periods they are filled to the ceiling with rapidly flowing water, which makes them exceedingly dangerous at that time. During dry seasons I have seen fresh leaves caught in cracks in the ceiling of cave Cm–14, and Nelson (1970, p. 15) found a green pineapple plant in the ceiling of cave Cm–8. In the same general area, several other intermittent streams originate in the clayey upper part of the Cibao Formation and disappear in blind valleys eroded in limestone beds in the top of the Cibao and the base of the Aguada Limestone.

CLOSED DEPRESSIONS

The topographic maps of Puerto Rico show by closed contours thousands of depressions that result from solution of the underlying rocks, as well as many that result from landslides and the excavation of sand by wind. The contour interval of most topographic maps is 10 m, but many of the maps have intervals of 5 m or less. Depressions are indicated by the presence of barbed depression contours. The depressions range in shape from irregular areas of hundreds of square metres to almost circular holes, and they range in depth from only a metre or so to more than 70 m.

In my study of the closed depressions, I used as a starting point the highest closed contour in a group, and I considered that altitude as the lowest point on the rim of a basin. I determined the depth of the various low points within that area by subtracting the altitude of the lowest closed contour of each depression from the altitude of the assumed lowest point on the rim of the basin. Thus, the figures are conservative, and true depths may be as much as a contour interval greater.

Puerto Rico contains several thousand solutional depressions deeper than 5 m; the general areas where these are abundant are shown by an outline on plate 1. Most of these are in the karst belt of northern and northwestern Puerto Rico, the area of outcrop of the rocks of middle Tertiary age. In some areas, solutional depressions are deeper than 30 m and are shown on the map as solid masses of color. All but three of these depressions are within the outcrop area of the middle Tertiary rocks.

The closed depressions in the blanket-sand belt in the northern part of the karst belt are generally rather large, have gently sloping sides, and seldom exceed 5 m in total depth. But the blanket sands may be underlain in places by deep depressions, for directly south of the inner belt of the blanket sands that rest on the Aymamón and Aguada Limestones, depressions as deep as 30 m are relatively common. Some of these contain a flat plain of blanket sand in the bottom, although many drop down to a conical hole containing only a little residual clay at the very bottom.

The deepest depressions are in the Aguada Limestone, near the exposed contact of the Aymamón and Aguada Limestones, and in the area near the exposed contact of the Lares Limestone and the overlying Montebello Limestone Member of the Cibao Formation. Although many of these very deep solutional depressions are irregular in shape, and many of them contain several individual sinks, most are rather narrow at the narrowest point. About 830 depressions are 30–40 m below the lowest point on the rim of the major basin, and the narrowest of these have a width of only 50 m, with an average narrowest width of about 110 m. About 366 depressions are 40–50 m deep, and the narrowest of these also have a width of about 50 m, but the average width at the narrowest point is about 133 m. Some 107 depressions have an altitude at the bottom 50–60 m below the lowest point on the rim; the narrowest point in any of these is 80 m, with an average width at the narrowest point of 154 m. Only 12 depressions are 60–70 m deep, and the narrowest is about 110 m across, with an average width at the narrowest point of 166 m. On all the maps, I have found only 10 depressions deeper than 70 m. Two of these are collapse dolines along the course of the Río Camuy, where the roof of the Camuy Cave has collapsed. Another is just northwest of the Río Tanamá at the east side of the Bayaney quadrangle; its dimensions and near-circular plan met the requirements for the huge dish reflector of a radio and radar telescope, so this depression became the site of the Arecibo Ionospheric Observatory (fig. 13). It consists of a conical bowl whose bottom is about 70 m below the lowest point on the rim, which is surmounted by several towerlike hills that rise as much as 50 m higher, making a total relief of more than 120 m. Four of the other depressions deeper than 70 m are in the Quebradillas quadrangle near the Río Guajataca. The bottoms of these depressions are in the Aguada Limestone, but the rim is composed of Aymamón Limestone, and peaks of Aymamón rise to still higher altitudes on the rims. That area is densely wooded, however, so that the depths and altitudes which were determined by photogrammetric methods may not be accurate. The other three depressions

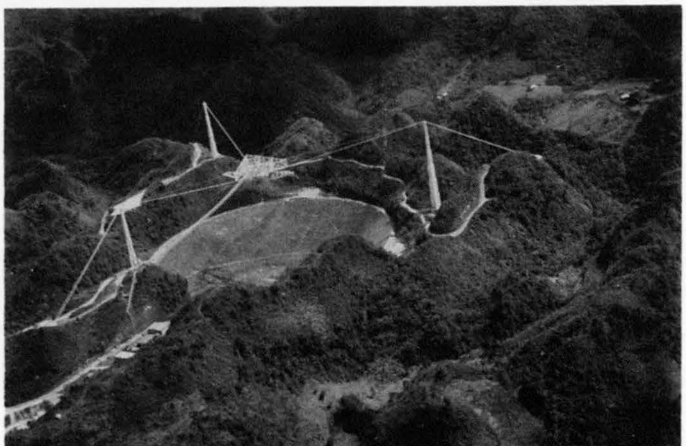

FIGURE 13.—Aerial view of Arecibo Ionospheric Observatory from the north. The cave through which the Río Tanamá flows is directly behind the right-hand pylon. The cleared fields in right background are on an exhumed hill of volcanic rock.

deeper than 70 m are in another highly wooded area in the Utuado quadrangle.

Nearly all deep depressions have concave slopes, which in the upper parts approach the vertical. This is the result of the tendency of the depressions to deepen by solution at the bottom, whereas little if any solution takes place at the sides. Consequently the sides get steeper, and eventually there is sloughing off in small landslides, leaving vertical slopes. This tendency of limestone walls to get steeper as they get higher is well shown on the cuesta scarps described earlier and on the steeper sides of the mogotes that separate the various belts of blanket sand. These vertical walls give the impression of collapse features at places where there is no evidence of the presence of underground caverns, much less of their collapse. It shows up especially in the areas of cone karst and even more in the areas of cliffed cone karst characteristic of the area where the Montebello Limestone Member of the Cibao Formation overlies the Lares Limestone. An excellent example of a very deep solution doline is the bowl of the Ionospheric Observatory (fig. 13). Drainage from this bowl is through porous limestone in the Lares Limestone at the bottom, but no large cave or evidence of a former large cave now collapsed has been found beneath the bowl, even though the Río Tanamá flows through a very large cave just south of the bowl.

Doline karst is characterized by more or less circular or oval depressions in a plain; this type of karst is believed to be characteristic of temperate climates, whereas cone karst consisting of conical hills is supposed to be more characteristic of tropical climates (Lehmann, 1960). In Puerto Rico, however, there are several areas of doline karst. The most typical of these is in the outcrop belt of the Aguada Limestone in the southern part of the Manatí quadrangle, where the ridges between the depressions form a gently undulating plain, which is perforated by dozens of subcircular solution dolines ranging in depth from about 10 m to more than 30 m (figs. 11, 12, 14). The southern edge of this area of doline karst is at the scarp produced by the outcrop of the base of the Aguada Limestone, and the northern edge is marked very sharply by the southern towers held up by the Aymamón Limestone; typical dolines continue north of the Aymamón scarp, but they are not so regular because they are modified by the high towers on the ridges separating the depressions. Still farther north, the dolines are filled by blanket sands, and the doline karst merges into mogote karst characteristic of the Aymamón Limestone. This area

FIGURE 14.—Aerial view of doline karst in Aguada Limestone, 3–4 km southeast of Manatí. Pointed hills in background are capped by Aymamón Limestone.

of doline karst in the Manatí quadrangle is notable for its lack of caves; the Aguada Limestone itself is perforated by many solution passages a few centimetres in diameter, but none are known that are large enough to enter, so there is no evidence of large-scale collapse to account for the depressions. Sweeting (1972, p. 69) considered the karst in this part of the Manatí quadrangle typical cone karst, but a characteristic feature of cone karst is star-shaped, irregular, closed depressions, whereas the closed depressions in this area are mostly subcircular, which is typical of doline karst. Both doline karst and cone karst are present in other areas of the outcrop of the Aguada Limestone.

Many of the highest depression contours in a basin enclose a rather irregular area of several hundred square metres; these areas at some places contain subsidiary solution depressions, some of which may be deep. Presumably these families of closed depressions constitute uvalas. Most of them do not show any particular pattern of orientation of the depressions, constituting more evidence that they are formed by random patterns of solution holes that gradually became deeper. In the Camuy quadrangle, two such families of depressions, one west of El Saco and the other south of Rafael Capó (shown on the Camuy quadrangle topographic map), are accentuated by oval-shaped ranges of hills, shown on the limestone map (pl. 1) as ridges, one of which is partly included in the cuesta scarp produced by the Aymamón Limestone.

Many of the dry valleys discussed earlier are beaded with relatively small depressions that serve as swallow holes during rainstorms. Also, some of the large zanjones north of Lares cross rather long closed depressions that appear to be formed in part by concentration of jointing.

Although most of the closed depressions in Puerto Rico are believed to be the result of simple solution of the limestone, some are the result of collapse of large underground cavities. The largest and best known of these are along the underground courses of the Río Camuy and Río Tanamá. The Río Camuy flows through a very large cavern, some of the rooms of which are more than 50 m high. At seven places the roof has collapsed, producing very deep collapse dolines, and at four of these places the river is now exposed to the sky (figs. 8 and 15).

All these collapse features are shown on the karst

FIGURE 15.—Stereopair of aerial photographs of topography above part of the Río Camuy Cave system, showing Tres Pueblos Sink, Empalme Sink, and Empalme Ravine, which leads to Empalme Cave. East-west lineations near Tres Pueblos Sink are zanjones. See also figures 7 and 8.

map (pl. 1), but the ones of most interest are the Angeles Sink (B–11), Spiral Sink (B–7), Tres Pueblos Sink (B–6), Empalme Sink (B–3), and the three sinks in line (B–1); these three sinks do not reach the underground Río Camuy, but they probably have collapsed above caves along the course of the river.

The largest of these collapse features is Tres Pueblos (see fig. 8), which is a sheer-walled pit more than 120 m deep and about 140 m in diameter. The Río Camuy flows into the bottom from the south, flows along the foot of the southeast cliff, and flows out at the northeast side; the ceilings of the entrance and exit of the river are both about 30 m high. Until about 1965, cooking bananas were raised commercially on the bottom slopes of the collapse debris, and the matured fruit was carried out by hand up a homemade wooden ladder over a short vertical slope on the western side of the pit. Since then, the ladder has rotted away, and the land is not used for farming.

Downstream from Tres Pueblos at the southwest corner of the intersection of Highways 129 and 455 is a vertical cave known as Empalme Sink (B–3). It is about 50 m across at the surface and is about 125 m deep. At the bottom, the Río Camuy flows in from the west and flows out toward the north; according to Norman Veve (oral commun., 1968), the river drops down into an impenetrable siphon about 100 m north of the sink. About 40 m above the river along a muddy trail is Empalme Cave, on the south side of the shaft; this is a tunnel about 200 m long that opens into a deep ravine farther south. This cave provides an easy access to the bottom of the shaft and has been much used by local people to reach the river for fishing. Apparently the coincidence of the Empalme Cave above the Camuy Cave (the Camuy Cave ceiling here is less than 5 m above the river) so weakened the rock between the two caves that the strata collapsed.

In the general area of the Camuy Cave are many other collapse sinks, such as El Humo (B–20), and dozens of other features that may be collapse sinks, or solution dolines, or a combination of both.

The Río Tanamá flows through a valley crossed by nine bridges or short tunnels (Gurnee, 1972), so the entire valley can well be considered a collapse feature in which the original rock remains in only five places, where the river flows through short tunnels. The other four tunnels are apparently very low passages covered by travertine that may have formed across the narrow valley by accretion from the sides; if this is true, these low tunnels are not collapse remnants like the others, but instead have been formed by deposition of calcium carbonate from springs at the sides of the canyon.

Just north of Highway 2, about 4 km northwest of Vega Alta, a series of extensive caves in the Aymamón Limestone have partially collapsed to form many vertical collapse dolines. Many of these are connected by short tunnels known as the Monserrate Caves (V–1), which are well decorated by stalactites, mostly of the rather spongy type that forms in daylight because of incorporation of moss and other plant material. This area has recently been developed as a housing area, so the areas that have not collapsed are now covered with small houses and gardens, and many of the depressions are being used for disposal of used building materials and trash.

Although not in the northern karst belt, an excellent example of collapse structures is in barrio Sumidero of Aguas Buenas (Cg–1) where a band of limestone of Cretaceous age crops out in an area of impounded karst (karst barré) surrounded by various kinds of volcanic rocks. Here the Río Cagüitas flows underground through the Aguas Buenas Caves, and the land has sunk in several collapse dolines known collectively as Los Sumideros (The Sinks).

In several parts of the northern karst area of Puerto Rico are relatively narrow vertical caves of unknown origin. Some of them may be collapse features like the Empalme Sink, but most are vertical for 30 m or so and end either in a small hole or in a flat chamber that has no side passages. Most of them are only a few metres in diameter and are surrounded by a hedge of bushes or trees planted to prevent cattle and people from falling in. Three kilometres east-southeast of Hatillo are twin shafts (Cm–1). The eastern one is about 10 m in diameter and descends vertically 30 m. A few tens of metres farther west is a similar, slightly narrower shaft that slopes steeply east and intersects the other at the bottom. No passages could be seen leading internally from the bottom of the two vertical caves. It is difficult to imagine how these shafts were formed, as they do not seem to be collapse features, they do not reach the water table, and they are only about 30 m above sea level at the bottom. They have been dissolved in the upper rather sandy chalky member of the Camuy Formation, and they do not reach the top of the middle member of the Camuy Formation, a hard limestone that contains many small solution cavities. Apparently the shafts have been formed by solution alone. Several others nearby have been filled with debris, such as abandoned automobile bodies.

Collapse features are fairly common in the blanket sands, and they will be discussed in the section describing the formation of the mogotes in the Aymamón belt.

Scattered through the northern karst belt are some larger than usual closed depressions, which are characterized by a flat bottom covered with alluvial material that appears to be the same as blanket sand and surrounded by steep slopes that intersect at a sharp angle. In some of these depressions, a small stream enters as a spring at one side and flows out the other, generally through holes too small for a man to enter. All these features are characteristic of poljes (Sweeting, 1972, p. 193), but none of the Puerto Rican depressions are as large as the minimum size established by Gams (1973, p. 62), who specified that in the classical sense the flat floor must be at least 500 to 1,000 m wide. The largest of these polje-like depressions is in the Camuy quadrangle (Cm–21) on the east side of Highway 487 (coordinates 113,400 E, 62,800 N). This depression is roughly U-shaped; the larger leg is 600 m long and 140 m wide, far too small to be considered a polje by Gams. A somewhat smaller but similar feature is present about 600 m farther northeast. Both of these depressions are in the Aguada Limestone. Many similar but much smaller depressions are present in the southern part of the Manatí and Quebradillas quadrangles, also commonly in the Aguada Limestone.

Near the boundary of the Cibao Formation and the Aguada Limestone are many nearly flat depressions that slope gently toward the north. The floors of these depressions may be covered with a thin mantle of alluvium, but beneath the alluvium and cropping out in many of them is clay weathered from the Cibao Formation. The walls on the east, north, and west sides are of the Aguada Limestone, and in some places the Cibao forms a low wall to the south. These depressions are really a modification of the blind valleys so common at this stratigraphic horizon.

HILL FEATURES

The karst area of northern Puerto Rico is very well known internationally for the variety of hill features that have formed on the limestone. Especially well known are the cone karst, mogote karst, and the river and coastal walls or ramparts.

CONE KARST

The conical hills of the Lares Limestone have been of interest to geomorphologists since Spanish colonial days. Hill (1899a, b) called them *pepino* hills (*pepino* is the Spanish word for cucumber). They were next described in much more detail by Hubbard (1923), who referred to them as *pepinos* or haystack hills. Hubbard (1923, p. 90–93) pointed out that the pepino hills are best developed in the belts of outcrop of the Lares and Los Puertos (Aguada and lower Aymamón) Limestones at places where the limestone is most cavernous. Because of linear grouping of the hills and intervening sinks, he believed that the hills are residual, having been left by collapse of caverns of underground streams similar to such through-flowing rivers as the Camuy and Tanamá. He believed that the collapse was accompanied by "extremely rapid surface solution." Hubbard's views were generally accepted by geologists (Meyerhoff, 1933; and others) until Lehmann (1954) visited the Greater Antilles and applied to the cone karst of Cuba and Puerto Rico the name Kegelkarst and the mode of formation that he had worked out in his studies in Java. Lehmann attributed the cone karst in general and especially in Puerto Rico to solution along joints, and he used as a typical area the cone karst northwest of Ciales, which he termed "gerichtete Karst" or directed karst and ascribed it to joint control. I have found that the area of "directed karst" near Ciales (see pl. 1 and fig. 9) is controlled by a superposed drainage system.

Cone karst is also known as cockpit karst, a term used in Jamaica because of the supposed resemblance of the depressions to the arenas where cockfights are held. Typically cockpit karst consists of abundant round cone-shaped hills surrounded by sinuous or star-shaped depressions. The cockpit karst in Jamaica was studied by Sweeting (1958), who, following Lehmann, ascribed the alinement of the cockpits to solution along joints and faults. Subsequently, Sweeting (1972, p. 274) modified her views, quoting Conrad Aub as stating that in many areas the depressions or cockpits do not seem to be related to any joint or fault system. She also quoted Aub (Sweeting, 1972, p. 276) as explaining the star shape of the cockpits as caused by gullying by torrential rainstorms, an explanation that certainly can explain some of the irregular shapes of the interhill depressions in Puerto Rico. Similarly, Wiliams (1971) ascribed the star shape of the closed depressions in New Guinea to radiating centripetal stream channels within the depressions.

Cone karst in Puerto Rico is best developed in the Lares Limestone. Perhaps the best examples are in the area west and southwest of the Arecibo Ionospheric Observatory, west of the Río Tanamá, in the Bayaney quadrangle where many of the cones are sharp, pointed nearly circular or oval hills 200–

300 m in diameter at the base that rise 50–75 m above the bottoms of the adjacent depressions. Many of these cones are joined together to form linear ridges, but separate ridges do not seem to have any preferred direction of alinement. In adjacent areas, however, the ridges are cut by gullies into sawteeth, and the gullies extend entirely across the ridge. This scoring of the cones and ridges seems to have a trend more or less northeast, but there are so many exceptions that predominating directions could not be determined. Probably the gullying is related to regional jointing, but there seems to be no perceptible relationship between the trends of the hills and cockpits and the trends of the gullies. Thus, it seems unlikely that the arrangements of lines of cones and cockpits can be due to preferred directions of jointing in this area.

Cone karst much like that in the Bayaney quadrangle is common throughout most of the outcrop belt of the Lares Limestone, except in the few areas where it is interrupted by the relatively flat zanjón karst.

A very typical area of cone karst is the area of Lares Limestone just east of the Río Grande de Manatí at Ciales (fig. 16). In that area, the depressions are very sinuous and are relatively shallow, the deepest extending down only 30 m from the lowest point on the rim. The hills, on the other hand, rise from 50 to 100 m above the bottoms of the depressions.

Thrailkill (1966) called attention to the cone karst of the Lares Limestone in the area near the Río Camuy and suggested that the area of outcrop of the Aguada Limestone is another area of cone karst. Sweeting (1972, fig. 33) also considered the solution pattern of the Aguada Limestone to be typical of cone karst, but my own studies show that the Aguada is characterized by much more circular or oval depressions and that the hills or ridges are commonly sinuous. Thus, the solution pattern of the Aguada is more closely related to doline karst rather than cone karst, even though many of the hills in the area of outcrop of the Aguada Limestone are rounded and the peaks are commonly cupola shaped (see figs. 10 and 13).

An unusual form of cone karst is present in the southern part of the karst belt in the Florida and Utuado quadrangles in the area where the Montebello Limestone Member of the Cibao Formation overlaps nearly all the Lares Limestone. The Montebello is a relatively coarse calcarenite that tends to break with a vertical fracture, whereas the Lares is a denser, more tightly cemented calcarenite. Consequently, the Lares is dissolved into the usual cone karst, but the cones are capped by vertical cliffs that form towers. This type of karst can well be called cliffed cone karst (fig. 17). The cliffed cone karst does not extend west of the Utuado quadrangle into the Bayaney, for in the Bayaney the lower part of the Montebello has weathered into zanjones.

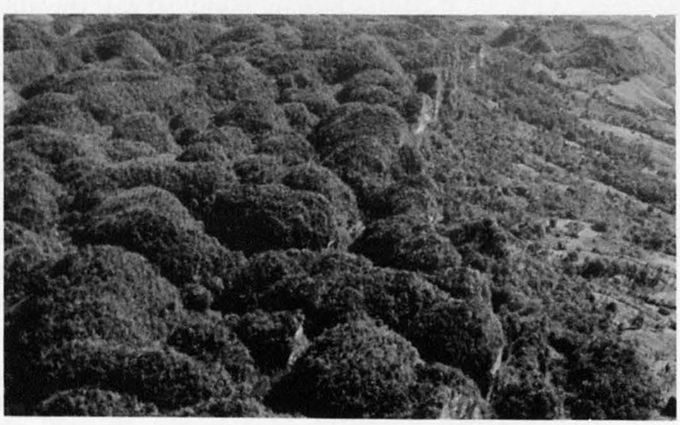

FIGURE 16.—Aerial view of cone karst in Lares Limestone on upland east of Río Grande de Manatí, a kilometre east of Ciales. The cliff at the top of the slope is the breakaway cliff of a landslide area that slopes down to the river.

FIGURE 17.—Aerial view of cliffed cone karst southwest of Florida. Cliffs are composed of Montebello Limestone Member of Cibao Formation, lower slopes, of Lares Limestone.

RIVER AND COASTAL RAMPARTS

In 1953, Flint and others described natural walls of limestone at the tops of canyon walls, fault scarps, and around sinks in Okinawa. They ascribed these walls to secondary cementation and differential erosion. Such walls or ramparts are very common along the tops of the river canyons in Puerto Rico and at many places at the tops of limestone sea cliffs.

The most prominent and best known ramparts in Puerto Rico are on the west side of the Río Guajataca canyon (fig. 18), 3 km south of the mouth of the river. The altitude of the top of the rampart here is about 165 m. The river has cut a steep-walled canyon, at the bottom of which the altitude of the river is a little less than 10 m, or 155 m below the top of the rampart. The west side of the rampart slopes down to a body of blanket sand that ranges in alti-

FIGURE 18.—Stereopair of 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 blanket sand to the west. In southern part of the photograph, the limestone has been dissolved into cone karst. Aerial photographs from U.S. Soil Conservation Service, 1963.

tude from 130 to 150 m, so that the top of the rampart stands 15–35 m above the blanket sand, making in effect a wall between the generally flat field to the west and the river canyon to the east. Figure 18 is a stereopair of aerial photographs showing this area, and figure 19 shows the relationship of the rampart to the canyon and to bodies of blanket sand on both sides of the river.

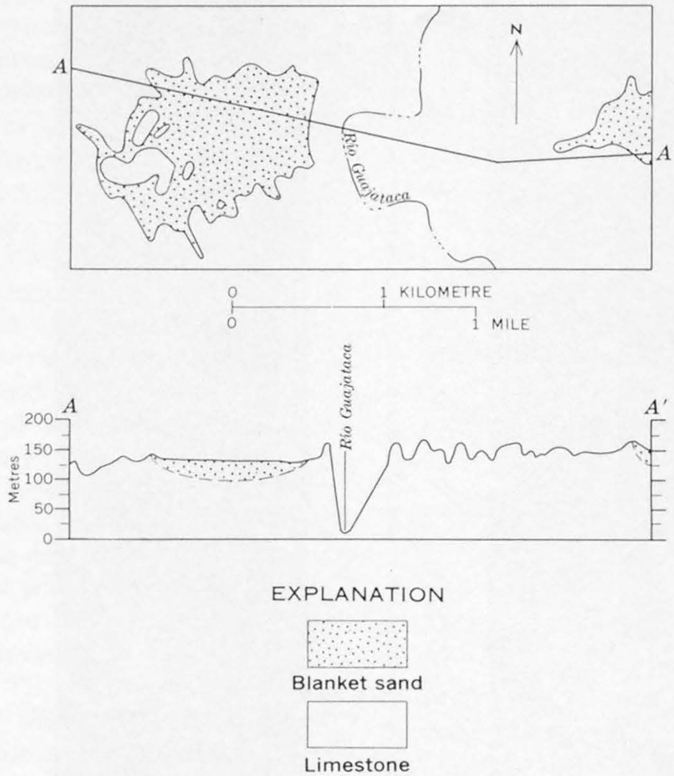

FIGURE 19.—Map and profile showing relation of the Río Guajataca rampart to the canyon and the plain covered by blanket sand (Monroe, 1967, 1969c).

Kaye (1957b, p. 112) described this wall and ascribed it to casehardening by reprecipitation of calcite, probably in a joint and on the wall of the canyon. He considered that the flat west of the wall is a blanket of soil residual from the limestone, but, as has been pointed out earlier in the present report, the Aymamón Limestone contains only 1–5 percent impurities, none of which is quartz sand, so the soil, which contains quartz grains, cannot be residuum. It is instead a remnant of the blanket sand described earlier in this report.

I described the same locality (Monroe, 1969c) as an example of the solution of the very pure Aymamón Limestone under the cover of the blanket sands, leaving limestone hills as residuals. Blanket sand is present on both sides of the canyon of the river at approximately the same altitude of 130–150 m; on the east side of the river, however, instead of a wall there is a series of mogotes having about the same altitude as the top of the wall on the west side of the canyon (fig. 19). Blanket sand is present about 1.4 km east of the river at about the same altitude (130–140 m) as on the west side of the river, west of the wall of limestone. The blanket sand obviously once constituted a nearly continuous cover, but at that time it had to have an altitude at least as high as the mogotes and the wall—its base had to be at an altitude of at least 165 m. Since then, the plain has been lowered at least 35 m to its present altitude, leaving the wall and the mogotes exposed as residuals of limestone that had been casehardened or indurated by reprecipitation, as suggested by Kaye (1957b). In my paper (Monroe, 1969c), I explained this lowering as being accomplished by subsoil sheet solution, but Miotke (1973) has since pointed out that part of the lowering of the blanket sands between mogotes is the result of collapse, probably of cavernous areas in the limestone below the blanket sand. His illustration (fig. 20) of such a collapse under a road is particularly striking. I have seen several examples of such collapse, both in the Aymamón Limestone and in the plains covered by blanket sand, so I agree with him that collapse as well as sheet solution is a factor in the lowering of the sand plains. In some areas, the lowering may be the result of piping or suffosion in which the lower part of the blanket sand itself flows away into caves and cavities in the underlying limestone. Undoubtedly, however, the original altitude of the blanket sand was higher than the present alti-

FIGURE 20.—Collapse sink in plain of blanket sand on public road 2 km east of Miraflores, 11 km east-southeast of Arecibo. Photograph taken by Dr. Franz-Dieter Miotke, Hanover, Germany, and published with his permission.

tude of the tops of the river ramparts and of the mogotes, and the present level of the sand plains is much lower than it was at the time the sand was deposited.

Kaye's explanation of casehardening of the exposed limestone is quite correct, but such induration is not limited to joints or faults—in fact, what little evidence is available about jointing in the limestones suggests that joints are marked by depressions, not ridges.

Less obvious river ramparts are present at intervals on both sides of the Río Guajataca canyon from a point 1 km above the mouth as far upstream as the large landslide mass below the dam of Lago de Guajataca. The date of erosion of the valley in relation to the river rampart is uncertain. It seems obvious that the belts of blanket sand are older than the river valley, but of course the blanket sands were deposited at a higher altitude relative to their enclosing hills than is their position today. It is reasonable to assume that the river may have eroded away the sand in the area of its present canyon before the lowering of the blanket-sand plains began on the two sides. The bare limestone left by such erosion would soon be indurated by reprecipitation of the calcite, as in the formation of mogotes. If the river canyon is a collapsed river cave, however, erosion of the blanket-sand cover near the newly collapsed valley would be rapid enough to scour off the tops of the ridges and the mogotes.

The induration of the limestone in the canyon walls is undoubtedly a factor in the preservation and, possibly, in the origin of the ramparts, for ramparts are also present on the sides of the canyon of the Río Guajataca upstream from the typical wall described above. These upstream ramparts rise more than 100 m above the river, but on the sides away from the river they are accentuated by very deep closed depressions that are probably solution dolines rather than collapse dolines.

The Río Guajataca has the best examples in Puerto Rico of river ramparts, but they are present elsewhere and are especially notable on the east side of the Río Grande de Manatí (fig. 21), both in the area where blanket sand is present and also upstream in the outcrop area of the Aguada Limestone, which is characterized by deep solution dolines.

Very similar in origin to the river ramparts are low walls at the top of sea cliffs composed of Aymamón Limestone, especially in the Quebradillas and Isabela quadrangles; in the latter quadrangle, however, the phenomenon is complicated by the presence of ridges of eolianite at several places. At all the places where coastal ramparts of indurated limestone have been seen, the inland side of the wall is bordered by blanket sand.

MOGOTES

Mogotes are hills that rise out of the blanket sand deposits of northern Puerto Rico and are also known as towers, pepinos, and haystack hills. The term "mogote" was first used in Cuba for flat-topped hills in the Sierra de los Organos; those hills are composed of limestone that has been tilted to steep angles during folding of the mountain range, and many Cuban specialists consider that the hills in northern Puerto Rico should not be called mogotes, as the limestone of which they are composed is nearly flat. The term mogote, however, has been adopted for worldwide use in describing isolated karst towers, so I choose to use it here rather than the other more local terms.

The mogotes of Puerto Rico consist of very steep-sided hills that rise out of the surrounding plains covered by blanket sands (fig. 22). Most of the mogotes are about 30 m high, but some are more than 50 m high, and a few areas contain typical mogotes only a metre or so high. Commonly, the top of a mogote is rounded to form a cupolalike hill (fig. 23), but some have a flat or pointed top. In many parts of the northern coastal area, mogotes are alined in ridges, along which the individual mogotes form a series of sawteeth (fig. 24). Solution caves are visible on the sides of many mogotes, but caves that pass through the hill are relatively rare; most caves

FIGURE 21.—River rampart on east side of Río Grande de Manatí, 2–3 km south of Manatí. Ridge of the rampart is mainly Aguada Limestone, but higher peaks on the ridge are capped by Aymamón. Top of rampart is 125 m above flood plain of river.

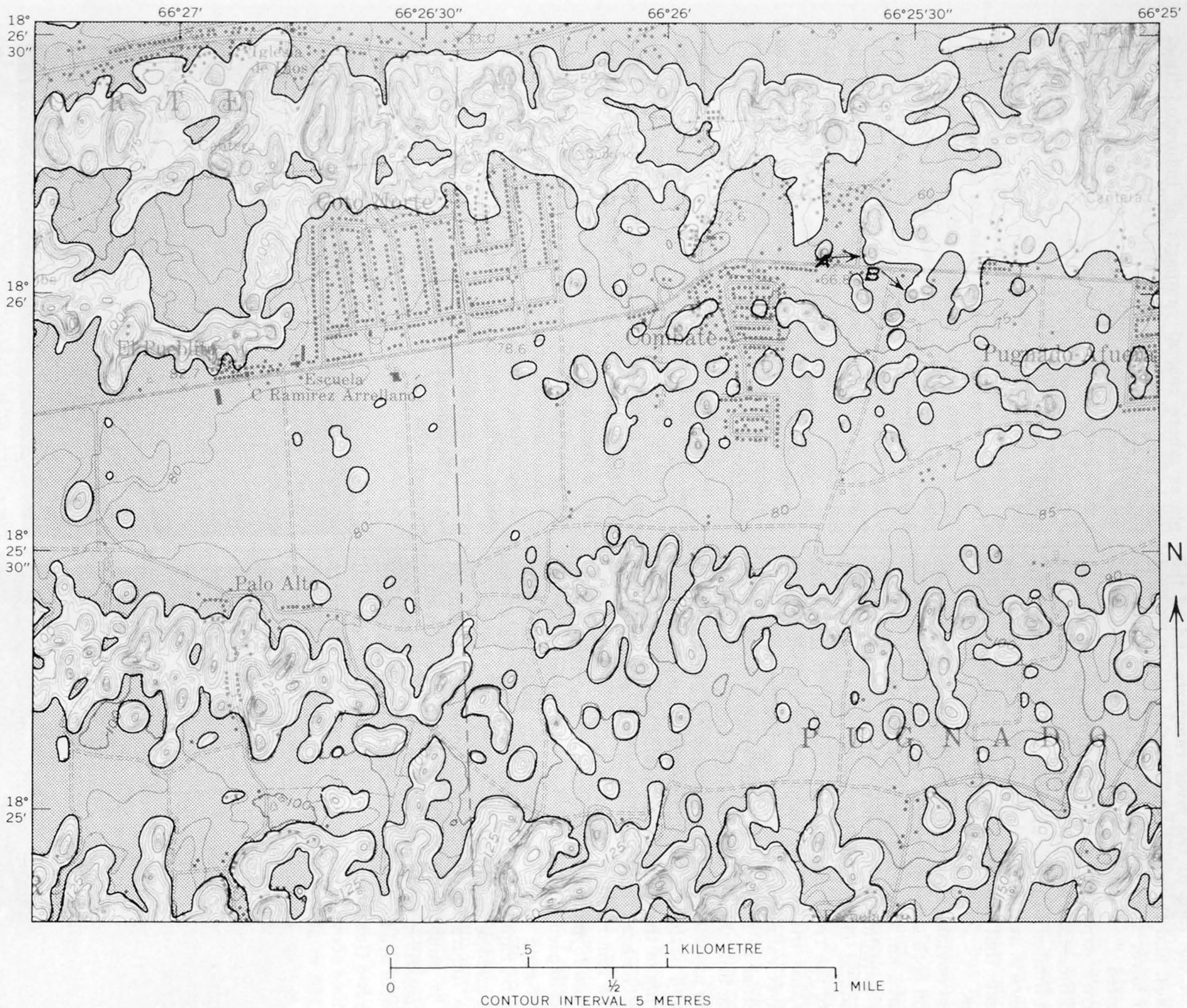

FIGURE 22.—Part of geologic map of Manatí quadrangle showing lines and clusters of mogotes projecting from plain of blanket sands (stippled). *A*, site of photograph, figure 23. *B*, site of photograph, figure 24.

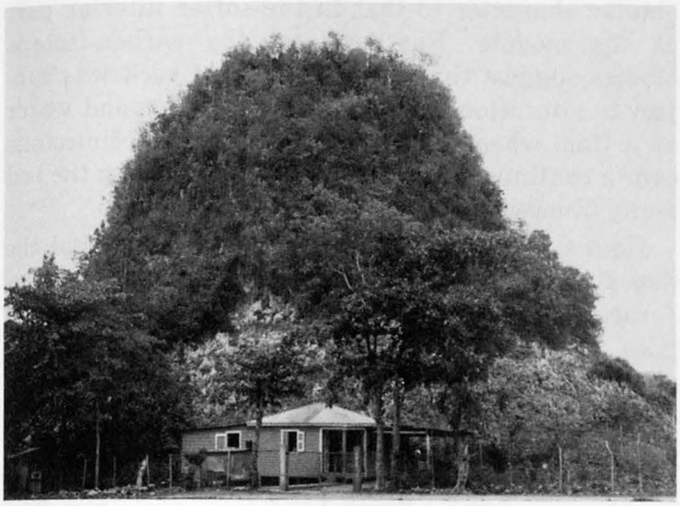

FIGURE 23.—West side of mogote north of Highway 670, east of Combate, 4.3 km west-southwest of Vega Baja.

FIGURE 24.—Asymmetric mogotes rising out of pineapple field in plain of blanket sand, on south side of Highway 670, 4.1 km west-southwest of Vega Baja. View toward southeast.

would be classed as rock shelters, or at largest as shelter caves.

Almost all the mogotes studied in Puerto Rico are composed of Aymamón Limestone, but a few along the southern limit of the Aymamón Limestone outcrop area are composed of caps of Aymamón resting on Aguada Limestone. The Aymamón Limestone exposed within the mogotes by deep roadcuts or by quarries consists of very fine crystalline chalk, so soft that it can be excavated by fingernails, or of a mass of cobblelike solution remnants. Neither the chalk nor the solution cobbles are representative of the original limestone deposited on organic reefs in the sea, as was explained in the section on karstification. The altered limestone commonly is composed of very fine calcite crystals, which apparently are easily dissolved and equally easily recemented by loss of either carbon dioxide or water, which results in reprecipitation of calcium carbonate. Very finely crystalline, only slightly consolidated or chalky limestone has been seen in deep roadcuts (V–6), in quarries, and in an underground chalk mine (Cm–2) about 5 km southwest of Arecibo.

The essential features of the exterior and interior of a mogote are especially well shown in a cut through a mogote (V–6) at Km 34, Hm (hectometre) 6 on the southwest side of Highway 2 between Vega Baja and Vega Alta.

The side and top surfaces of this mogote are composed of solution-sculptured, very hard limestone containing molds of mollusks and occasional coral fragments. Sinter or dripstone (nearly pure crystalline $CaCO_3$) is present locally in this surface rind.

The cut face shows the internal features of the hill. The limestone is rather crudely bedded in nearly horizontal layers several metres thick. The most illustrative limestone bed is at highway level. It is 5 m thick and consists of very pure, finely crystalline calcium carbonate containing abundant crystalline molds of fossil mollusks. Throughout its length of 60 m it is honeycombed by abundant perforations (fig. 25), 2–20 cm in diameter, which were apparently caused by solution. At the northwest end of the cut, the perforated bed is very hard, tightly cemented limestone that rings when struck with a hammer. Dripstone is present in a few perforations in the outer metre. Southeast 8 m toward the center of the cut, this hard limestone grades laterally into

FIGURE 25.—Roadcut in solution-perforated chalk of Aymamón Limestone in side of mogote on south side of Highway 2, 4 km northwest of Vega Alta.

compact but unindurated almost powdery limestone composed of very fine crystals of calcium carbonate, but still resembling the harder rock in the abundance of molds of mollusks and in the abundant solution perforations, which in this part of the cut are lined only with a film of loose carbonate dust. This soft phase extends 9 m southeast to a point where the rock is slightly more indurated but still has local powdery zones. Some 35 m from the northwest end of the cut, there is an abrupt change; the limestone is all tightly cemented, and many solution perforations are lined, and some filled, with dripstone and cave onyx. This condition of cementation extends 25 m to the southeast end of the cut.

Above the perforated bed is a rubbly layer about 4 m thick, and above that is a succession of indistinct layers of perforated and rubbly beds, some of which are chalky. The top of the mogote is composed of very hard solution-pitted limestone.

The significant features are: (1) the unconsolidated but solution-perforated limestone containing molds of mollusks near the northwest end; (2) the induration of the same bed at the ends of the cut; (3) the absence of dripstone in solution perforations in the northwestern two-thirds of the cut, except in the outer rind itself; (4) the abundance of dripstone in the southeastern third of the cut; (5) very steep sides; and (6) the thick cap of very hard, solution-pitted limestone.

The molds of fossils both in the soft chalk and in the indurated limestone in equal abundance show that the bed is a continuous entity within the mogote and indicate that the limestone was much more extensive but now is isolated because of erosion of the mogote from the limestone that formerly surrounded it.

The distribution, concentration, and diameters of the perforations are constant throughout the bed—the same in the soft interior part as at the sides of the mogote. Thus, these holes seem to be unrelated to the shape of the mogote, and their solution probably took place beneath or possibly at the water table at some time in the past when the average surface level of the entire area was at least as high as the present top of the mogote. Such a high permeability probably would produce a water table near the base level, presumably the sea level at that time. Therefore, it is reasonable to assume that this bed was at or below sea level at the time that the perforations were dissolved, and that the extensions of the limestone on all sides of the mogote have since been dissolved or eroded away. The mogote is a remnant of a once-continuous body of limestone, probably of similar character to that in the softer interior part of the mogote. Furthermore, the carbon-isotope studies suggest that the original reef rock was subject to alteration by circulating fresh ground water at a time when the upper surface of the limestone over a continuous area was much higher than the bed being discussed.

Both the induration of the soft limestone and the deposition of dripstone within and without the perforations seem to be related to the shape of the mogote, to local conditions of rainfall, and to the constancy of the trade winds. As pointed out earlier, most rainstorms in Puerto Rico consist of torrential showers that last a relatively short time and are immediately followed by sunshine and the consequent rapid evaporation of much of the rainwater. The trade winds blow rather constantly from a generally easterly to northeasterly direction in this part of Puerto Rico at an average rate of about 18 km/hr. The winds tend to blow rain into crevices in the rocks on the eastern and northeastern sides of hills and thus to soak those sides more than the western sides.

The limestone is completely indurated on the outside rind of the mogote, is indurated to a very hard limestone in the southeastern half of the mogote, and is indurated only locally in the northwestern half. The induration may well result from partial solution of the soft powdery limestone by thorough wetting under conditions of extremely high humidity, followed by almost immediate reprecipitation of crystalline calcium carbonate owing to a sudden rise in temperature, which would drive off carbon dioxide, or to circulation of drier air, which would evaporate the water. The greater induration on the eastern side is clearly an effect of the trade winds soaking windward slopes more than lee slopes.

The concentration of dripstone in the perforations on the windward half of the mogote and the almost complete lack of dripstone in perforations on the lee half, even in the indurated part of the rock, indicates that the dripstone is secondary, that it was deposited after formation of the mogote, and that it is closely related to the local conditions of rainfall.

The very hard caprock on the top and sides of the mogote, generally 5–10 m thick, forms by repeated soaking of the limestone, followed by almost complete evaporation of the water. The caprock is generally thicker on the eastern side; on the western, it tends to form a rimrock that locally overhangs the softer material. This results in the asymmetric form (fig. 26), steeper on the western side than on the

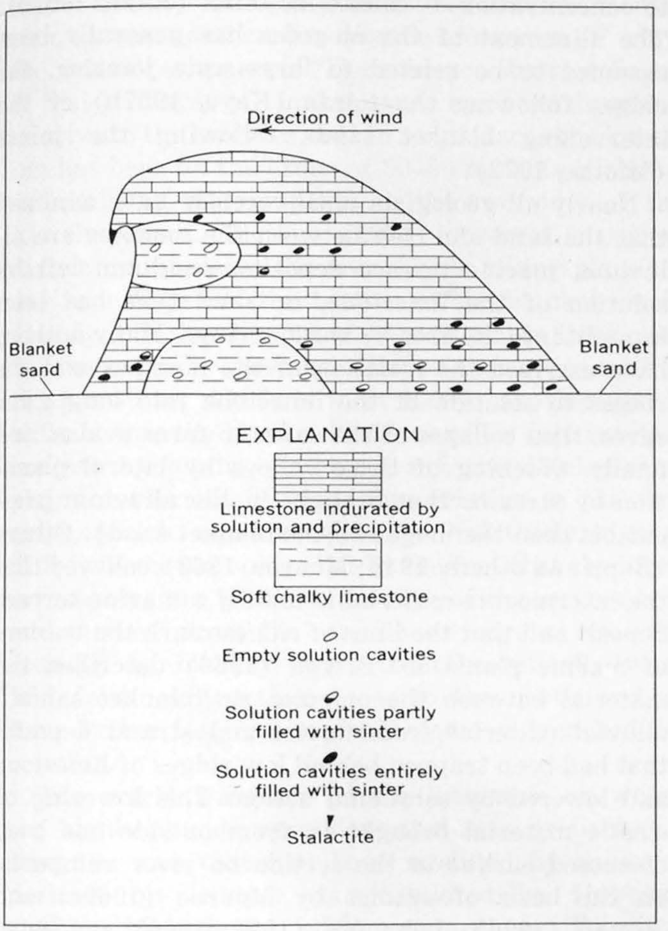

FIGURE 26.—Diagram showing characteristic features of an asymmetric mogote.

eastern, that was noted by Hubbard (1923) and Thorp (1934).

Hubbard (1923, p. 92) stated that

> this asymmetry has no relation to slumping or tilting, no relation to difference in structure of or composition of the rock, and no relation to vegetation covering the hills. The only apparent explanation left is that of differential weathering and solution. The daily showers occur usually in the afternoon, when the sun has been shining on the hills from the west, and hence while the rock on the west is at a higher temperature than that on the east or shaded sides. This increases the rate of solution, and results in a more cavernous structure being developed on the west sides. Such differential surface solution would be noticeable only where the process is extremely rapid.

Thorp (1934) ascribed the asymmetry to action by the trade winds. He pointed out that the winds in the area south of Arecibo generally come from the east-northeast. The pepino hills or mogotes in that area have gentle slopes, from a few to 45° on the windward side, whereas they are very steep and in place overhanging on the lee side. The steepness is not related to sinks. Furthermore, only the higher hills are asymmetric; small hills in the lee of larger ones are more symmetric. He pointed out that rain falling in still air falls vertically, whereas the trade winds cause the rain to beat more heavily on the windward side than on the lee side. Thus, more solution takes place on the windward slopes, and these slopes are accordingly gentler. Thorp's theory is adequate to explain the asymmetry, but he was not aware that the interior rock of many mogotes is much softer than the exterior, for when he studied the hills there were very few cuts through the hills that could show him the internal structure. Thus he was not aware of the casehardening of the limestone, and he certainly was not aware that the casehardened rind on the windward side of the hills is thicker than on the western or lee side, where locally it is absent.

The asymmetry of the higher mogotes (fig. 27) that are affected by the rains driven against them by the trade winds from the east and east-northeast is probably in part due to solution, as proposed by Thorp; the asymmetry remains, however, because the part of the mogote that gets soaked by rain then dries out and the calcium carbonate from the partially dissolved limestone recrystallizes, resulting in the induration. All limestone in Puerto Rico exposed on hill crests is ridge forming because it is more resistant to erosion, including solution, than the more easily weathered clastic, volcanic, and plutonic rocks. Thus all mogotes, both the symmetric and the asymmetric, are resistant to lowering after induration or casehardening. This feature undoubtedly accounts for the normally steeper western sides of the hill, because the overhanging visorlike rimrock

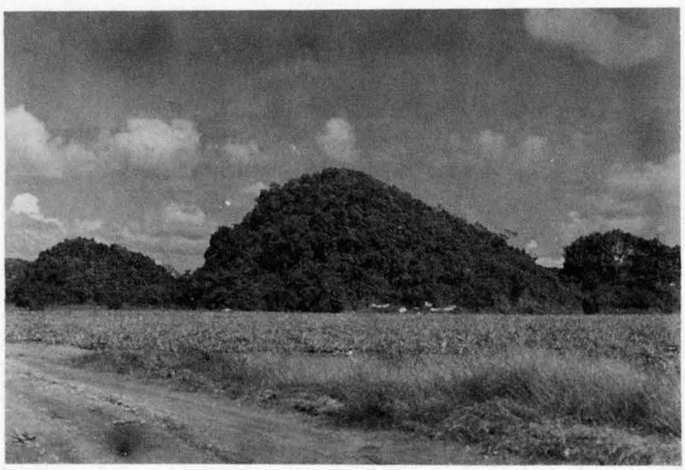

FIGURE 27.—Asymmetric mogotes north of Highway 2, just northwest of junction with Highway 140, about 4 km southwest of Barceloneta. Plain of blanket sand in foreground. Gentle slope to east, steep slope on west side of mogote.

FIGURE 28.—Rock shelter in Aymamón Limestone on west side of mogote, 400 m southwest of Highway 2, 3.8 km northwest of Vega Alta.

(fig. 28) at the crest of the steep side consists of indurated or casehardened marblelike limestone, whereas the underlying less indurated material is subject to slumping. This is similar to the vertical cliffs at the top of the cliffed cone karst in the area where the relatively pure but not tightly cemented calcarenite of the Montebello Limestone Member of the Cibao Formation forms a cliff above the much more tightly cemented calcarenite of the Lares Limestone.

As has been pointed out by early workers (Hubbard, 1923; Meyerhoff, 1933), the presence of mogotes is not related to any concentration of coral reefs, nor has it any apparent relationship to the secondary structure of the rocks, although many of the ridges of mogotes are parallel to the strike of Aymamón. Detailed study of the lithology of the Aymamón Limestone by Briggs (1965, 1968) and Monroe (1962; 1963a, b; 1966a; 1967; 1969a, b; 1971; 1973b) published in the texts of the geologic maps of the coastal strip from Aguadilla to Bayamon shows that the location of the hills and the ridges has little relationship to the stratigraphy of the formation, except that the less crystalline upper part of the formation in northwestern Puerto Rico has few mogotes. Several authors have noted the induration of the Aymamón in the mogotes and have either assumed that the entire formation was cemented tightly (Monroe, 1962) or have ascribed the cementation to concentration of calcite in joints (Kaye, 1957b). The alinement of the mogotes has generally been assumed to be related to large-scale jointing, the ridges following the joints (Kaye, 1957b) or the intervening blanket sands following the joints (Miotke, 1973).

Nearly all geologists until recently have assumed that the sand and clay between the mogotes are alluvium, marine terrace deposits, residuum left by solution of the limestone, or sand that has been brought into the area by karst springs. Many authors have ascribed the isolation of the mogotes and the ridges to solution of the limestone into long river caves, then collapse of the caves to form uvalas, and finally widening of these valleys by lateral planation by streams that brought in the alluvium present between the mogotes (the blanket sand). Others (Zapp and others, 1948; Monroe, 1962) believed that the intermogote material is mainly a marine terrace deposit and that the lines of ridges mark the borders of marine planation. Briggs (1966) described the material between the mogotes as "blanket sands," alluvial material from fluvial and strand deposits that had been trapped behind low ridges of limestone and lowered by solutional action. This lowering of clastic material brought in from outside has been discussed earlier in the section on river ramparts, on the basis of studies by Monroe (1969c) and Miotke (1973). Lehmann (1954, 1960) suggested that the mogotes were formed by lateral cutting of the limestone by migrating streams and by coastal action which involved the formation of footcaves (Fusshöhlen) at the bottom of cliffs. Several sea caves are known in Puerto Rico that have been cut at the foot of cliffs, but caves caused by lateral corrasion and corrosion are rare except at the sides of streams that are actively cutting today. Gerstenhauer (1964) showed one photograph of a cliff-foot cave (solution undercut at the foot of the cliff) at the bottom of a mogote of Aguada Limestone, but such caves are not common at the sides of the blanket-sand-covered plains. Miotke (written commun., 1971) explained this absence as evidence that the mogotes are not residual hills left by lateral planation by moving water, but instead are residual hills left by solution that mostly took place under the adjacent blanket sand.

The more recent studies by Briggs (1966), Monroe (1969c), and Miotke (1973) have shown incontrovertibly that the mogotes are residual limestone hills composed of material that is probably identical with that beneath the blanket sand, except that it has been indurated by reprecipitation resulting from slight solution of chalky limestone and recementation, as water and carbon dioxide are driven off when the rainfall evaporated. The evidence shows definitely that the layer of blanket sands has been dropping relative to the mogotes, and in some places the lowering has been on the order of 30–50 m. This is shown definitely by the ramparts on the two sides of the Río Guajataca. Miotke's (1973) observations show that in many places the lowering is taking place today by collapse of the bottom of the blanket sands (see fig. 20), leaving closed depressions in the sands. Miotke explains these as collapse of cavities within the limestone, which is most likely; another possibility is that the blanket itself may flow into cavities beneath by piping. In any event, the blanket-sand plains are gradually subsiding relative to the mogotes, which consequently grow relatively higher. This is borne out somewhat by the fact that the highest mogotes are in the south edge of the mogote belt and farthest from the sea. These mogotes are surrounded by blanket sands that theoretically were laid down earlier than those to the north and so have had a longer time to become entrenched by solution.

The original surface of the limestone on which the blanket sands were deposited was probably an irregular one that had been modified by solution, perhaps by collapse, as postulated by Hubbard (1923), Meyerhoff (1933), and others. Possibly, however, the original surface may have had a depositional pattern of reefs that would tend to be parallel to the shore, and the sand deposits may have dominantly filled in the valleys between these original depressions. As soon as the sand cover was present and plants began to grow on it, however, the subsoil and subterranean solution began to take place, and the blanket-sand plain began to subside.

The arrangement of the mogotes in lines and ridges (figs. 22 and 29) has generally been ascribed to jointing: (1) a concentration of calcite in the joints produces a casehardened surface resistant to erosion (Kaye, 1957b); or (2) solution along joints results in widening, as believed by Hubbard (1923) and many others. The possibility also exists, although not previously noted, that the linear arrangement of the mogotes and mogote ridges may be related to the trade winds. In general, the ridges trend west (fig. 22), the usual direction toward which the trade winds blow, but in the area between the Río Grande de Manatí and the Río Grande de Arecibo (see hydrogeologic map, Briggs and Akers, 1965) the ridges trend west-southwest to southwest, which is consistent with the north-northeast direction from

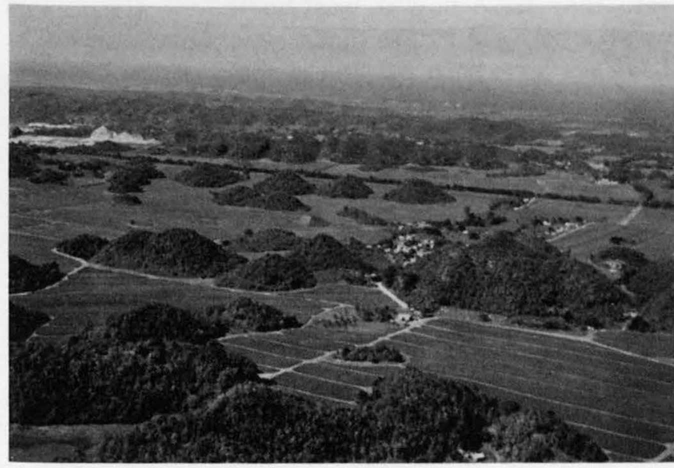

FIGURE 29.—Aerial photograph of mogotes rising out of pineapple fields in plain of blanket sand near Coto Sur. Quarry in left background is 1 km east of Manatí.

which the trade winds tend to come in that area. There is also the possibility that these trends may be related to some late Tertiary drainage pattern. The eastward trends at the sides of the Río Camuy, described under the section on dry valleys, seem definitely related originally to jointing, supplemented by erosion of valleys to the river caused by corrasion by the blanket sands themselves.

Finally, attention should be called to an area 2–4 km northeast of Vega Alta (fig. 30) which is characterized by very low mogotes surrounded by somewhat ferruginous sand. The altitude of the plain of blanket sand in this area is about 50–65 m, and many of the mogotes are less than 5 m high. During an interglacial stage of the Pleistocene, the Río de La

FIGURE 30.—Aerial view of very low mogotes rising out of blanket-sand plain on plateau north of Vega Alta. View toward south-southeast. Area in foreground is cultivated in pineapples; background is in pasture.

Plata may have flowed west-northwest across this low area between ridges that rise to more than 100 m above sea level both north and south of the lowland. The loose sand indicates a very young deposit of blanket sand. If this is a high-level alluvial deposit, the river was later diverted to a lower channel south of the Cerros de Higuillar farther northeast, where cobble-bearing ancient alluvium is found up to a channel altitude of 18 m above sea level. The present level of the flood plain of the river is 1–5 m above sea level.

ZANJONES

Zanjones are groups of parallel trenches resulting from solution of limestone along joints. They were first described by Monroe (1964b) from several examples between Morovis and Florida in northern Puerto Rico, as follows: "Zanjones are trenches as long as 100 m or more, with vertical sides, ranging in width from a few centimeters to about 3 m and in depth from about 1 to 4 m. They occur as parallel trenches oriented generally in the same direction * * * as many as 8 in a distance of 100 m."

When I named these groups of trenches "zanjones" in 1964, I could not find reference in the literature to any similar features, so I selected the term "zanjón," which is Spanish for "deep drainage ditch," as an appropriate term as they had first been seen in Spanish-speaking Puerto Rico. In 1965, Wilford and Wall described "corridors" in Sarawak as follows: "Joint-determined corridors at Subis are about 100 feet apart and are estimated to be from 10 to 500 feet deep." They do not say how long the corridors are, but their maps show that groups of parallel corridors are several hundred feet long and that some individual lineations, generally those that cut the others at an angle, are nearly a mile long.

"Straight to broadly arcuate, closely spaced joints in the western part of the semiarid Stockton Plateau of Trans-Pecos Texas form a system consisting of two joint sets," according to Lattman and Olive (1955). The joints of one of the sets have been widened by solution to as much as a foot across, apparently by solutional activity of meteoric waters, which move downdip within the joint opening. They do not indicate how long individual joint-trenches are, but their photographs suggest that some are several hundred feet long.

Sweeting (1972, p. 86–89) pointed out that zanjones are a variety of Kluftkarren, which is probably correct, but she considers that they might properly be termed "bogaz" or "strugas," using the terms of Cvijic (1893). The last term is certainly not appropriate, as a struga is a solutionally enlarged bedding plane. They might be considered a giant variety of bogaz, but according to Sweeting, bogaz are "corridor-like features from 2 to 4 m wide and stretching for some tens of meters." Zanjones are much larger and longer than the bogaz she describes, so I believe the term "zanjón" or perhaps "corridor" should be retained for this much larger feature.

Since 1964, many additional examples of zanjones have been discovered, some of which are several metres wider and deeper than those first described. The general areas and local trends of zanjones are shown on plate 1. Some of the best developed zanjones are north of Lares (figs. 31 and 32), where individual trenches are more than 1,800 m long. In this area more than 20 long zanjones are present in a belt a kilometre wide—they are so close together that they have partially coalesced to produce a strongly oriented east-west topography in which individual zanjones cut longitudinal hills, rising up one end, running along the crest, down the other end, and then repeating the same pattern on the next hill

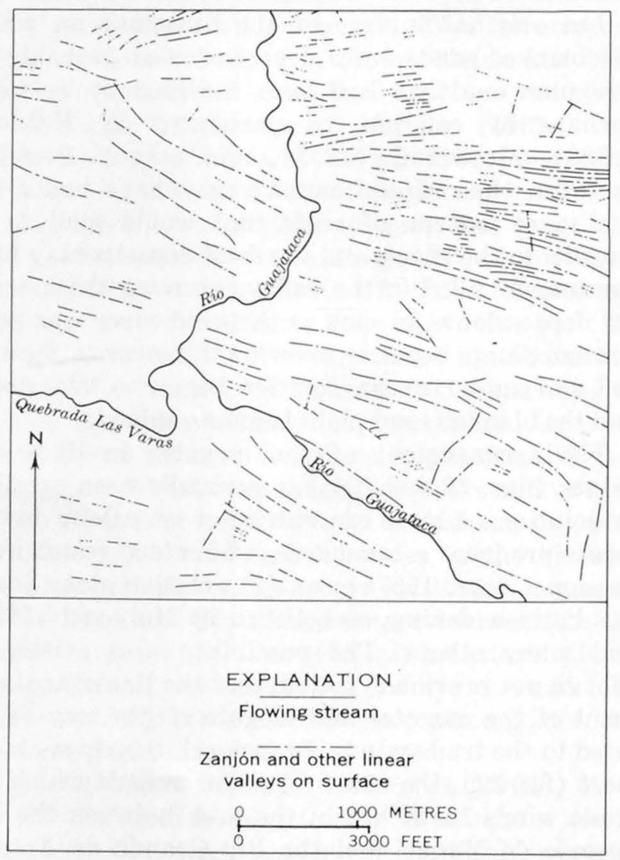

FIGURE 31.—Map of an area north-northwest of Lares showing zanjones and the course of the Río Guajataca. Figure 32 is a stereopair of the northeastern part of the area.

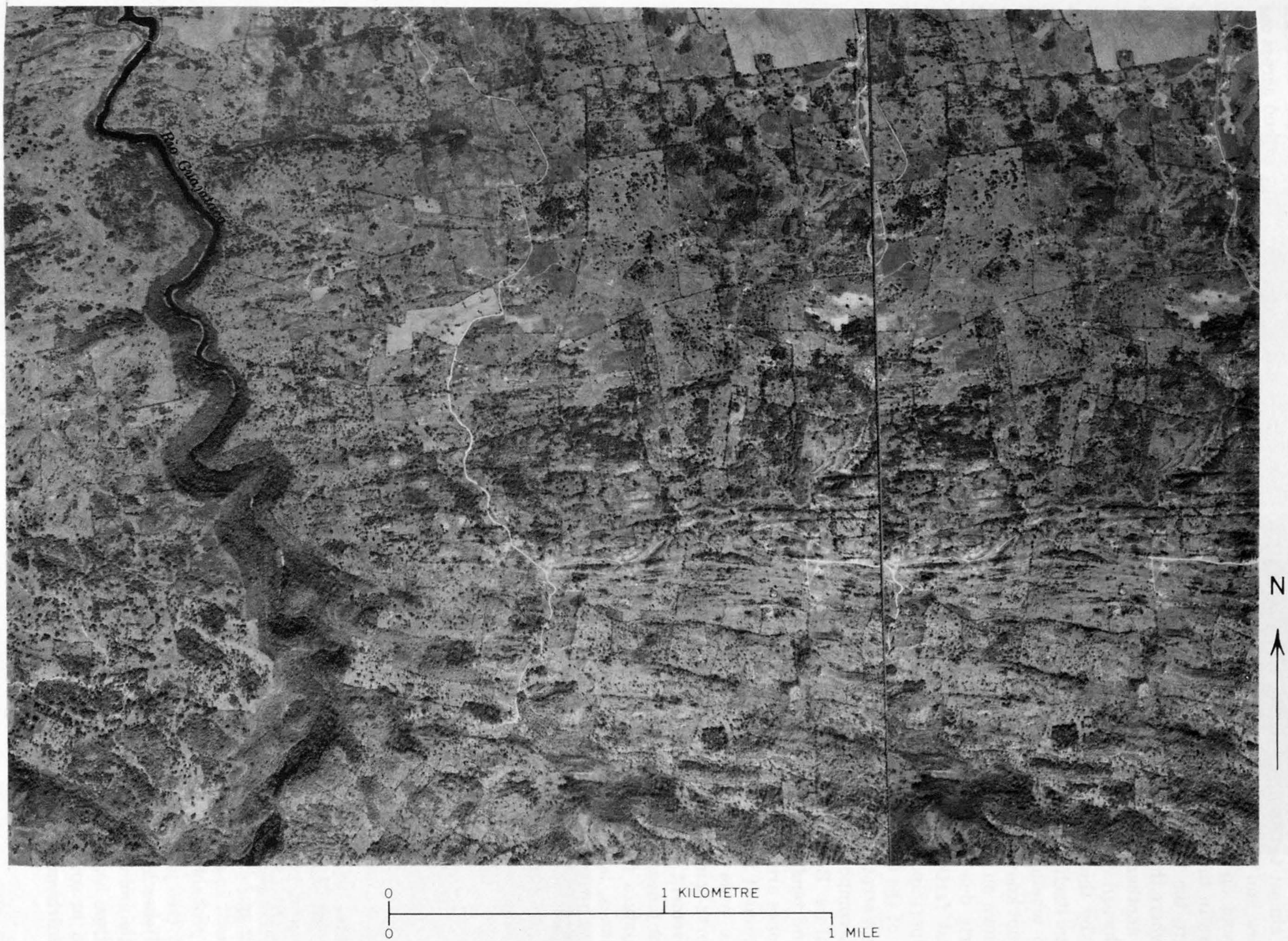

FIGURE 32.—Stereopair showing zanjones north of Lares. Valley of Río Guajataca in left part of western photograph. Aerial photographs from U.S. Soil Conservation Service, 1964.

in line. In this area, the zanjones extend from east to west almost to the brink of the gorge of the Río Guajataca and then can be picked up following the same trend on the western side of the river. The meanders in the gorge, however, do not seem to be related to the trends of the zanjones, except near Lares, where the river follows deep joint valleys that may be another set of zanjones. In other words, in its northward course the river does not seem to be affected by the joints that produced the zanjones. The gorge itself has not been examined by any geologists, so whether or not joints are present in the walls is not known.

As shown on figure 31, the trends of the zanjones are nearly due west in the north and about west-northwest farther south. Those in the north have been superimposed on the Montebello Limestone Member of the Cibao Formation, which here as elsewhere is a stratified loosely cemented very pure calcarenite, composed largely of shell fragments and foraminifers. Because this material is not very cohesive and tends to cave off to form vertical walls, the zanjones are wider here than at most places, several prominent trenches having a width of about 10 m. These wide trenches with their vertical walls make north-south movement much more arduous than movement to the east or west along the trend of the zanjones. The area farther south, where the Río Guajataca follows the west-northwest trend of the zanjones, is in the outcrop area of the Lares Limestone. Still farther south near the base of the Lares Limestone, a small group of zanjones has a trend of about west-southwest. In both areas, a very few trenches cut the main trends at angles of as much as 90°, as would be expected if the trenches are opened joints.

The area north of Lares is the only place in which zanjones have been found in strata above the Lares Limestone. The trends described here, however, extend eastward into the Bayaney quadrangle in the upper part of the Lares Limestone (Nelson and Tobisch, 1968). There they trend across the river caves of the Río Camuy and have no relation to the bends in the cave beneath the surface (fig. 7), as mapped by Gurnee and others (1967). Farther east in the Bayaney quadrangle, very deep valleys, probably enlarged zanjones, trend east-northeast (see pl. 1).

No zanjones have been seen between the Bayaney quadrangle and an area south of Florida considered as their type locality (Monroe, 1964b), where they are found in some of the dry valleys that form a dendritic drainage pattern. In this area, narrow, closely spaced zanjones have a strongly dominant trend of N. 25° E. (fig. 33). They extend across one of the valleys, but extend up the bottoms of tributaries coming in from the north and south. The zanjones are present only in stratified limestone, and they stop abruptly on hill slopes where the stratified limestone is overlain by massive limestone. In this area most of the zanjones are 1 m or more wide, but a few apparently incipient ones are only a few centimetres wide (fig. 34). All the zanjones in this area have formed in strata about 20–40 m above the base of the Lares. A short distance farther east, but still in the Florida quadrangle (see pl. 1), are smaller groups of zanjones that are less regular in their alinement, trending from about N. 15° E. through northeast to S. 80° E. A singular occurrence in this area is a prominent doline about 300 m in diameter (142,250 E., 53,000 N.) which contains in its center a conical hill 25 m high; cutting across the hill N. 75° W. is a zanjón about 10 m wide and 2 m deep; this zanjón is intersected by a smaller one about 3 m wide that trends N. 10° E.

The most accessible zanjones are probably the Torrecillas group 2–4 km northwest of Morovis (fig. 35). The zanjones are more subdued here, possibly because the area has been under cultivation and in pasture for many decades; this would tend to round off the crests of the trenches. Most of the trenches trend N. 25–40° E., but they are cut by a few very wide trenches that trend mainly east and N. 80° E. Some of the zanjones in the principal trend are continuous for more than 1 km. Dr. J. N. Rinker has studied the Torrecillas zanjones in detail more than anyone else, and he called my attention (oral commun., 1972) to the north side of a cross valley (152,400 E., 57,130 N.) 3.5 km northwest of Morovis, 150 m east of Highway 155, where some of the joints beneath the zanjones open up into very low short caves.

The only common feature of the areas of zanjón karst in Puerto Rico is that all are in areas of strongly stratified limestone in the lower part of the stratigraphic succession of Oligocene limestone. At places where the stratified limestone grades laterally into more massive limestone, the type of topography changes abruptly from a generally flat landscape cut by the deep trenches to cone karst. The change in topography is amazingly sharp, taking place in a horizontal distance of less than 100 m (fig. 36).

CAVES

There are hundreds of caves in Puerto Rico, but most of them have never been explored scientifically,

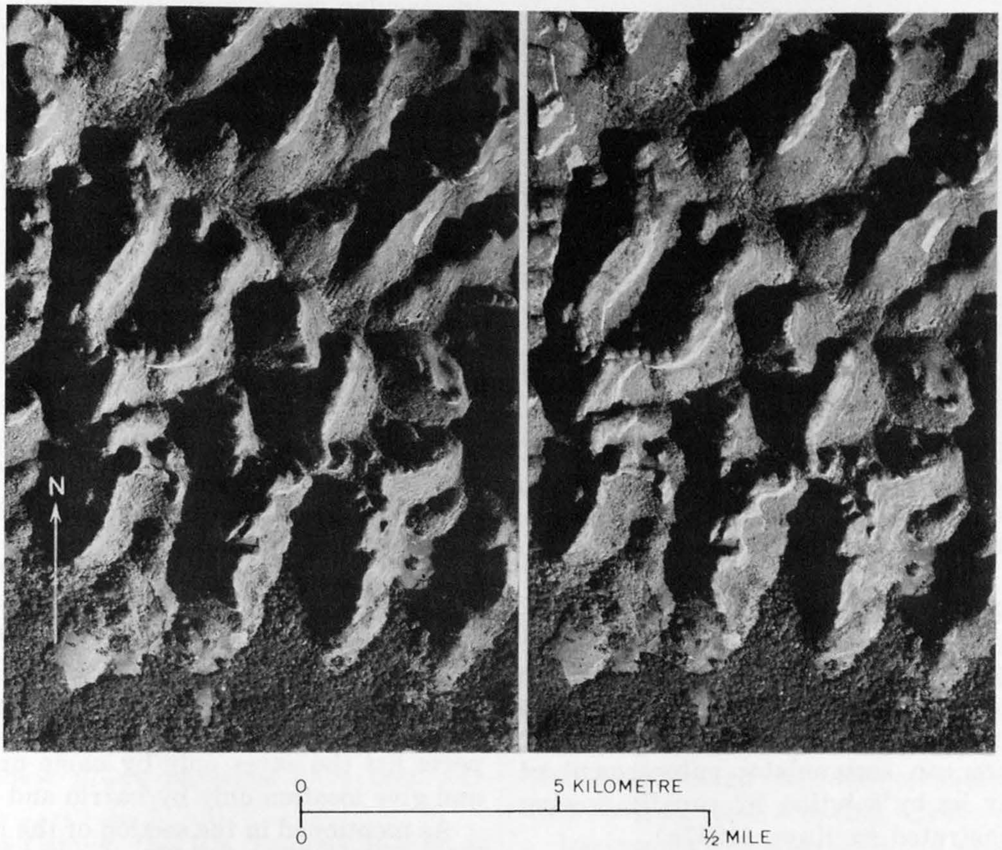

FIGURE 33.—Stereopair of aerial photographs showing zanjones in bottoms of karst valleys 6 km southeast of Florida. The zanjones are present only in thin-bedded limestone at the bottoms of the valleys and do not extend upward into overlying massive limestone.

FIGURE 34.—Small zanjón in karst valley, 6 km southeast of Florida. Fully developed zanjones nearby are commonly 1.5–3 m wide and 3–4 m deep.

FIGURE 35.—Aerial view of southern edge of area of zanjones at Torrecillas, 4 km northwest of Morovis. The zanjones rise up the sides of hills, but commonly coalesce to form linear valleys.

and very few indeed have been mapped. Most explorers to date have been interested only in the large river caves, which have been discussed earlier in the section of this report on valley features. The cave system of the Río Camuy is the largest known and

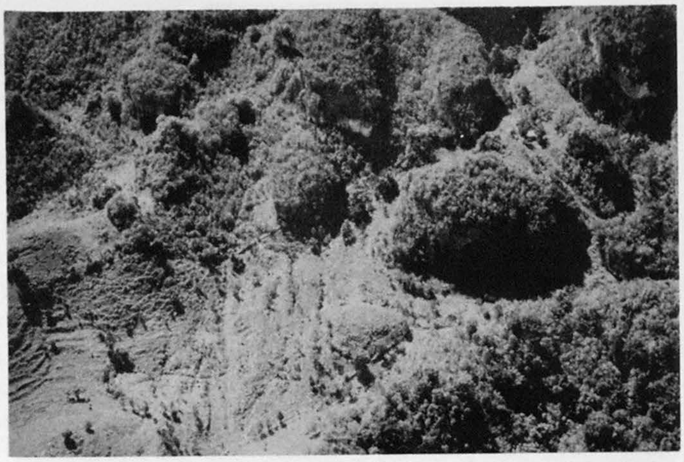

FIGURE 36.—Aerial view at boundary between area of zanjones to left (east) and of cone karst to right. No zanjones occur in the massive limestone that forms the cone karst.

is characterized by very large river-eroded rooms. The caves of the Quebrada system previously described are typically smooth tubes containing no decoration, because the flood waters flow through them so rapidly that no deposition of flowstone or even of alluvium can accumulate; enlargement of these caves may be by solution by rapidly flowing water, as demonstrated by Kaye (1957a).

Cliff-foot caves (Fusshöhlen) are common at the sides of rivers and tributaries (fig. 37), and sea caves have formed where limestone and eolianite are present at sea level. In some of these, air gets compressed, and when waves come in, sea spray gets projected strongly to considerable heights. A very

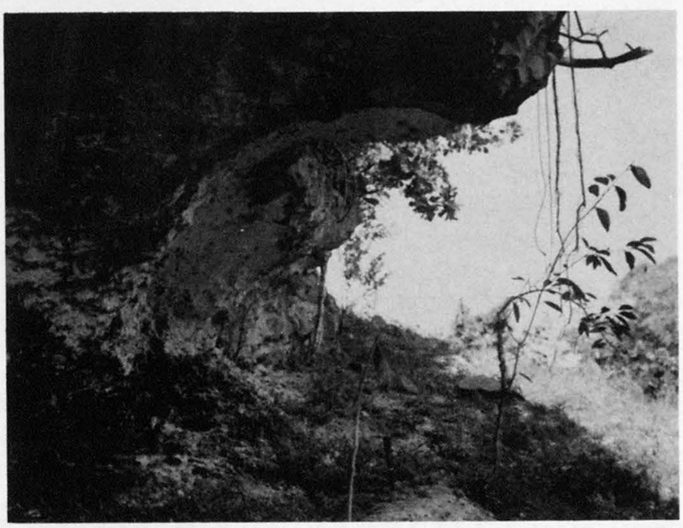

FIGURE 37.—Rock shelter at side of small intermittent tributary of Quebrada de los Cedros, 4.6 km west southwest of Isabela.

spectacular sea cave of this kind is present at the foot of the walls of the fortress San Felipe del Morro at the west tip of San Juan island. Another one that has been breached is Foso Jacinto (I–1) in the Isabela quadrangle.

The locations of all known caves in Puerto Rico, except rock shelters, are shown by symbol on the karst map (pl. 1) ; in some places one symbol represents several caves that are close together. In the list of karst features by quadrangle (p. 58), these caves are identified and described, if I have information about them. Exact locations are given for those for which I personally know the location. Many of the caves whose locations are shown on the karst map have been visited and location supplied by José Martínez Oquendo (oral commun., 1972), who visited all caves he had heard of in order to list them in the Inventory of Natural Resources of the Puerto Rico Department of Natural Resources. The inventory has locations of all these and other caves accurate to within 500 m. Besides the caves shown on plate 1, many more are listed by Anthony (1926) and by Gile and Carrero (1918), but both these reports list the caves only by name or owner's name and give location only by barrio and Municipio.

As mentioned in the section of the report on valley features, most of the large river caves and probably many of the caves through which smaller streams flow have been cut to their present size largely as the result of corrasion by floodwaters carrying alluvium. Sand, gravel, and even cobbles of volcanic and intrusive rock have been found at many places in the Camuy system. These caves probably started as a network of solution passages similar to those seen in the Aymamón Limestone (fig. 25) and in the middle member of the Camuy Formation. As streams started to flow through the small interconnected solution passages, they introduced such scouring elements as quartz and other hard minerals derived from weathering of the volcanic rocks, and especially of the intrusive rocks of the mountains of Puerto Rico. These grains and also gravel composed of angular fragments of lava and silicified siltstone cut away the relatively softer limestone and enlarged the stream channels into through-flowing passages, which eventually became the large passages of today. Some of these in the Camuy system are more than 30 m high.

Many large caves of the Camuy system, such as the Empalme Cave (B–5) which connects the Empalme Ravine with the Empalme Sink (B–3), are well above the present river level. Some of these probably were carved by the river before it reached its present level. One of these caves is a tunnel (B–15) through the ridge on the right side of the river (fig. 38). This tunnel is about 50 m above the present water level in the river. The Empalme Cave is about 40 m above the river, and it seems reasonable that both were excavated by the Río Camuy at about the same time and that the river once flowed through these passages, even though neither can be traced for any great distance today.

The topographic map of the Bayaney quadrangle shows in the northern part a valley labeled Río Camuy, which actually is occupied by a relatively small intermittent stream; the main river is entirely underground from the Empalme Sink (B–3) to the Resurgence (Cm–19) in the Camuy quadrangle. At one stage of its history, however, the Río Camuy may have flowed through this valley.

Through 1973, nearly all the exploration of the Río Camuy system has been in the river passages, which have to be explored in rubber boats or by swimming. Consequently, only a little is known about the ramifications of the upper generally dry passages. The full history of the river cannot be known until these upper passages have been surveyed.

Like the Río Camuy, the Río Tanamá has many side caves at a level higher than the present river level (Gurnee, 1972), but only the river level has been completely surveyed. During the expedition of the Explorers Club (Gurnee, 1972) a few of the upper caves were surveyed, but none of these data have yet been published, and the account of the expedition mentions many high-level caves that were seen but not traversed. Some of the side streams such as Quebrada Pasto, entering the Tanamá, pass through relatively long caves which have never been surveyed. The abundance of caves between the Camuy and the Tanamá suggests that mapping of these caves might provide clues for working out the history of the two rivers.

Many large caves in Puerto Rico, such as the cave at Corozal (fig. 39), are near a large river and may once have been river caves but now are far above water level. Only careful surveying and search for collapsed entrances will determine their history.

Besides corrasion by scouring grains, some enlargement has probably resulted from solution by rapidly flowing water, as demonstrated by Kaye (1957a). Enlargement by solvent motion (Kaye, 1957a) is almost certainly the method of formation of the caves in the Quebrada Cave system (Nelson, 1970) in the southwestern part of the Camuy quadrangle. These caves are mainly smooth tubes that are filled completely by rapidly flowing water during rainy spells. The drainage area of the streams that flow through the caves contains very little sand that could act as a scouring agent.

Besides the river caves, many smaller caves probably formed entirely by solution are generally much more elaborately decorated (fig. 40) than the river caves. Besides dripstone and flowstone decoration, rimstone dams and pools are common in many.

Closely related to natural tunnels are the natural arches. The Río Tanamá flows under such an arch (Gurnee, 1972) about 30 m high. Much better known is La Pared Hueca(Cm–6, fig. 41), which is between two closed depressions in the Aguada Limestone in

FIGURE 38.—Natural tunnel penetrating ridge of Lares Limestone about 250 m south of place where Río Camuy goes underground. View toward east from Highway 129.

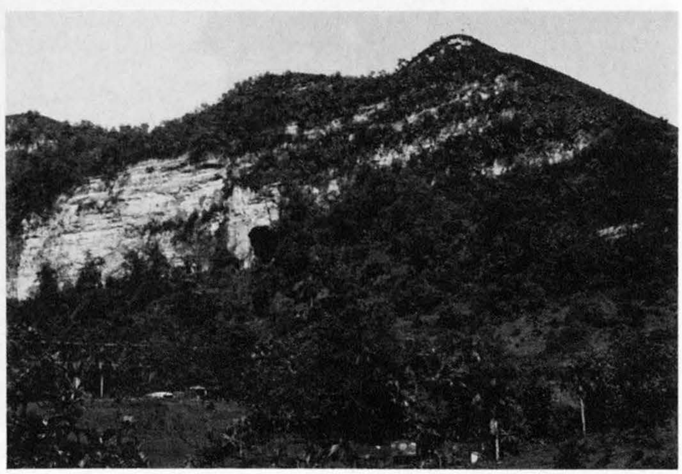

FIGURE 39.—Cave near top of Lares Limestone on right wall of Río Cibuco, 2 km northwest of Corozal.

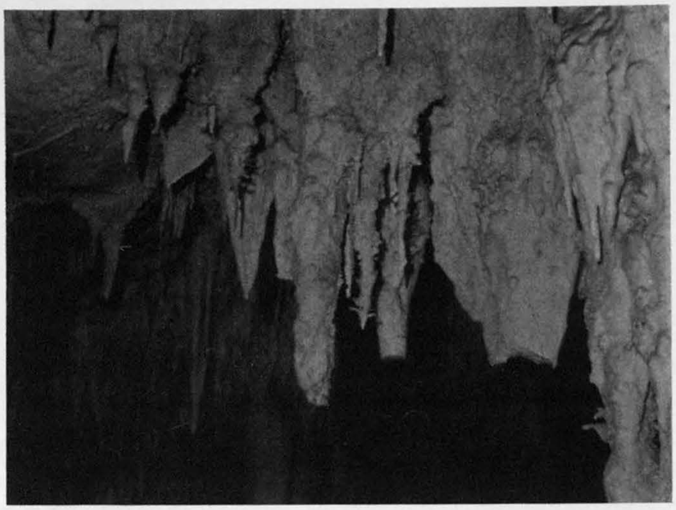

FIGURE 40.—Eccentric stalactites in Nuñez Cave, 200 m west of Highway 112, 7.5 km south of junction with Highway 2 at Mora.

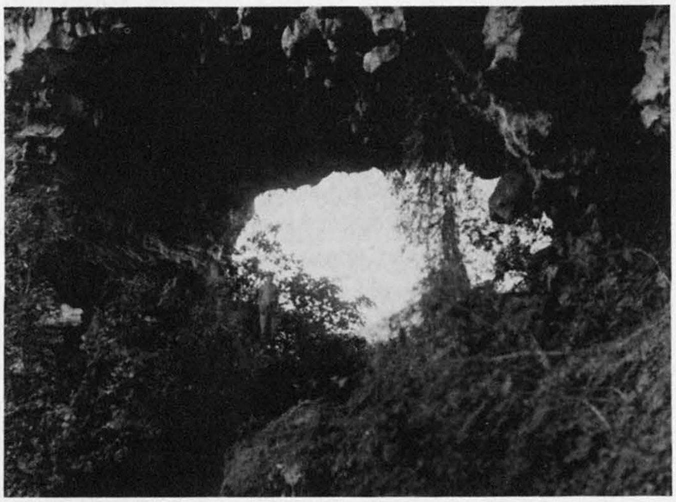

FIGURE 41.—La Pared Hueca, a natural arch in Aguada Limestone near center of barrio Santiago, Municipio de Camuy 9.2 km south of the Río Camuy mouth.

the general area of the Quebrada Cave system. Almost certainly the depressions on the two sides of this very short natural tunnel are collapse dolines, as the natural arch seems to be a part of the Quebrada Cave system that has now been abandoned by the stream, which goes underground a few hundred metres farther south at Cm–8.

The only other large natural bridge that I know of is also in the Aguada Limestone in the Quebradillas quadrangle (Q–7). The trail Vereda Caballo splits southeast of the bridge, and the main trail passes over the bridge en route to Pueblito de Ponce; a minor trail passes under the arch and heads west and then south into the karst wilderness.

Natural arches and bridges are ephemeral features, as is shown by the collapsed arch (fig. 42) in the Aguada Limestone, 1,800 m east of La Pared Hueca and at the same stratigraphic horizon.

Finally, a word should be said about the dripstone and flowstone deposits both inside and outside the caves. Those in the caves are composed of crystalline calcite, but those that are suspended from overhanging cliffs (fig. 9) are likely to be rather spongy as the dripping and seeping bicarbonate-laden water incorporates lichen and plant fragments as calcium carbonate is precipitated. The strength of the calcite in such features seems to be in inverse relationship to the amount of light that falls on the growing dripstone feature.

Travertine is common below karst springs in Puerto Rico, but little study has been made of it. The most interesting occurrences are the travertine or sinter tunnel caves through which the Río Tanamá flows (Gurnee, 1972). The geologists on the Tanamá expedition, D. B. Jordan and V. J. Latkovich, have explained these as accumulations of calcareous sinter below karst springs, although they did not see the springs themselves. This explanation seems to be the only tenable one, for otherwise the river itself would probably destroy the tunnels.

MINOR KARST FEATURES

Several distinctive solutional features are well shown along the coast of Puerto Rico at places where

FIGURE 42.—Abutments of collapsed arch in Aguada Limestone in barrio Santiago, Municipio de Camuy, 360 m west of Río Camuy, 9 km south of Hatillo. This locality is 1,800 m east of the existing natural arch, La Pared Hueca, at about the same stratigraphic horizon, shown in figure 41.

limestone is exposed to wave action or to sea spray. The limestone formations involved are the Aymamón Limestone in northern Puerto Rico, the Ponce Limestone in southern Puerto Rico, and such Quaternary units as eolianite and beach rock. Most eolianite and beach rock are largely calcarenite composed of almost pure calcium carbonate. However, some occurrences contain appreciable quantities of quartz and other mineral and rock grains.

The most common karst phenomena are low spitzkarren (karren spikes) or pinnacles and solution pans (fig. 43), which have been fully described by Kaye (1959a, p. 83–88) as forms of "pitting." Kaye ascribed most of this action to solution by rainwater, but some of the solution may be due to sea spray, whose dissolving power would increase slightly by cooling as the spray flies through the air. Kaye's examples of pitting are all on eolianite, but similar features are present on sea-level outcrops of Aymamón Limestone north of Quebradillas (fig. 44). Kaye (1957a; 1959a, p. 93–95); also described the formation of the sea-level notches (figs. 45 and 46), which are common at all coastal limestone outcrops in Puerto Rico. West of Camuy, the Aymamón Limestone crops out in a cliff face, which near Quebradillas rises from the sea itself. Most of the coastal karst features, common on eolianite, are well shown on the limestone in this area. Sea-level notches and small sea caves a few metres in diameter can be seen at most outcrops, and small natural arches (fig. 46) are present at many places. At places where exceptionally thin walls of pure limestone enter the sea, spectacular natural arches many metres in diameter are dissolved, such as the window at Punta Ventana (fig. 47) in southern Puerto Rico. Small bridges and arches are common in bedrock limestone, and they have also been seen in beach rock and eolianite.

Sea caves have been formed both recently and in higher stages of the sea during the Pleistocene by solution and by abrasion by wave action. Some of these caves, such as Las Golondrinas (Mn–1), eroded in eolianite near Mar Chiquita in the Manatí quadrangle, and the Loíza Aldea Cave (Ca–1) in the side of a mogote of Aymamón Limestone (fig. 48) in the Carolina quadrangle, are quite large. Las Golondrinas has an entrance 22 m wide, is 20 m deep, and has a ceiling 15 m high. The floor is 4 m above sea level, so it was probably eroded when sea level was

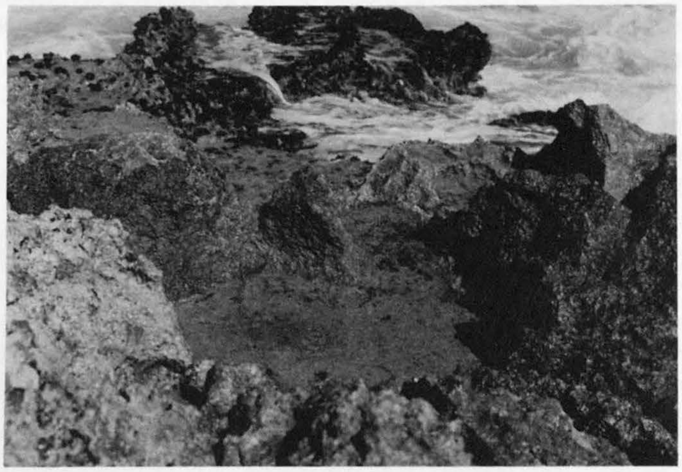

FIGURE 44.—Solution pan and karren spikes dissolved in Aymamón Limestone by sea spray and wave splash at the end of Highway 485, 3.6 km east-northeast of Quebradillas.

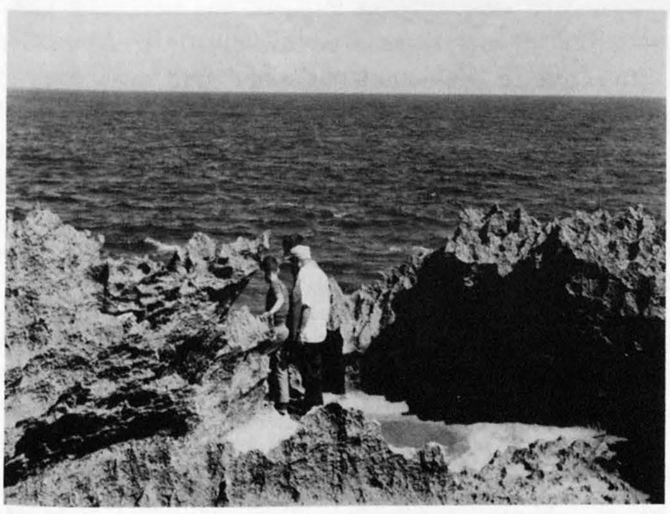

FIGURE 43.—Large solution pan in eolianite on ridge on north side of Mar Chiquita, 5 km north of Manatí.

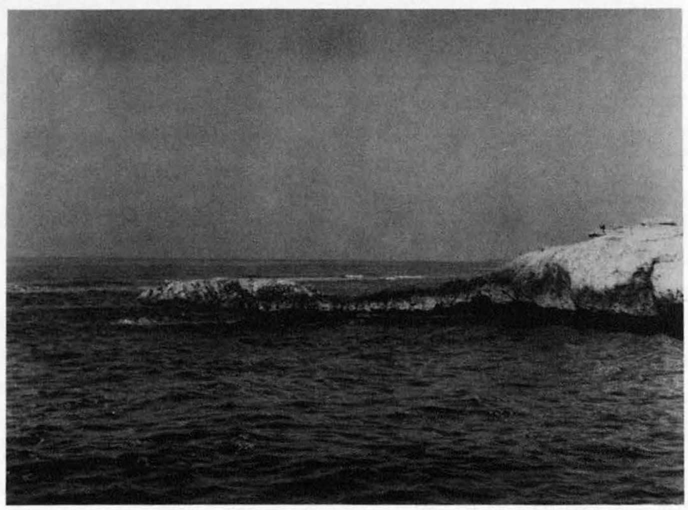

FIGURE 45.—Deep tidal notch and low arch dissolved in Ponce Limestone on shore of Caribbean Sea at Punta Vaquero, 7.5 km east of Guánica.

FIGURE 46.—Window (at arrow) dissolved in wall of Aymamon Limestone on Atlantic coast, 1.8 km north of Quebradillas. Tidal notch shows at right of photograph.

FIGURE 47.—Punta Ventana, a natural window dissolved in Ponce Limestone at edge of Caribbean Sea, 6 km south by west of Guayanilla.

slightly higher than today. Other sea caves at the same altitude are cut in the cliff 3.5 km northeast of Quebradillas at the back of a low wave-cut terrace, and at a few places, fossil beach rock (Monroe, 1963a) is exposed at the same altitude, which probably marks a Pleistocene stillstand. La Cueva del Indio (Ar–5) between Arecibo and Barceloneta is eroded in eolianite; it consists of relatively small caves and a very prominent natural arch. The cave

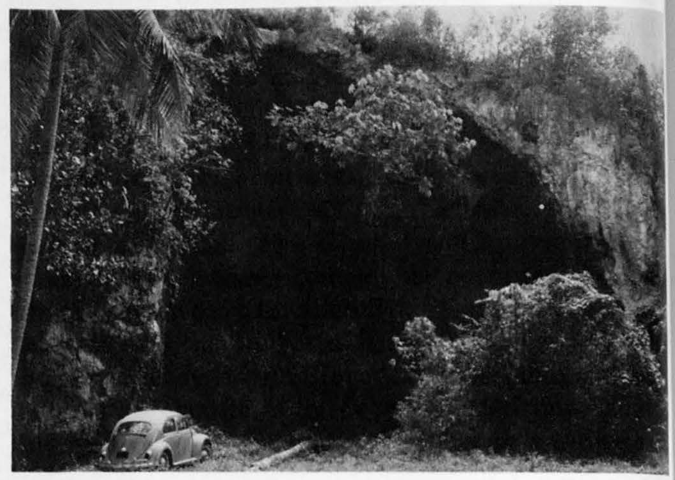

FIGURE 48.—Large sea cave in mogote of Aymamón Limestone at Loíza Aldea, 22 km east of San Juan. The mogote is about 1.5 km south of the present shoreline, and the flat is about 3 m above sea level.

contains petroglyphs believed to have been carved on the walls by Precolumbian Indians. On the high eolianite ridge south of Mar Chiquita, small dolines may indicate the presence of small collapsed sea caves, as closed depressions are not common on other eolianite ridges.

The common karren, such as Rinnenkarren (Bögli, 1960; Sweeting, 1972, p. 75), are so rare in the karstified rocks of northern Puerto Rico that I suspect they can be formed only in relatively dry climates. Perhaps long baking by the sun may cause the limestone to get a powdery coating that can be washed off into Rillenkarren at a sudden shower, and then repetition of the same process could produce the larger Rinnenkarren. Whatever the reason, karren are very rare in most of the northern karst belt, but a few were seen dissolved in Aymamón Limestone in the somewhat more arid area west of Isabela on the south-facing slope of a tributary of Quebrada de los Cedros. In contrast, various kinds of karren are present in the semiarid southern part of Puerto Rico, especially in the dense limestones of the Cretaceous (fig. 49). Near the coast I have seen fairly typical karren on Ponce Limestone (fig. 50).

Miotke (1973) suggested that many of the karren owe their origin to flowing water, especially to water flowing down the slopes after a sudden shower or, on the coast, after overflow by breaking surf and a rain of sea spray. This is borne out by the excellent karren shown on a broken block of eolianite at sea level near the sea cave Foso Jacinto, west of Isabela.

FIGURE 49.—Karren on Cretaceous limestone on side of hill on left bank of Río Guayanilla, 1.5 km north of Highway 2, 5 km east of Yauco.

FIGURE 50.—Karren on Ponce Limestone at side of trail just east of Punta Vaquero, 7.6 km east of Guánica.

SUMMARY

The karst landforms of Puerto Rico are controlled primarily by climatic factors such as precipitation and wind direction. Most of the forms are best developed in areas of moderate rainfall, but some are seen only in the more arid areas. The prevailing easterly trade winds have not only brought in moisture from the Atlantic Ocean but have also had a part in the shaping of the mogotes.

Of only slightly less importance is the rock type, certain landforms being best developed in the belts of outcrop of specific geologic formations.

Some landforms can only be explained by adjustment to the regional drainage of the upland areas of the island.

The karst areas contain very few flowing streams, as most of the drainage is underground; most of the flowing streams head in areas underlain by rock other than limestone and then flow through the limestone either to the sea or into a nonkarst area. Dry valleys are scattered through the northern karst area. Some contain intermittent streams after periods of heavy rainfall, but many are lined with swallow holes that carry rainfall underground within a few hours.

Closed depressions are present in all the terrain above soluble limestone. The type of closed depressions varies, however, from formation to formation. Solution dolines are abundant in some parts of the Aguada Limestone, in the limestone members of the Cibao Formation, and in the less pure parts of the Lares Limestone. Collapse dolines are abundant in all the formations near the larger underground streams, even at considerable distances away from the river itself, probably because of collapse of caves that are tributary to the main stream. Such collapse dolines are especially abundant near the Río Camuy and the Río Tanamá. Vertical caves have been seen in the Lares, the Aguada, the Aymamón, and the Camuy. They may also be present in parts of the Cibao, but most of that formation is incompetent to support vertical shafts; vertical cliff faces, however, are common in the Montebello Member.

Tower karst has formed only in areas of fairly pure thick limestone formations. More specifically, cone karst is found in the outcrop areas of the thick-bedded to massive Lares Limestone and secondarily in parts of the Aguada Limestone; cliffed cone karst is found only at those places where the Montebello Limestone Member of the Cibao Formation overlaps the part of the Lares Limestone that forms cone karst. Mogote karst has formed only in the belt of outcrop of that part of the Aymamón Limestone composed of chalk that can be readily dissolved and reprecipitated into a casehardened surface. Furthermore, in order to form mogotes, the limestone must project through plains of blanket sand. A few mogotes are present in the upper, purer part of the Aguada Limestone at places where the blanket sands extend farther inland. In some contrast, the areas of blanket sand near Florida surround hills of Montebello Limestone Member that are much more rounded than the steep-sided mogotes of the Aymamón Limestone. Both kinds of hills can be considered tower karst, but the Montebello hills are not typical mogotes.

In northwestern Puerto Rico, the upper part of the Aymamón Limestone and the Camuy Formation do not appear to be susceptible to the rapid induration that takes place in the lower Aymamón, so rather than belts of mogotes, only long narrow ridges occur between the belts of blanket sand. The limestone in these ridges is susceptible to solution, for vertical caves and closed depressions are present, but the steep-sided mogotes are not.

The zanjones of Puerto Rico seem to be nearly unique. Similar forms are known from Sarawak, and short varieties, the bogaz, are common elsewhere, but continuous trenches in parallel groups a kilometre or more long are rare in other areas. Zanjones have been seen in Puerto Rico in those parts of the Lares Limestone where the bedding is regular and the beds are not thicker than 10 cm, and also in the lower part of the Montebello Limestone Member of the Cibao Formation in the area between the Río Tanamá and the town of San Sebastián, especially between the town of Lares and Lago de Guajataca.

Caves are present in all the calcareous formations but are largest and longest in the Lares Limestone; in the other formations, cave breakdown is likely to result in discontinuous shorter passages. The caves can be divided into three general classes: (1) caves containing rivers flowing from the volcanic and intrusive rocks of the interior; (2) caves containing streams originating in the Cibao Formation; and (3) irregular caves apparently formed entirely by solution by relatively quiet ground water.

The river caves containing streams originating in volcanic rocks commonly can be recognized by the cobbly and sandy alluvium; they generally have high narrow rooms that have been formed in part by scour by the clastic alluvium. The Camuy Cave system is the best example, but the short caves of the Tanamá and some of the short caves at the ends of streams south of Florida are of this kind.

The river caves carrying water from the calcareous clay of the Cibao Formation, best exemplified by the Quebrada caves in the southwestern part of the Camuy quadrangle, have smooth polished floors, walls, and ceiling. Their cross sections are commonly subcircular. Apparently they are being enlarged by rapidly flowing flood waters that carry little if any abrasive material, and they are formed by the process designated "solvent motion" by Kaye (1957a).

Neither kind of river cave contains the intricate speleothems that are present in the third type, the caves formed by quiet or only slowly moving ground water. These caves are present in all the harder limestones. They are mostly of irregular shape and may or may not have side passages. Most are difficult to find as they are likely to have very small entrances. Most of these caves are crudely disk shaped, the ceiling descending to the floor on all sides; many have a forest of short columns at the extremities. In addition to the three main groups of caves, Puerto Rico has thousands of rock shelters and slightly larger shelter caves.

Minor solution features such as the several kinds of karren and solution pans are present at all outcrops of limestone or eolian calcarenite on or near the coast and are apparently formed largely by sea spray. Inland from the coast they have been seen only in the more arid areas, especially in southwestern Puerto Rico.

The description of the landforms of Puerto Rico in this paper may serve as a starting point for much more quantitative studies. So far, little work has been done on underground tracing of the karst waters, on rate of solution of limestone in the various climatic areas of Puerto Rico, on the rate of denudation as the rocks are carried away in solution, on the relationship of surficial lineations to different karst features, or on the morphometry of the karst depressions and hill features. The caves of Puerto Rico have hardly been touched (except for a few that have been sadly vandalized). So far, fewer than 10 caves have been surveyed, and none of these surveys have been more accurate than Grade 4B of the classification of the Cave Research Group of Great Britain (Butcher and Railton, 1966).

KARST FEATURES KEYED TO PLATE 1

The following list shows by quadrangles the various karst features that are shown by symbols and crosses on the karst map, plate 1. The name of the feature is given, if known, and is followed by a brief description, if one is available. A location is given by Puerto Rico metre-grid coordinates, if the exact location is known to me by visit or by study of aerial photographs. Many of the features that show only an approximate location have been located by José Martínez Oquendo, Puerto Rico Department of Natural Resources, and the location shown on plate 1 is plotted from his maps and is believed to be approximately correct. The names of these features are shown in the list, but neither a description nor an exact location follows. The approximate location on plate 1 is probably sufficiently accurate to enable interested speleologists to find the caves by asking nearby residents. Finally, the name of the formation in which the feature appears is given, if known.

In some areas, several features close together are assigned the same number.

Aguadilla quadrangle:

A-1, Very large rock shelter on south side of bypass. 78,000 E., 67,420 N. Aymamón Limestone.

A-2, Rock shelter that looks like an ancient sea cave at altitude of 95 m. 76,390 E., 69,050 N. Aymamón Limestone.

A-3, Cueva Honda, located behind quarry, according to Martínez. Approx. 77,200 E., 66,000 N. Aguada Limestone

Aguas Buenas quadrangle:

The Trujillo Alto Caves in barrio Cuevas. Apparently were destroyed during relocation of Highway 181.

Arecibo quadrangle:

Ar-1, Window on top of ridge, visible from highway 10. 122,560 E., 65,060 N. Aymamón Limestone.

Ar-2, Location of collapse in road (fig. 20) reported by Miotke (1973). 131,530 E., 65,400 N. Blanket sand on Aguada Limestone.

Ar-3, San Pedro Springs at side of Highway 10. 124,650 E., 63,780 N. Aguada Limestone.

Ar-4, Cueva de los Nacionalistas or Biáfara No. 1. Tunnel near crest through ridge to second entrance 50 m farther south. Name comes from Nationalist revolt in 1952, when a small group hid in the cave after failure of the revolt. 127,880 E., 62,880 N. Aguada Limestone.

Ar-4, Biáfara No. 2. A small cave about 60 m west of Biáfara No. 1. Window in side opposite entrance. 127,820 E., 62,880 N. Aguada Limestone.

Ar-5, Cueva del Indio. Small sea cave with petroglyphs and natural arch. 130,320 E., 73,240 N. Quaternary eolianite.

Bayamón quadrangle:

Ba-1, Vertical cave about 15 m deep on top of ridge. 172,580 E., 63,360 N. Aymamón Limestone.

Bayaney quadrangle:

B-1, El Embudo. A large collapse sink into which two streams flow intermittently. 111,790 E., 59,500 N. Cibao Formation.

B-2, Golondrinas. Steeply sloping shaft northwest side of Highway 129. Does not connect with Camuy Cave system. 111,815 E., 57,405 N. Lares Limestone.

B-3, Empalme Sink. Bottle-shaped vertical cave about 125 m deep. At bottom, Río Camuy flows in from west and out toward north. Empalme Cave is 40 m above river on south side; a short extension of the same cave appears on north wall. Río Camuy goes into siphon about 100 m downstream from Empalme. 111,555 E., 57,100 N. Cibao Formation on Lares Limestone.

B-4, Cueva Minga No. 1. Approx. 108,000 E., 56,500 N.

B-4, Cueva Minga No. 2. Approx. 108,100 E., 56,400 N.

B-5, Empalme Cave. South entrance to 200-m tunnel connecting with Empalme Sink (B-3). 111,490 E., 56,915 N. Lares Limestone.

B-5, Unnamed vertical shaft, 30 m deep. Above roof of Camuy Cave, according to R. H. Gurnee (oral commun., 1970). 111,200 E., 56,880 N.

B-6, Tres Pueblos Sink (fig. 8). Collapse sink nearly circular in plan, about 140 m in diameter, about 120 m deep. Río Camuy enters on southwest side, flows out on east side. Junction of Hatillo, Lares, and Camuy Municipios. 111,060 E., 56,650 N. Lares Limestone.

B-7, Spiral Sink. Steeply slanting shaft from cave mouth to Río Camuy. 111,186 E., 56,430 N. Lares Limestone.

B-7, Large rock shelter extending under Highway 129. 111,540 E., 56,140 N. Lares Limestone.

B-8, Observatory Sink (fig. 13). Largest known closed depression of Puerto Rico. Bottom altitude is 225 m, top of lowest point on divide is 295 m, top of highest peak at side is 380 m; diameter is 500 m, nearly circular. Site of Arecibo Ionospheric Observatory, a radio-radar telescope. 118,630 E., 56,800 N. Cibao Formation on Lares Limestone.

B-9, Observatory tunnel cave of Río Tanamá, entrance. 118,560 E., 56,500 N. Lares Limestone.

B-10, Hoyo Hondo Sink. Approx. 108,000 E., 55,400 N.

B–11, Angeles Resurgence. A long cave that connects with Cueva del Humo and contains porphyritic cobbles brought in by Río Camuy. River appears at surface and immediately goes underground to connect with West Tributary of Gurnee and others (1967). Mapped by Emily Davis and others (McKinney and Miller, 1972). 109,945 E., 55,775 N. Lares Limestone.

B–12, Cueva La Ventosa. Vertical shaft that leads down to bat cave from which another vertical shaft leads to Río Camuy. 111,160 E., 55,770 N. Lares Limstone.

B–12, Vertical shaft seen on aerial photographs. 111,615 E., 55,540 N. Lares Limestone.

B–13, Cueva de las Caras, also known as Cueva del Indio. Short cave having supposed Indian carvings on stalactites near entrance. 112,040 E., 55,420 N. Lares Limestone.

B–13, Cueva Comején. Precipitous cave reported by F. E. McKinney (oral commun., 1971) to be about 30 m deep. 112,075 E., 55,455 N. Lares Limestone.

B–14, Blue Hole (Hoyo Prieto). Entrance cave of Río Camuy, blocked by thick log jam of rotten, waterlogged tree trunks. 110,900 E., 54,290 N. Lares Limestone.

B–15, Tunnel through ridge on east side of Río Camuy (fig. 38), visible from Highway 129. 111,100 E., 54,130 N. (west end); 111,160 E., 54,200 N. (east end). Lares Limestone.

B–15, Cave extension of tunnel cave across valley east of the tunnel (M. D. Turner, oral commun., 1956).

B–15, Unnamed small cave just above water level of Río Camuy. 111,030 E., 54,150 N. Lares Limestone.

B–16, La Luz. Single-room cave about 100 m long, lighted by electricity. 114,560 E., 54,500 N. Lares Limestone.

B–17, Sol. Small cave, partly collapsed. Approx. 107,670 E., 54,200 N.

B–18, Cueva Pajita. Tunnel about 60 m long, used as a bar-restaurant. 107,790 E., 53,960 N. Lares Limestone.

B–18, Machos. Small cave. Approx. 107,700 E., 53,600 N.

B–19, Cueva del Agua No. 1. Approx. 108,200 E., 53,500 N.

B–19, Cueva del Agua No. 2. Approx. 108,200 E., 53,500 N.

B–20, Cueva del Humo. A long complex cave that connects with Angeles to the north. Map published in McKinney and Miller (1972). 110,430 E., 53,740 N. Lares Limestone.

B–21, Lagartos No. 1. A moderate-sized cave, according to Mario Soriano, U.S. Corps of Engineers (oral commun., 1967). 113,910 E., 53,920 N. Lares Limestone.

B–21, Cueva Oscura. Approx. 114,000 E., 53,800 N.

B–21, Lagartos No. 1. A moderate-sized cave, 53,700 N.

B–22, Cueva El Humo No. 2. Approx. 114,600 E., 53,900 N.

B–22, El Agua. Cave. Approx. 114,600 E., 53,600 N.

B–22, Los Muertos. Moderate-sized cave. Approx. 114,400 E., 53,800 N.

B–23, Valentín. Cave. Approx. 114,600 E., 53,600 N.

B–24, Lagartos No. 2. Cave. Approx. 114,100 E., 53,600 N.

B–25, Entrance to first tunnel on Rio Tanamá. 115,635 E., 53,400 N. Resurgence at 115,880 E., 53,590 N. Lares Limestone.

B–26, High arch over Rio Tanamá. 116,520 E., 53,620 N. Resurgence at 116,545 E., 53,590 N. Lares Limestone.

B–27, Cueva La Alta. Approx. 116,900 E., 53,500 N.

B–28, Arocho. Cave. Approx. 117,300 E., 52,700 N.

B–29, Cueva Antonio. Resurgence of small stream on east side of ridge. Cave is 6 m wide, 1.5 high; trends southwest from portal about 10 m, then turns west-northwest and northwest. Active stream enters cave on other side of ridge. 118,850 E., 52,140 N. Lares Limestone.

Caguas quadrangle:

Cg–1, Aguas Buenas Caves. Drained by Río Caguitas. Many of the rooms are infested with the fungus that causes the lung disease of Histoplasmosis. Caves explored and surveyed by a party led by R. H. Gurnee in February 1968. Several entrances. 186,480 E., 44,100 N. (Bandera); 186,660 E., 44,180 N. (Don Julio); 186,740 E., 44,250 (Caguax). Another area of karst topography 1.5 km farther south-southwest may contain additional caves. Cretaceous limestone.

Camuy quadrangle:

Cm–1, Twin shafts, each about 30 m deep. Eastern shaft is vertical, western slopes steeply toward east. The two join in an archway at bottom. 113,660 E., 71,325 N. Camuy Formation.

Cm–2, Manmade cave or underground quarry for soft chalk. 118,910 E., 67,625 N. Aymamón Limestone.

Cm–3, Abra Honda. A large collapsed cave; wide overhangs remain. 107,810 E., 66,275 N. Aymamón Limestone.

Cm–4, Cueva Oscura. Two-level cave near top of ridge. Larger and upper one, about 30 m long, has a window at the end. 108,090 E., 63,930 N. Aymamón Limestone.

Cm–4, Hoyo Oscura. A very deep sink. 107,830 E., 64,200 N. Aguada Limestone.

Cm–5, Cueva Clara. Near Cueva Oscura.

Cm–6, La Pared Hueca (fig. 41). A natural arch, 12 m from wall to wall, 14 m through arch, ceiling about 8 m high at point where floor is lowest. Limestone of walls is thin bedded and gently crossbedded, but roof is thick bedded. Many stalactites on ceiling and nearby canyon walls. 109,850 E., 63,380 N. Aguada Limestone.

Cm–7, Collapsed natural bridge (fig. 42). Same stratigraphic horizon as La Pared Hueca. 111,450 E., 63,280 N. Aguada Limestone.

Cm–8, Entrance of stream believed to emerge at Boca del Infierno. Passable for a few hundred metres, then blocked by breakdown. 109,750 E., 62,970 N. Upper part of Cibao Formation.

Cm–9, Boca del Infierno. Probable resurgence of stream that enters limestone at Cm–8. 111,-225 E., 63,740 N. Top of Cibao Formation or base of Aguada Limestone.

Cm–10, Stream flows into low cave. Water goes past natural well described next, but resurgence is unknown. 107,360 E., 62,250 N. Cibao Formation.

Cm–10, Natural well in which roar of rushing water can be heard from surface; well is nearly circular, about 4 m in diameter. Well is about 50 m from cave entrance described above at Cm–10. 107,350 E., 62,300 N. Cibao Formation.

Cm–11, Campanario. Cave near top of hill east of Highway 486. Approx. 108,940 E., 62,780 N.

Cm–12, Cave resurgence of streams that enter limestone at Cm–13, Cm–14, and Cm–18. 109,300 E., 62,470 N. Cibao Formation.

Cm–13, Cave in sink reported by Nelson (1970). 109,475 E., 62,325 N. Cibao Formation.

Cm–14, Large cave into which stream flows. Explored as clean polished tube for about 300 m. Cave No. 5 of Nelson (1970). 109,-340 E., 61,950 N. Cibao Formation.

Cm–15, Entrance of stream cave that emerges at Cm–16. 108,980 E., 61,550 N. Cibao Formation.

Cm–16, Resurgence of stream that enters at Cm–15. 109,030 E., 61,650 N. Cibao Formation.

Cm–17, Emergence at head of swamp. 109,490 E., 61,610 N. Cibao Formation.

Cm–18, Unexplored cave entrance. Stream may go past the cave in sink Cm–13 and emerge at Cm–12. 109,650 E., 62,000 N.

Cm–19, Resurgence of Río Camuy. Low cave entrance on west side of valley. Extends south-southwest about 200 m to blockage by cave breakdown. 112,100 E., 60,115 N. Cibao Formation.

Cm–20, Large swallow hole at side of small, flat, closed depression. 110,900 E., 61,740 N.

Cm–20, Short surface stream in closed depression; probably resurgence from swallow hole described above. 111,060 E., 61,825 N. Cibao Formation.

Cm–21, Polje-like closed depression. 113,200–113,800 E., 62,800 N.

Cm–22, Polje-like closed depression. 118,500 E., 62,000 N.

Carolina quadrangle:

Ca, Loíza Aldea Cave (fig. 48), a large sea cave on west side of a mogote. Site of several archeological excavations. 210,590 E., 65,-940 N. Aymamón Limestone.

Central Aguirre quadrangle:

CA–1, Coquí Cave. Small cave mentioned by Berryhill (1960). 172,940 E., 16,410 N. Cretaceous Limestone.

Ciales quadrangle:

Ci–1, Acueducto Cave. Stream from this cave forms a source of municipal water supply of Vega Baja. 157,130 E., 58,800 N. Lares Limestone.

Ci–2, Cueva Bonita. Shelter cave on side of cliff, about 4 m in diameter and 2 m high. 157,540 E., 57,540 N. Lares Limestone.

Ci–3, Mingo I. Cave. Approx. 149,000 E., 57,000 N.

Ci–4, Del Abono. Cave. Approx. 149,800 E., 57,600 N.

Ci–5, Felipe I. Cave. Approx. 150,350 E., 57,800 N.

Ci–5, Felipe II. Shelter cave. Entrance 3 m high, 12 m wide. North of dripline 5 m, entrance drops to height of 1 m and is obstructed by stalactites. Inner cave seems to extend about 4 m north by about 8 m east and is about 1.5 m high. 150,255 E., 57,780 N. Lares Limestone.

Ci–5, Felipe III. Entrance 15 m wide and 2 m high. Cave follows winding course downwards for about 25 m to point where rising earthfill stops further passage. Many stalactites. 150,300 E., 57,670 N. Lares Limestone.

Ci–6, Frío. Cave. Approx. 150,600 E., 57,300 N.

Ci–7, Del Indio. Cave. Approx. 150,900 E., 57,200 N.

Ci–8, Archilla No. 1. Two short caves at trail side; no dark zone. 157,490 E., 55,450 N. Lares Limestone.

Ci–9, Archilla No. 2. Cave about 30 m long, sloping down toward west. 157,500 E., 55,580 N. Lares Limestone.

Ci–10, Cueva Archilla. Large cave containing abundant bats and swallows. West entrance 8 m wide; cave extends generally eastward for about 100 m. Has two large rooms with large windows. 149,930 E., 56,400 N. Lares Limestone.

Ci–11, Encarnación. Large natural tunnel. 150,530 E., 56,320 N. Lares Limestone.

Ci–12, Lucero. Large opening seen only from distance. 150,100 E., 56,290 N. Lares Limestone.

Ci–13, Cueva Class. Approx. 151,000 E., 56,900 N.

Ci–14, Cueva Antón. Approx. 150,700 E., 56,800 N.

Comerío quadrangle:

Three caves about 1.6 km southeast of town of Comerío:

Co–1, Los Santos. Approx. 175,200 E., 41,600 N. Cretaceous limestone.

Co–2, Cueva La Mora. Said to be about 100 m long. Approx 175,300 E., 41,500 N. Cretaceous limestone.

Co–3, Guaraguao. Cave. Approx. 175,300 E., 41,600 N.

Corozal quadrangle:

Cr–1, Stream flows into cave to pass through Convento II, Convento III, and Ocho Puertas. 168,540 E., 59,550 N. Cibao Formation.

Cr–2, Convento II and Convento III. Continuation of cave Cr–1.

Cr–3, Ocho Puertas. A stream cave. 169,150 E., 59,810 N. Cibao Formation.

Cr–4, Convento I. Stream flows from low-roofed cave. 166,350 E., 59,020 N. Cibao Formation.

Cr–5, Cave with spring. Cave about 2 m high, walled up to provide catchment basin for water. 165,040 E., 58,500 N. Lares Limestone.

Cr–6, Quintero. Small tube slopes west from road to enter large cave that leads southwest to the Corozal Cave; artificially closed by dumped material in 1973. 163,180 E., 57,830 N. Lares Limestone.

Cr–7, Corozal Cave. Large opening on side of cliff (fig. 39), a notable landmark for several kilometres. Connects with Quintero (Cr–6). 163,980 E., 57,740 N. Lares Limestone.

Florida quadrangle:

F–1, Cueva del Río Encantado. Cave at south end of sink trends south-southwest to stream from south. Level of stream about 18 m below dripline, and 35 m below bottom of broad sink. 141,130 E., 58,040 N. Lares Limestone.

F–2, Cueva del Viento. Cave at south edge of closed depression, extends east about 400 m. Ceiling 5–15 m high. 143,050 E., 58,180 N. Lares Limestone.

F–3, Very large karst spring used as public supply in March 1963, but by June 1972 the pump had been removed. 133,140 E., 57,640 N. Cibao Formation.

F–4, Las Golondrinas. Cave. Approx. 138,700 E., 54,400 N.

F–5, El Convento. Cave. Approx. 138,400 E., 54,400 N.

F–5, González I. Cave. Approx. 138,400 E., 54,600 N.

F-5, González II. Cave. Approx. 138,500 E., 54,500 N.

F-6, Unnamed cave. 139,440 E., 54,070 N.

F-7, Cave into which a stream flows. 138,750 E., 53,890 N. Lares Limestone.

F-8, Cacique de Don Alonzo, also known as Indian Cave. 132,540 E., 53,630 N. Lares Limestone.

Isabela quadrangle:

I-1, Foso Jacinto. Partly collapsed sea cave. When waves enter cave, water rises out of window at top. 84,724 E., 75,770 N. Quaternary eolianite.

Manatí quadrangle:

Mn-1, Las Golondrinas. A sea cave above Mar Chiquita, 22 m wide, 20 m deep, and 15 m high. Floor is 4 m above sea level. Eroded into sandy calcarenite. 146,980 E., 70,820 N. Quaternary eolianite.

Mn-2, Jiménez, probably same as Boquillas. Bat cave with two entrances, second about 100 m farther east. Never thoroughly explored because of very bad air. All people who have entered cave have become ill (Histoplasmosis?). 146,850 E., 69,550 N. Aymamón Limestone.

Mn-3, Altagracia. Large shelter cave trending about 40 m north and 20 m west from large entrance to west wall. Ceiling about 20 m high and has window. Some speleothems. Swallows and guano. 147,250 E., 67,230 N. Aymamón Limestone.

Mn-4, Collapse shaft in blanket sand on west side of road. Originally about 5 m deep; now nearly filled with bodies of old automobiles. 151,930 E., 65,320 N. Aymamón Limestone.

Mn-5, Cueva del Abono. Approx. 156,500 E., 63,700 N.

Mn-6, Cueva Manahena. A two-level cave connecting Quebrada Las Lajas and Quebrada Las Torres. Water from the lower level emerges from a spring about 100 m downstream from west entrance to cave. 157,240 E., 60,350 N. Cibao Formation.

Mn-6, Cueva Convento. A small cave from which a stream flows. A few metres inside cave, roof lowers to less than 1 m above water. 157,260 E., 60,250 N. Cibao Formation.

Mn-7, Ojo de Água. A large karst spring. 155,900 E., 68,400 N. Aymamón Limestone.

Mn-8, Cueva La Campana. A very large nearly circular shelter cave on west side of valley. Cave trends south-southwest from entrance, about 30 m in diameter. Ceiling about 15 m high. Several windows, on sides and in ceiling. Two levels. 156,550 E., 67,510 N. Aymamón Limestone.

Mn-9, Cueva Baja. Entrance on north side of hill. Very large shelter cave, trends 40 m east, 20 m south from entrance. Ceiling about 20 m high, dome extends about 5 m higher. Two windows in ceiling of dome. 156,780 E., 67,420 N. Aymamón Limestone.

Maricao quadrangle (Locations by D. H. McIntyre):

Mr-1, Naranjal. A small cave. 92,750 E., 43,976 N. Cretaceous limestone.

Mr-2, Río Mayaguecilla Cave. Small cave on south side of hill, and spring at river level 150 m farther northeast on northwest side of river. 94,150 E., 43,110 N. Cretaceous limestone.

Moca quadrangle:

Mo-1, Los Cedros dam. A concrete dam which never held any water because of extremely high permeability of Aymamón Limestone. 83,740 E., 73,180 N. Aymamón Limestone.

Mo-2, Jobos. Cave in quarry wall. 90,790 E., 70,500 N. Aymamón Limestone.

Mo-2, Caña de Indio. A deep collapse sink, not entered. 90,530 E., 70,500 N. Aymamón Limestone.

Mo-2, Sin Fin. A large complex cave in process of being quarried away. 90,790 E., 70,580 N. Aymamón Limestone.

Mo-3, Las Golondrinas. Cave. Approx. 81,000 E., 69,500 N.

Mo-4, La California. A large collapse sink with walls covered by dripstone decoration. Entrances to about four small caves at bottom. 82,930 E., 67,040 N. Aguada Limestone.

Mo-5, Cueva Del Guano. Approx. 84,200 E., 63,500 N.

Mo-6, Las Armas. Cave. Approx. 86,300 E., 63,000 N.

Mo-6, Cueva Del Abono I. Approx. 85,800 E., 62,900 N.

Mo-6, Las Golondrinas. Cave. Approx. 86,000 E., 63,000 N.

Mo-6, Del Pozo. Cave or sink. Approx. 86,100 E., 63,200 N.

Mo–7, Cueva Del Abono II. Approx. 87,800 E., 63,700 N.

Mo–8, Nuñez. Entrance is a small hole in side of hill which has a vertical drop of about 1.5 m and then a steep slope for another 1.5 m to an antechamber which has a diameter of about 3 m and a height of 2 m. Then a crawlway for 1 m to the southwest followed by a passage 2–3 m high toward the northwest for about 10–15 m into a room about 80 m wide having a large column in the middle. Ends of cave are very low passages containing short columns. Total area about 4,000 m^2. Cave is notable for abundant drapery, straw stalactites, and eccentrics in which side stalactites range from horizontal to about 135° (fig. 40). 87,920 E., 63,100 N. Cibao Formation.

Mo–9, Cueva Los Barbudos. Sink southwest of Highway 112, more than 30 m deep; a cave stream crosses the bottom from south to north. 88,680 E., 65,170 N. Aguada Limestone.

Parguera quadrangle:

Pa–1, Cueva de Ayala. On Isla Cueva, not open to public.

Peñuelas quadrangle:

Pe–1, El Convento. Resurgence of Quebrada de los Cedros. Several other entrances toward northeast including a breached dome pit, which gave cave its name. Mapped by Barry Beck, Puerto Rico Department of Natural Resources, in 1972 (written commun.). 119,070 E., 23,620 N. Juana Díaz Formation.

Pe–2, El Viento. A large cave some 30 m above and east of valley of Quebrada de los Cedros. Has small window at top. 119,240 E., 23,740 N. Juana Díaz Formation.

Pe–3, Mapanche. Large cave sloping steeply down toward west. 119,600 E., 23,940 N. Juana Díaz Formation.

Pe–3, Vertical cave. 119,530 E., 24,000 N. Juana Díaz Formation.

Playa de Ponce quadrangle:

Pl–1, Two caves reported by Gile and Carrero (1918), on Isla Caja de Muertos northeast of lighthouse.

Ponce quadrangle:

Po–1, Cave reported by Richard Krushensky (oral commun., 1972). 141,460 E., 30,740 N. Limestone of early Tertiary age.

Puerto Real quadrangle:

PR–1, Cofresí. A large cave with many narrow labyrinthine passages totaling more than 100 m. Contains tomb of the brother of the pirate Cofresí. Mapped by Limeres and Gurnee (written commun., 1960) in 1960. 71,390 E., 23,130 N. Limestone of Cretaceous age.

Punta Verraco quadrangle:

PV–1, Ballena. A large collapsed sea cave now partly filled with oil-impregnated sand. At north edge is a sink containing saltwater and mangroves and a short cave. 107,260 E., 13,920 N. Ponce Limestone.

PV–2, Murcielago or Tierco. Cave about 100 m long consisting of a series of rooms 10–30 m wide, now largely collapsed. Hole in ceiling is about 7 m wide. 108,240 E., 14,300 N. Ponce Limestone.

PV–3, Punta Ventana (fig. 47). A large window or natural arch. 112,220 E., 14,600 N. Ponce Limestone.

Quebradillas quadrangle:

Q–1, Hoyo Grande. Large vertical cave about 5 m in diameter, with window opening to north on sea cliff. 97,900 E., 73,030 N. Aymamón Limestone.

Q–2, El Tunel. East entrance of tunnel of abandoned railroad, 50 m long. 96,750 E., 73,000 N. Aymamón Limestone (dolomitic).

Q–3, Window in spur of limestone (fig. 46). 99,460 E., 72,850 N. Aymamón Limestone.

Q–4, Abandoned railroad tunnel about 180 m long makes wide curve underground. East entrance: 97,850 E., 72,190 N. Aymamón Limestone.

Q–5, Las Golondrinas. Shelter cave about 10 m long. 102,370 E., 69,030 N. Aymamón Limestone.

Q–6, Vertical cave. More than 15 m deep, probably having side passages. On south side of road at west edge of deep sink. 99,220 E., 66,630 N. Aymamón Limestone.

Q–7, Natural bridge. The trail Vereda Caballo splits southeast of bridge. Main trail passes over bridge on way to Pueblito de Ponce; minor trail goes under the bridge. 98,125 E., 64,825 N. Aguada Limestone.

Q–8, Cueva Del Abono. Opening about 20 m above valley floor. 102,690 E., 63,460 N. Aguada Limestone.

Q–9, Cueva de La Luz. A cave more than 300 m long having a running stream in eastern part. 100,980 E., 62,620 N. Cibao Formation.

Q–10, Small cave with low roof. 104,400 E., 61,360 N. Cibao Formation.

Q–11, El Calvario. A mogote about 30 m high used as a religious shrine. 103,445 E., 66,650 N. Aymamón Limestone.

Q–12, Rimmed sink. A closed depression about 20 m deep surrounded on west, north, and east by a rampart 8–20 m high. 94,500 E., 67,220 N. Aymamón Limestone.

Q–13, River rampart (fig. 18) rises 35 m above plain to west and 160 m above river to east. 95,670–95,760 E., 68,800–69,400 N. Aymamón Limestone.

Río Descalabrado quadrangle:

Ri–1, Golondrinas. Cave. Approx. 150,000 E., 25,600 N. Limestone of early Tertiary age.

Ri–1, Honda. Cave. Approx. 149,950 E., 25,700 N. Limestone of early Tertiary age.

Ri–1, Juana Díaz. Cave. Approx. 149,400 E., 25,700 N. Limestone of early Tertiary age.

Ri–2, Naranjo. Cave. Approx. 148,700 E., 24,100 N. Limestone of early Tertiary age.

Rosario quadrangle:

Ro–1, Five caves near crest of ridge. Approximately 83,400 E., 36,000 N. Limestone of Cretaceous age.

Ro–2, Cueva Cantera Cerro. Cave near quarry west of Highway 348 about a kilometre southeast of Rosario. Approximately 85,400 E., 35,600 N.

Ro–3, Cueva La Muerta. Cave near Ro–2.

Sabana Grande quadrangle:

Sb–1, Cueva Majina. Large opening above highway, difficult of access. Said to be a deep, partly vertical cave. 98,980 E., 22,910 N. Limestone of Cretaceous age.

San German quadrangle:

SG–1, Cave containing Indian relics. Location by Richard Volckmann, geologist, U.S. Geological Survey (oral commun., 1972). 80,220 E., 27,730 N. Limestone of Cretaceous age.

SG–2, Cueva del Señor Cuevas or Monte Grande. 81,050 E., 27,480 N. Limestone of Cretaceous age.

SG–3, La Tuna. Nearly vertical cave on crest of ridge. 79,810 E., 26,560 N.

SG–4, Malano Grande. Cave. Approximately 81,270 E., 25,600 N.

SG–5, Cueva de Sindi. Location by Volckmann (oral commun., 1972). 85,200 E., 25,690 N.

SG–6, Cave reported by Mario Soriano of U.S. Corps of Engineers. Approx. 90,000 E., 24,700 N.

San Juan quadrangle:

SJ–1, Cave near crest of ridge. About 30 m in diameter, ceiling 10 m above floor, 2 entrances, 1 wide window to east, and 1 ceiling window. 187,100 E., 65,170 N. Aguada Limestone.

SJ–1, Small cave 2 m high, about 15 m diameter. May be artificial. 186,970 E., 65,010 N. Aguada Limestone.

San Sebastián quadrangle:

SS–1, Tunnel about 60 m long through which Rio Guajataca flows. 102,190 E., 54,450 N. Lares Limestone.

SS–2, De las Brisas. Cave. Approx. 102,100 E., 54,000 N.

Utuado quadrangle:

U–1, Entrance of Río Tanamá tunnel, which is about 100 m long. A trail crosses the river over the top of this tunnel. 121,175 E., 59,300 N. Cibao Formation.

U–2, Los Chorros. A large stream flows out of cave on west side of Highway 10 and forms waterfall. Cave was reported by Graham Nelson (oral commun., 1968) to be more than 300 m long. 126,100 E., 57,930 N. Lares Limestone.

U–3, Resurgence of Río Tanamá below Observatory Cave. High, narrow opening; river flows into a narrow canyon with nearly vertical sides. 119,000 E., 56,420 N. Lares Limestone.

U–4, Entrance of travertine tunnel No. 1 of Río Tanamá. 119,040 E., 56,440 N.

U–5, Entrance of travertine tunnel No. 2 of Río Tanamá. 119,135 E., 56,485 N.

U–6, Entrance of travertine tunnel No. 3 of Río Tanamá. 119,410 E., 56,640 N.

U–7, Entrance of travertine tunnel No. 4 of Río Tanamá. 119,910 E., 56,900 N.

U–8, Soto. Cave. Approximately 123,500 E., 55,700 N.

U–9, Misterio. Cave. Approximately 119,600 E., 51,800 N.

U–10, Golondrinas. Cave. Approximately 119,400 E., 51,200 N.

U–11, Spring. Water flows about 100 m across shallow depression and disappears in swallow hole on west side. 131,930 E., 57,370 N. Cibao Formation.

Vega Alta quadrangle:

V–1, Monserrate. A large number of collapse sinks, many interconnected by caves. A low-cost housing project is being built (1972) above the caves and entrances, and the sinks are being filled with trash. Following four entrances are listed: 161,000 E., 67,500 N.; 161,140 E., 67,840 N.; 160,950 E., 67,630 N.; 161,370 E., 67,470 N. Aymamón Limestone.

V–2, Los Muertos. Cave. Approximately 159,400 E., 66,100 N.

V–2, Tres Ventanas. Shelter cave with three windows. Approximately 159,300 E., 66,000 N.

V–3, Golondrinas. Cave. Approximately 168,200 E., 64,200 N.

V–4, Rodriguez. Cave. Approximately 168,000 E., 60,300 N.

V–5, Cave 366. About 3 m below trail. Slopes toward east for about 25 m. Ceiling about 3 m high. Inside entrance narrow passage spirals down beneath entrance. 170,000 E., 60,800 N. Cibao Formation.

V–6, Prominent mogote (fig. 25) on southwest side of Highway 2. 160,800 E., 67,320 N. Aymamón Limestone.

V–7, Cueva Pedro. Slopes steeply northeast for 60 m, bottom muddy; then at slightly higher level trends northwest for 30 m. At bend is small passage trending northeast. No bats or swallows. 167,800 E., 60,130 N. Cibao Formation.

V–8, Nearly vertical cave trending southeast. Not explored. 167,820 E., 60,320 N. Cibao Formation.

Yauco quadrangle:

Y–1, Cuevas de Duey (Convento and Negro). Approximately 110,100 E., 30,700 N.

Y–2, Murcielagos. See Y–3.

Y–3, Prominent trail ends at wall of limestone, probably marking entrance to a cave. The local residents say that this is the location of Cueva Murcielagos, but according to data of Puerto Rico Planning Board, the border of the Municipios of Peñuelas and Guayanilla passes the high point of Cueva Murcielagos. The residents assure me, however, that there is no cave near the border. 117,840 E., 23,590 N. Juana Díaz Formation.

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