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Geology and Hydrogeology of the Caribbean Islands Aquifer System of the Commonwealth of Puerto Rico and the U.S. Virgin Islands

Regional Aquifer-System Analysis

Professional Paper 1419

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Geology and Hydrogeology of the Caribbean Islands Aquifer System of the Commonwealth of Puerto Rico and the U.S. Virgin Islands

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REGIONAL AQUIFER-SYSTEM ANALYSIS—CARIBBEAN ISLANDS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1419

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FORWARD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (ASA) Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and, accordingly, transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information; to analyze and develop an understanding of the system; and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number beginning with Professional Paper 1400.

Charles G. Groat
Director

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CONVERSION FACTORS

Multiply SI unit	By	To obtain inch-pound unit
	Length	
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
centimeter (cm)	2.590	inch (in)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow	
liter per second (L/s)	15.85	gallons per minute (gal/min)
cubic meter per day (m^3/d)	264.2	gallons per day (gal/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
	Specific capacity	
liter per second per meter [(L/s)/m]	4.831	gallon per minute per foot [(gal/min)/ft]
	Transmissivity	
square meter per day (m^2/d)	10.76	square foot per day (ft^2/d)

ABBREVIATIONS

yr BP	years before present
m.y.	millions of years

VERTICAL DATUM

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)— a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929".

REGIONAL AQUIFER-SYSTEM ANALYSIS

GEOLOGY AND HYDROGEOLOGY OF THE CARIBBEAN ISLANDS AQUIFER SYSTEM OF THE COMMONWEALTH OF PUERTO RICO AND THE U.S. VIRGIN ISLANDS

By Robert A. Renken[1], W.C. Ward[2], I.P. Gill[3], Fernando Gómez-Gómez[1], Jesús Rodríguez-Martínez[1], and others

ABSTRACT

Poorly lithified to unconsolidated carbonate and clastic sedimentary rocks of Tertiary (Oligocene to Pliocene) and Quaternary (Pleistocene to Holocene) age compose the South Coast aquifer and the North Coast limestone aquifer system of Puerto Rico; poorly lithified to unlithified carbonate rocks of late Tertiary (early Miocene to Pliocene) age make up the Kingshill aquifer of St. Croix, U.S. Virgin Islands. The South Coast aquifer, North Coast limestone aquifer system, and Kingshill aquifer are the most areally extensive and function as the major sources of ground water in the U.S. Caribbean Islands Regional Aquifer-System Analysis (CI-RASA) study area.

In Puerto Rico's South Coast ground-water province, more than 1,000 meters of clastic and carbonate rocks of Oligocene to Pliocene age infill the South Coast Tertiary Basin. The pattern of lithofacies within this basin appears to have been controlled by changes in base level that were, at times, dominated by tectonic movement (uplift and subsidence), but were also influenced by eustasy. Deposition of the 70-kilometer long and 3- to 8-kilometer wide fan-delta plain that covers much of the South Coast ground-water province occurred largely in response to glacially-induced changes in sea level and climate during the Quaternary period. Tectonic movement played a much less important role during the Quaternary.

The North Coast ground-water province of Puerto Rico is underlain by a homoclinal coastal plain wedge of carbonate and siliciclastic rocks that infill the North Coast Tertiary Basin and thicken to more than 1,700 meters. A thin basal siliciclastic sequence of late Oligocene age is overlain by a thick section of mostly carbonate rocks of Oligocene to middle Miocene age. Globigerinid limestone of late Miocene to Pliocene age crops out and lies in the shallow subsurface areas of northwestern Puerto Rico. Oligocene to middle Miocene age rocks tentatively can be divided into five depositional sequences and associated systems tracts; these rocks record carbonate and minor siliciclastic deposition that occurred in response to changes in relative sea level. The Cibao Formation represents the most complex of these sequences and contains a varied facies of carbonate, mixed carbonate-siliciclastic, and siliciclastic rocks that reflect differential uplift, subsidence, and transgression of the sea.

Uplift, graben formation, and gradual shallowing of the sea are reflected within the bathyal-dominated sedimentary facies of the Kingshill Limestone in St. Croix, U.S. Virgin Islands. Reef-tract limestone beds of Pliocene age were subject to exposure, resubmergence, and meteoric leaching of aragonitic skeletal debris; these beds contain patchy lenses of dolomite that are restricted to a small, structurally-controlled embayment.

The South Coast aquifer, the principal water-bearing unit of Puerto Rico's South Coast ground-water province, consists of boulder- to silt-size detritus formed by large and small coalescing fan deltas of Pleistocene to Holocene age. Deep well data indicates that it is possible to vertically separate and group a highly complex and irregular-bedded detrital sequence that underlies distal parts of the fan-delta plain into discrete water-bearing units if correlated with 30- to 40-meter thick, eustatically-controlled depositional cycles. Lithofacies maps show that greatest hydraulic conductivity within the fan-delta plain is generally associated with proximal fan and midfan areas. Distal and interfan areas are least permeable. Alluvial valley aquifers located in the western part of the South Coast ground-water province are important local sources of water supply and appear to contain some of the same physical and hydraulic characteristics as the South Coast aquifer. Older sedimentary rocks within the basin are poor aquifers; conglomeratic beds are well-cemented, and carbonate beds do not contain well-developed solution features, except locally where the beds are overlain by alluvium. Ground-water occurs under unconfined conditions in proximal and midfan areas. Confined conditions within deeper parts of the system and in interfan and some midfan areas are created largely by the intercalated nature of discontinuous fine-grained beds that retard vertical ground-water movement.

The development of water resources in southern Puerto Rico has modified the hydrologic system of the South Coast aquifer considerably. Under predevelopment conditions, the South Coast aquifer was recharged in the unconfined, proximal fan and some midfan areas by infrequent rainfall and seepage from streams near the fan apex. Discharge occurred as seabed seepage, baseflow discharge along the lower coastal reach of streams, seepage to coastal wetlands, or evapotranspiration in areas underlain by a shallow water table. Under development conditions, seepage from irrigation canals and areal recharge from furrow irrigation represented a principal mechanism for recharge to the aquifer. Increased ground-water withdrawals in the 1960's and 1970's resulted in declines in the water table to below sea level in some places and intrusion of salt water into the aquifer. By the middle 1980's, a reduction in ground-water withdrawals and a shift from furrow irrigation to drip-irrigation techniques resulted in the recovery of water levels. Under present-day (1986) conditions, regional ground-water flow is coastward but with local movement to some well fields. In addition to the discharge mechanisms described above, ground-water discharges also to coastal canals.

The North Coast limestone aquifer system consists of limestone, lesser amounts of dolomite, and minor clastic detritus of Oligocene to Pliocene age

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that form an unconfined upper aquifer and a confined lower aquifer; these aquifers are separated by a clay, mudstone, and marl confining unit. Topographic relief and incision of carbonate coastal plain rocks by streams are the principal factors controlling the direction of ground-water flow. The North Coast limestone aquifer system is recharged principally by precipitation that enters the upper and lower aquifers where they crop out. Regional ground-water movement from the upper aquifer is to the major rivers, wells, coastal wetlands, coastal, nearshore, and offshore springs, or as seabed seepage. Regional discharge from the lower aquifer is to the major rivers along its unconfined parts or where the confining unit has been breached by streams. Discharge from the lower aquifer also occurs in the San Juan area where the Mucarabones Sand provides an avenue for diffuse upward ground-water flow. Transmissivity within the upper limestone aquifer appears to be largely regulated by the thickness of the freshwater lens. The lens is thickest and transmissivity is greatest in interstream areas that lie in a zone that closely corresponds to the landwardmost extent of the underlying saltwater wedge. Hydraulic conductivity of the upper aquifer generally increases in a coastward direction and reflects lithologic control, karstification in the upper 30 to 100 meters of the section, and enhanced permeability in a zone of freshwater and saltwater mixing. Transmissivity of the lower aquifer is an order of magnitude smaller than that of the upper aquifer; highest transmissivities in the lower aquifer largely correspond to a coarse grainstone-packstone and coral-patch-reef depositional facies contained within the outcropping parts of the Montebello Limestone Member and its subsurface equivalents. Porosity within the North Coast limestone aquifer system is high in grainstone-packstones and low in wackestone and marl. Dolomitized zones and moldic grainstone-packstone strata are the most porous carbonate rocks, but occur in thin beds that usually are only a few meters thick. Processes of karstification that include the development of caverous zones and large vugs, and dissolution along possible regional fracture sets has enhanced permeability within the upper part of the aquifer system. Stratigraphic and lithologic control play an important role controlling permeability within the lower part of the system.

The Kingshill aquifer of St. Croix, in large part, is composed of deep-water limestone that contains only microscopic pores and is poorly permeable; however, the upper part of the aquifer, a shallow-water skeletal and reef limestone, is fairly permeable, but restricted in areal extent. Permeability within these uppermost beds of the aquifer has been enhanced by meteoric leaching, dissolution within a mixing zone of saltwater and fresh water, and dolomitization. However, most large-yield wells completed in the Kingshill aquifer are also screened in alluvium that overlies or infills incised channels. The alluvial deposits serve as a temporary storage zone for rainfall, runoff, and ground water slowly entering the Kingshill aquifer.

INTRODUCTION

By Robert A. Renken[1]

Three major aquifers underlie the North Coast and South Coast ground-water provinces of Puerto Rico and the central plain of St. Croix, U.S. Virgin Islands. Together, they combine to form the principal aquifers of the U.S. Caribbean Island aquifer system (Gómez-Gómez, 1987). The Caribbean Island aquifer system is one of twenty-eight major aquifer systems that are located in the United States, its territories, and the Commonwealth of Puerto Rico. Collectively, these 28 aquifer systems contain most of the Nation's ground-water supplies. The U.S. Caribbean Island Regional Aquifer-System (CI-RASA) investigation was studied as part of the U.S. Geological Survey's (USGS) Regional Aquifer-System Analysis (RASA) program (Sun, 1986; Weeks and Sun, 1987), a series of investigations that present an overview and assessment of hydrogeologic, hydrologic, and hydrochemical conditions within regionally extensive aquifer systems. The major objectives of the Caribbean Island aquifer system study are to (1) identify and map the permeability distribution within major aquifers and aquifer systems of Puerto Rico and St. Croix, (2) describe the hydrochemistry of major aquifers, (3) examine the pattern of ground-water flow, and (4) simulate flow patterns by use of digital computer.

Deposits of boulders, gravel, sand, and silt that underlie most of the eastern two-thirds of Puerto Rico's South Coast ground-water province, form one of two of the island's principal aquifers, and supply nearly one-half of all ground-water withdrawn on the island. In the North Coast ground-water province, highly karstified reef and platform carbonate rocks and minor clastic beds form an aquifer system that contains two aquifers separated by a confining unit. The upper limestone aquifer contains water mostly under unconfined conditions. A lower aquifer is more restricted in extent and contains water in middip and downdip areas under artesian conditions; unconfined conditions prevail at outcrop. Alluvial deposits, mostly those associated with stream deposition, are locally important aquifers in the East Coast, West Coast, and Interior ground-water provinces and in Lajas Valley (Valle de Lajas). Shelf and shelf-slope hemipelagic limestone, interbedded turbidites, and shallow water limestone make up the Kingshill aquifer, the principal aquifer in the island of St. Croix. Alluvial-fan, debris flow, and alluvial deposits that overlie the aquifer in some areas function as a temporary storage zone slowly releasing water to the aquifer. Alluvial and alluvial fan deposits are also locally important in Isla de Vieques, St. Thomas, and St. John. Yields to wells completed in volcaniclastic, fractured bedrock and weathered-rock mantle aquifers in Puerto Rico and the U.S. Virgin Islands are small (less than 1 liter per second). The area underlain by these rocks in each of the islands is large and in those areas represent the only source of ground water. Collectively, these rocks constitute about 6 percent of total ground-water withdrawals in Puerto Rico and 75 percent of the total ground water withdrawn in the Virgin Islands (U.S. Geological Survey, 1985).

Understanding the physical framework and facies of an aquifer or aquifer system is useful in predicting hydraulic conductivity. Hydraulic conductivity is a measure of how rapidly water will pass through an aquifer, and is a good indication of the probable yield of wells completed in the aquifer—the higher the hydraulic conductivity, the greater the expected yield. Permeability is another way of measuring the ability of an aquifer to transmit water under a hydraulic gradient. Permeability is equal to the hydraulic conductivity of an aquifer multiplied by the gravitational constant and divided by the dynamic viscosity of the water. Transmissivity is a

[1] U.S. Geological Survey

third way of measuring the capacity of an aquifer to transmit water of the prevailing viscosity. The transmissivity of an aquifer is equal to the horizontal hydraulic conductivity of an aquifer multiplied by the saturated thickness of the aquifer. The hydraulic conductivity, transmissivity, and permeability of an aquifer are directly influenced by the particle size, particle shape, degree of packing, sorting, amount of material that fills pore space, and cementation of the mineral and rock material comprising the aquifer. These factors are, in large part, a reflection of the of the depositional history of the rock. Therefore, the distribution of the hydraulic conductivity of an aquifer might be estimated from a map of the geologic facies, assuming a direct correlation exits between rock type and aquifer permeability. Hydraulic and lithofacies data can also be compared to help understand lateral variations within the geologic sequence. To a degree, lithofacies maps can be used as a predictive tool in the search for overlooked or undeveloped sites that might prove suitable for ground-water resource development.

This report provides a comprehensive description of the hydrogeology and hydrology of the Caribbean Island aquifer system. This report (1) defines the regional and local geology; (2) identifies, delineates, and maps the permeability distribution within clastic and carbonate aquifers; and (3) develops a suitable framework that helps explain major tectonic, depositional, and diagenetic controls on transmissivity and permeability.

PHYSIOGRAPHIC SETTING

Puerto Rico, its satellite islands, and the Virgin Islands are located in the northeastern Caribbean Sea region between latitude 17°30' and 19°00' and between longitude 64°15' and 68°00'. Puerto Rico is the easternmost island of the chain of large islands that forms the Greater Antilles (fig. 1). Puerto Rico is shaped roughly like a rectangle (170 kilometer [km] long and 60 km wide) and forms the western half of the Puerto Rico-Virgin Island platform. The Virgin Islands are the northwesternmost chain of small islands that form the Lesser Antilles. Much of the Lesser Antilles extends eastward and then southward. Together the islands of the Greater and Lesser Antilles geographically separate the Atlantic Ocean and the Caribbean Sea. The Virgin Islands include 80 islands and cays, 48 of which are U.S. territories with the remainder governed by the United Kingdom (U.K.). St. Thomas, the westernmost of the Virgin Islands, lies 70 km east of Puerto Rico's eastern shore. St. Croix, largest of the Virgin Islands (207 square kilometer [km^2]), is located 88 km southeast of Puerto Rico. St. Thomas (83 km^2) and St. John (49 km^2) both lie north of St. Croix and to the east of Puerto Rico.

Puerto Rico, the smaller islands of Vieques, Culebra and Mona, and the Virgin Islands (except St. Croix) are surrounded by an insular shelf in which water depth is less than 200 meters (m). In Puerto Rico, the insular shelf is narrow, varying in width from less than 2 km northwest of the island to greater than 25 km southwest of the island. A precipitous shelf break borders the island on three sides at depths less than 200 m. Vieques, Culebra, and the Virgin Islands lie in the southern half of the broad (40 to 50 km) insular shelf that extends eastward from Puerto Rico for about 140 km to the easternmost island of Anegada. St. Croix, located on the St. Croix ridge, is separated from the Puerto Rico-Virgin Island platform by the Anegada Passage. A narrow shelf surrounds the island of St. Croix.

PUERTO RICO

Puerto Rico's varied topographic relief, a function of the island's complex and varied geology, can be separated into several ground-water provinces. These ground-water provinces include upland (Interior ground-water province), northern (North Coast ground-water province), and southern (South Coast ground-water province) and several minor ground-water provinces (McGuinness, 1948) that conform well with major geologic areas (figs. 2, 3).

The mountains of the Cordillera Central and other highlands that form its eastern extensions, the Sierra de Cayey and Sierra de Luquillo, are underlain mostly by volcaniclastic, volcanic, and some plutonic rocks. These rocks have been uplifted and erosionally dissected to form an asymmetric mountain range in which the southern slopes dip more steeply than the northern slopes. The mountains of the Cordillera Central in the Interior ground-water province rise to more than 1,300 m above sea level and constitute the principal drainage divide. The drainage divide runs east-west, and lies an average of 35 km south of the northern coast and 15 to 25 km north of the southern coast of Puerto Rico. Geologic structure influences both topographic relief and drainage patterns in the central mountains. Drainage patterns in the central mountains and foothills lie parallel to subparallel to northeast and northwest fault and fracture patterns. Fractures or faults underlie many valleys or form notches; some fault-line scarps form prominent mountain and ridge fronts.

Orographic relief of the Cordillera Central greatly influences Puerto Rico's mildly tropical Caribbean climate. A rain shadow in the leeward side of the island intercepts most of the moisture carried by northeast trade winds. Windward northern slopes receive 2,000 to 5,000 millimeter per year [mm/yr] of precipitation as compared to the less than 1,000 mm/yr of precipitation on the leeward southern slopes (Calvesbert, 1970). Precipitation on the southern side of the island is, in places, less than 500 mm/yr.

Coastal plain deposits flank the northern (North Coast ground-water province) and the southern (South Coast ground-water province) sides of the island. The western one-

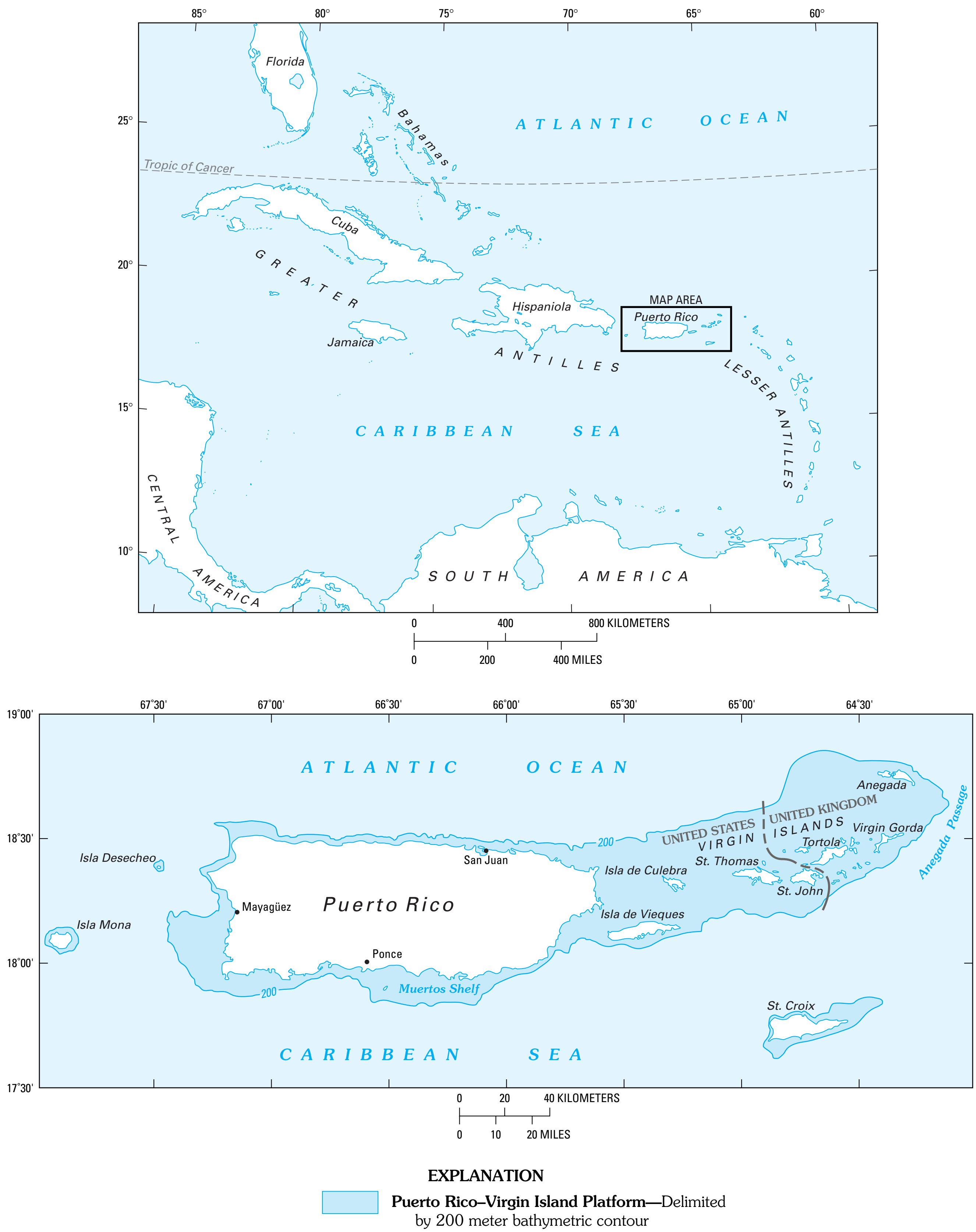


FIGURE 1.—Location of Puerto Rico and the U.S. Virgin Islands.

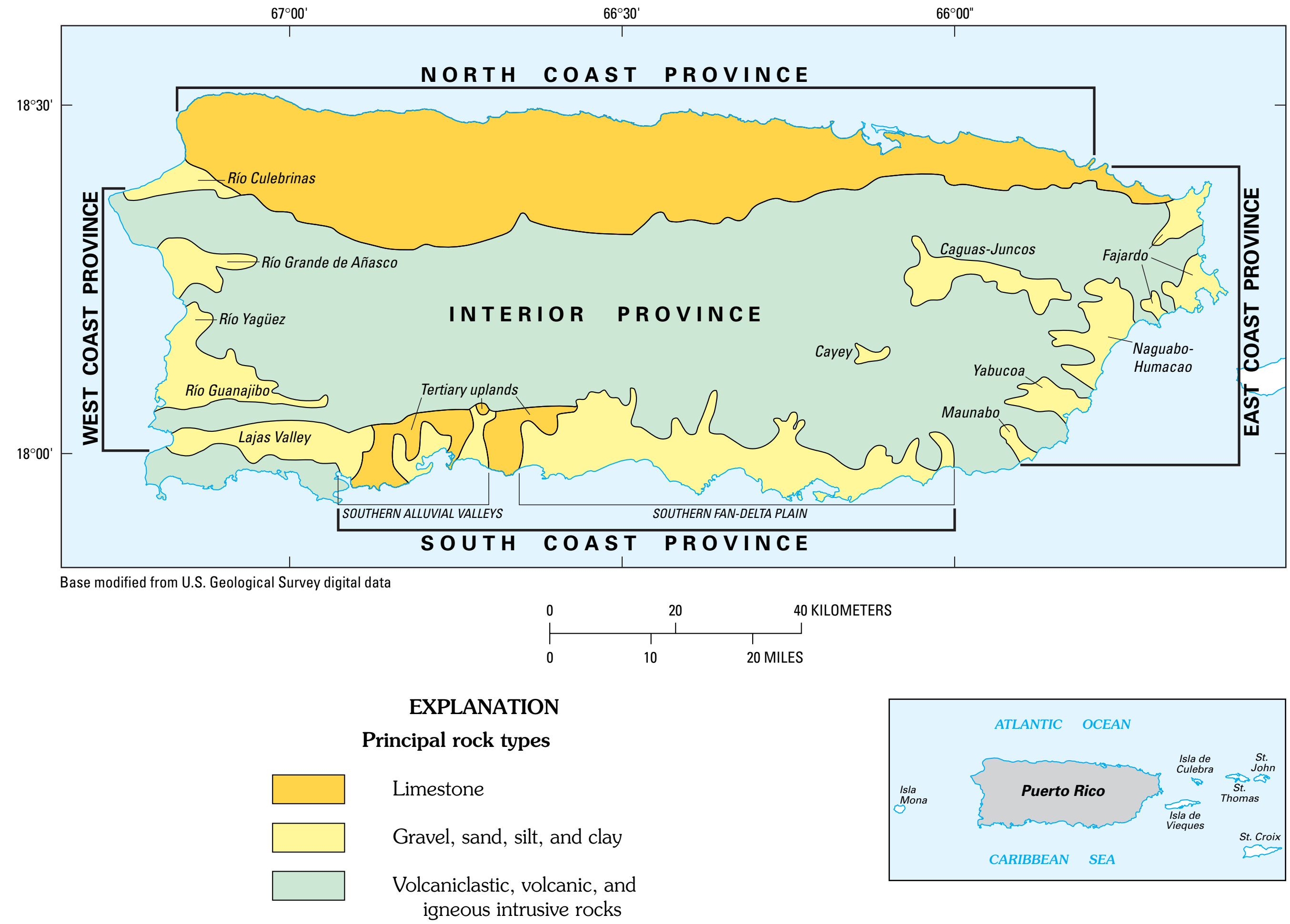
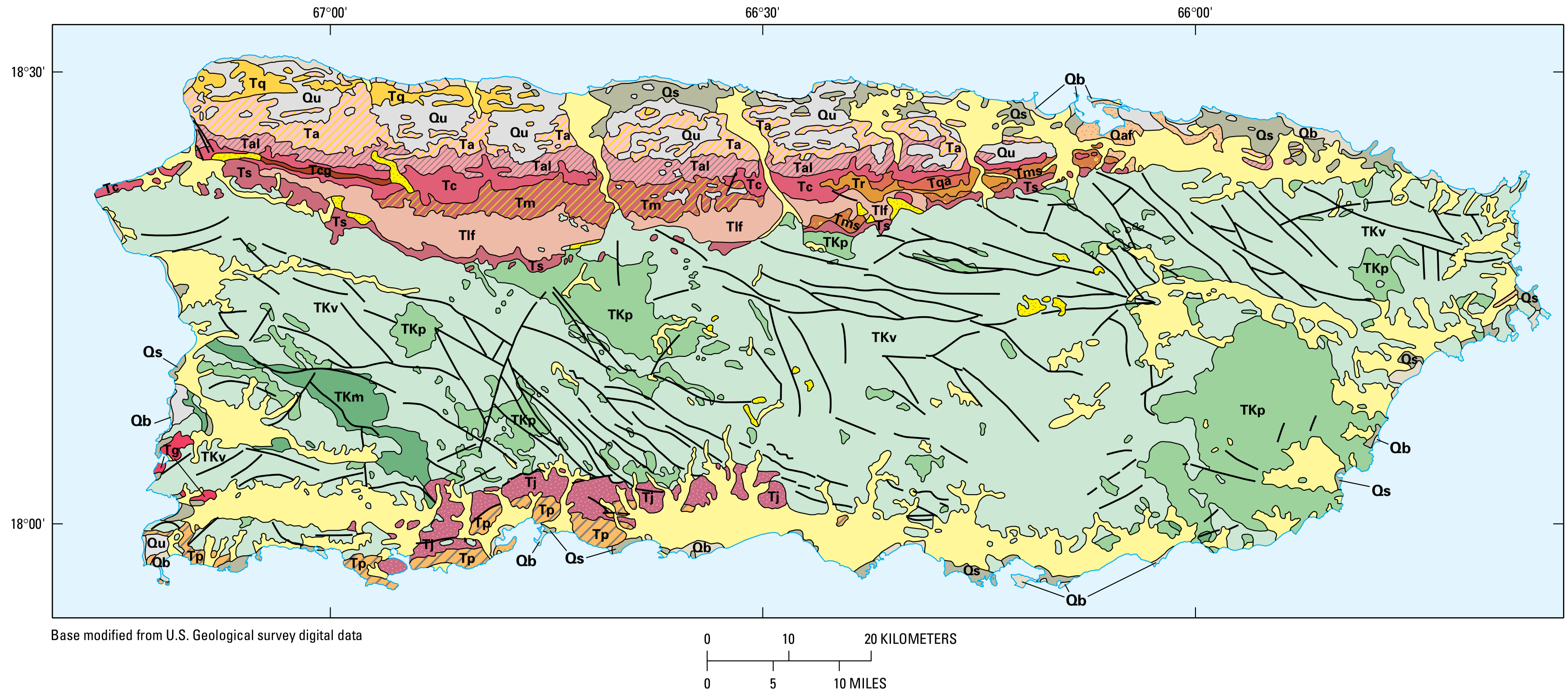


FIGURE 2.—Ground-water provinces of Puerto Rico (modified from McGuinness, 1948).

third of the South Coast ground-water province contains an upland area of low-ridge foothills underlain by carbonate and clastic rocks of late Tertiary age. The eastern two-thirds of the South Coast ground-water province is underlain by fan-delta deposits of Quaternary age that form a low-lying plain. The North Coast ground-water province, characterized by scenic karst topography, is underlain by limestone and minor clastic deposits of Oligocene to Holocene age. A series of discontinuous low-lying alluviated valleys occur along the eastern (East Coast ground-water province) and western (West Coast ground-water province) sides of the island and in the eastern part of the interior (Interior ground-water province). The physiography of Puerto Rico's semiarid South Coast ground-water province is highlighted by a steep-faced mountain front and thin soil cover on the lower mountains and foothill areas. Coastal plain foothills in the western half of the South Coast ground-water province are incised by alluvial-filled stream valleys along the Ríos Tallaboa, Macaná, Guayanilla, Yauco, and Loco. In the Bahía de Guayanilla area, the alluvial valleys of Macaná-Guayanilla-Yauco coalesce to form a low-lying plain that is about 8-km-wide (pl. 2*A*). A fan-delta plain, formed by several large and small fans, extends 70 km eastward from Ponce to Patillas and varies from 3 to 8 km wide (pl. 1*A*). The southern plain slopes gently coastward (1 to 6 meters per kilometers [m/km]) near the coast but at a steeper gradient (4 to 8 m/km) near the apex of the fans. A narrow coastal zone separates the plain from the Caribbean Sea. Bedrock hills, or cerros, protrude the plain in several localities. Mountain streams that enter the southern plain are comparatively straight and have incised deep valleys in the lower mountains and foothills. Recent erosion by the trunk streams where they enter the plain has resulted in different degrees of fanhead incisement.

Trunk streams that traverse the fan-delta plain display a straight to slightly sinuous channel morphology. For example, the stream that drains the Salinas fan, the Río Nigua at Salinas, is relatively straight and extends southwest from the fan apex. A similar channel morphology is present along the Río Coamo that drains the Coamo fan delta. Several of the fans that lie to the west are drained by two streams, which are



EXPLANATION

Quaternary deposits

- Qa — Alluvium
- Ql — Landslide deposits
- Qb — Beach deposits
- Qs — Swamp, marsh deposits
- Qaf — Artificial fill
- Qu — Undifferentiated surficial deposits

Pliocene and Miocene rocks

- Tq — Quebradillas Limestone
- Tp — Ponce Limestone

Miocene rocks

- Ta — Aymamón Limestone
- Tal — Aguada (Los Puertos) Limestone
- Tg — Guanajibo Formation
- Tc — Cibao Formation
- Tm — Montebello Limestone Member
- Tqa — Quebrada Arenas Limestone Member—Includes Miranda Sand Member
- Tr — Río Indio Limestone Member—Includes Almirante Sur Lentil
- Tcg — Guajataca Member

Miocene and Oligocene rocks

- Tms — Mucarabones Sand
- Tj — Juana Díaz Formation
- Tlf — Lares Formation
- Ts — San Sebastián Formation

Eocene, Paleocene, and Cretaceous rocks

- TKv — Volcanic and sedementary rocks
- TKp — Plutonic rocks—Mostly quartz diorite and granodiorite
- TKm — Metamorphic (serpentine), sedementary, and igneous rocks

——— **Fault**

FIGURE 3.—Geology of Puerto Rico (modified from Briggs and Ackers, 1965; Monroe, 1980; and R.D. Krushensky, written commun., 1993).

fairly straight where they enter the fan-delta plain, but develop a sinuous to meandering pattern as they extend coastward. Prior to being channelized for flood control, the confining channels of these western streams became distributaries and were lost in the distal coastal lowland areas allowing water to spread out as sheetflow.

Carbonate rocks of the North Coast ground-water province form the caprock of intensely karstified, northward-dipping cuesta slopes. Northern cueseta slopes conform to the gentle northward dip of beds and have been greatly modified by processes of karstification. Differential erosion of these carbonates has created a belted series of steep, south-facing scarps that range in height from 10 to 400 m and are scalloped or indented by blind valleys. The Lares cuesta scarp (Monroe, 1976, p. 19), the southernmost of the three east-west trending cuesta scarps, is nearly continuous and mappable for 100 km. Karst features are widely- and well-distributed within the North Coast ground-water province and documented in reports by Lehmann (1954), Gurnee (1967, 1972), Thrailkill (1967), Birot and others (1968), Blume (1968, 1970), Moussa (1969), Miotke (1973), Monroe (1976, 1980), Guisti (1978), and Troester and White (1984). Dissolution along a poorly defined fracture system and mass transport have contributed to the wide variety of karst relief features. Positive relief structures of the North Coast ground-water province include cone and tower karst. Negative relief structures include fracture-controlled zanjones, closed sinkhole depressions or dolines, and dry valleys. Cave collapse locally reveals an extensive, subterranean river system. With the exception of the Río Tanamá caves, Río Camuy cave, the Quebrada Infierno cave system, and the Río Encantado cave system (near Florida), however, most Puerto Rican caves have not been surveyed.

East Coast and West Coast ground-water provinces of Puerto Rico (figs. 2, 3) are indented by several alluvial valleys. The low-lying Humacao and Naguabo Valleys of the East Coast ground-water province are drained by several streams whose headwaters lie in the foothills and mountains of the Sierra de Cayey or Sierra de Luquillo. Both valleys are surrounded by steep-faced slopes and separated by a ridge that rises more than 90 m above the valley floor. A third alluvium-filled valley, the Yabucoa Valley, lies south of the Naguabo-Humacao area. Alluvium-filled valleys of the West Coast ground-water province include those drained by the Río Guanajibo, Río Grande de Añasco, Río Culebrinas, Río Yagüez, and Lajas Valley. Surrounded by dissected hills and ridges, the valleys are low-lying and narrow with the alluvial surface of the valley floor rising from the coast to no more than 60 m above sea level. The Lajas Valley (Valle de Lajas) is relatively narrow (1.5 to 9.5 km) and low-lying and extends 29 km in a nearly east-west direction. Foothills surround the valley on the northern and southern sides, rising nearly 300 m above sea level. Alluvium represents the principal aquifer in the Interior ground-water province and is located in the east-central part of the island. Alluvial deposits underlie a 91 km^2 area in this valley.

PUERTO RICO'S OFFSHORE ISLANDS

The principal offshore islands of Puerto Rico include Isla de Vieques and Isla de Culebra that lies to the east, Isla Mona and Isla Desecheo that are to the west. A generalized geologic description follows.

Isla de Vieques

Vieques, largest of Puerto Rico's adjacent islands, is located 14 km east-southeast of Puerto Rico's eastern coast. Vieques is approximately 23 km long, but no more than 5 km wide. The island's central ridge trends east-northeast with the altitude of its summit nearly 300 m above sea level at Monte Pirata (fig. 4). The central ridge is asymmetric, with northern slopes steeper than the south. The island's land surface is hilly, but includes two alluvial valleys, the Esperanza and Resolución alluvial valleys (fig. 4). The island of Vieques is underlain by highly weathered, plutonic rocks (dominated by granodiorite and quartz similar to the San Lorenzo Batholith in eastern Puerto Rico) and marine volcaniclastic rocks of Cretaceous age (Learned and others, 1973; U.S. Department of Defense, 1980). These older rocks are overlain by limestone of late Tertiary age in several localities, most notably along the northern coastline near Desembarcadero Mosquito, Punta Salinas on the eastern peninsula, and in isolated areas between Esperanza and Ensenada Honda on the southern coast. Alluvial deposits, consisting of sand, silt, and clay lie within the narrow (0.5 to 1 km wide by 5 to 6 km long) Esperanza alluvial valley on the south-central coast of Vieques. Alluvial fan deposits fringe the north side of Monte Pirata and coalesce to form Resolución alluvial valley located on the northwestern coast (McGuinness, 1945). Reported thickness of the alluvial section in Esperanza alluvial valley near Ensenada Sombe is 27 m. Geophysical studies in the Resolución alluvial valley area indicate alluvial deposits are less than 30 m (Torres-Gonzaléz, 1989).

Isla de Culebra

The island of Culebra is approximately 27 km east of Puerto Rico and 9 km north of Vieques (fig. 1); the island encompasses an area of 28 km^2. The island rises to a maximum altitude of only 195 m with ridge crests that average from 75 to 175 m in altitude. Culebra is underlain by volcanic, volcaniclastic, and dioritic rocks of Late Cretaceous age (Donnelly, 1959). Some minor alluvial deposits of silt, clay and some sand and gravel are located in major stream valleys near the coast (Jordan and Gilbert, 1976). Bedrock is exposed at land surface in 50 to 70 percent of the island and a

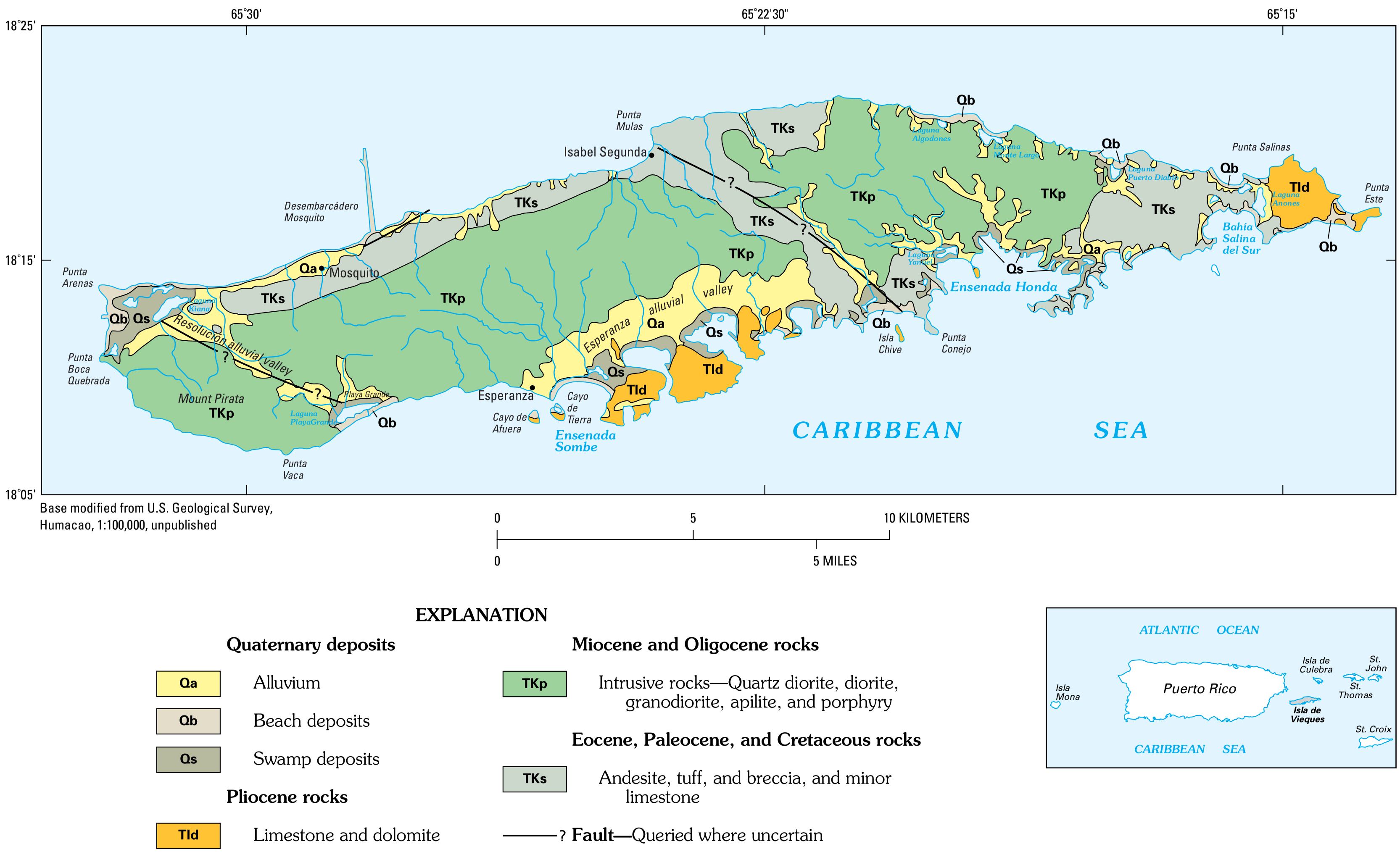


FIGURE 4.—Geology of Isla de Vieques (modified from Briggs and Ackers, 1965; Learned and others, 1973).

thin granulated soil (0.3 to 0.6 m-thick) soil occurs in pockets between rocky areas (Jordan and Gilbert, 1976).

Isla Desecheo

Isla Desecheo is a small island encompassing 1.2 km^2 and located approximately 21 km west of northwestern Puerto Rico and within the northeastern part of the Mona Passage (fig. 1). Ridge crests are only 100 to 200 (m) in height. Isla Desecheo is largely underlain by folded and faulted volcaniclastic sandstone, mudstone and breccia of Eocene age. Marine terrace deposits of calcite-cemented sand and gravel (1 m-thick) are discontinuously exposed along the coast of the island.

Isla Mona

Isla Mona encompasses an area of approximately 55 km^2 and is located in the Mona Passage and lies approximately 72 km due west of Puerto Rico's western coastline, about midway between Puerto Rico and the Dominican Republic. Isla Mona is underlain by carbonate rocks of Miocene age (fig. 1) and characterized by a relatively flat, gently sloping upland surface or tableland bordered by 45 to 85 m-tall, vertical sea cliffs. A narrow coastal lowland of beach and raised, relict reef deposits of Quaternary age are located along the western, southwestern and southeastern margins. The stratigraphic sequence of Isla Mona can be separated into two formational units that include in ascending order, the Isla Mona Dolomite and the Lirio Limestone of Miocene age (Briggs and Seiders, 1972). The thick-bedded, dense, finely crystalline dolomite and two 5 m-thick limestone zones compose the Isla Mona Dolomite. The maximum exposed thickness of the formation is approximately 80 m. The Lirio Limestone is approximately 10 m thick and forms the cap of the island. The Lirio Limestone is composed of thick to very thick bedded, fine-grained limestone; it is well indurated possibly due to surficial solution and recrystallization. Solution development of caves is mostly limited to the Lirio Limestone, with most located along the periphery of the island. Many caves contain flowstone, stalactites, and stalagmites, collapse rock rubble and some phosphorite deposits produced by alteration of bat guano by percolating groundwater. Lirio Limestone caves roofed near the island's upland surface often have openings that lead to the bottom of tableland sinkholes.

U.S. VIRGIN ISLANDS

The 212 km^2 island of St. Croix is the largest of the U.S. Virgin Islands and lies 88 km southeast of Puerto Rico. St. Croix is approximately 34 km long with an average width less than 9.6 km. St. Croix is separated into two physiographic areas: (1) incised and rugged hills and low mountain areas on the northern (Northside Range) and eastern sides (East End Range) of the island and (2) low-lying to gently rolling terrain that forms a central plain (fig. 5). The Northside Range, whose northern slopes steeply dip to the sea, forms the northern spine of the island, rising to more than 300 m above sea level. The East End Range is lower and somewhat less rugged. Summit altitudes do not exceed 244 m and two broad low areas separate the East End Range into the eastern and western parts. A nearly flat to gently rolling land surface typifies the southwestern part of St. Croix's central plain, and is a stark contrast to the hilly and dissected carbonate highland area that characterizes the northeastern part of the central plain. St. Croix's two upland areas, the Northside and East End Ranges, are underlain by consolidated volcanogenic sedimentary strata that include turbidites, mudstones, reworked sandstones, debris flow deposits, minor chert, and Maestrichtian plutons and dikes (fig. 5). These rocks are folded and faulted within an imbricated nappe structure that formed within the south- to southwest-facing Late Cretaceous island-arc accretion complex (Speed and Joyce, 1989). The central plain overlies a southward-facing demi-graben structure that has been infilled with late Tertiary rocks that include foraminiferal-rich clay or mud of Miocene to Oligocene(?) age; shelf and shelf-slope hemipelagic limestone and interbedded turbidite deposits of Miocene age; and shallow-water limestone of Pliocene age. Clayey to gravelly alluvium, alluvial fan, slope wash, and debris flow deposits of Quaternary age blanket these strata along the central plain's northern margin. Incisement by River Gut, Bethelem Gut, and the Salt River during the late Pleistocene lowstand resulted in the overdeepening of stream valleys that traverse the central plain. Stream valleys infilled during the Holocene contain clayey to gravelly alluvium ranging from 10 to 25 m thick.

St. Thomas (83 km^2) is the second largest island of the U.S. Virgin Islands and lies 72 km east of Puerto Rico. St. Thomas is 22.5 km long and 3 to 5 km wide. The spine of the island is formed by a 245- to 366-m-high central ridge that slopes steeply on its northern and southern slopes, and is dissected by streams that flow intermittently. St. John lies immediately east of St. Thomas, and is the smallest of the three principal U.S. Virgin Islands (47 km^2). St. John also is traversed by a east-trending central ridge 200 to 350 m high with steep northern slopes and prominent spur ridges on the southern side of the island and dissected by intermittent streams.

Rock units that underlie the highland ridges of St. Thomas and St. John consist of kerophyric lava, flow breccias and tuffs, spilitic lava, andesitic breccia and tuff, and minor limestone beds, all of Cretaceous age and intruded by Cretaceous and early Tertiary dikes and plugs (fig. 6). These rocks have been uplifted and faulted forming a northward-dipping homocline (Donnelly, 1966). Unconsolidated alluvial and

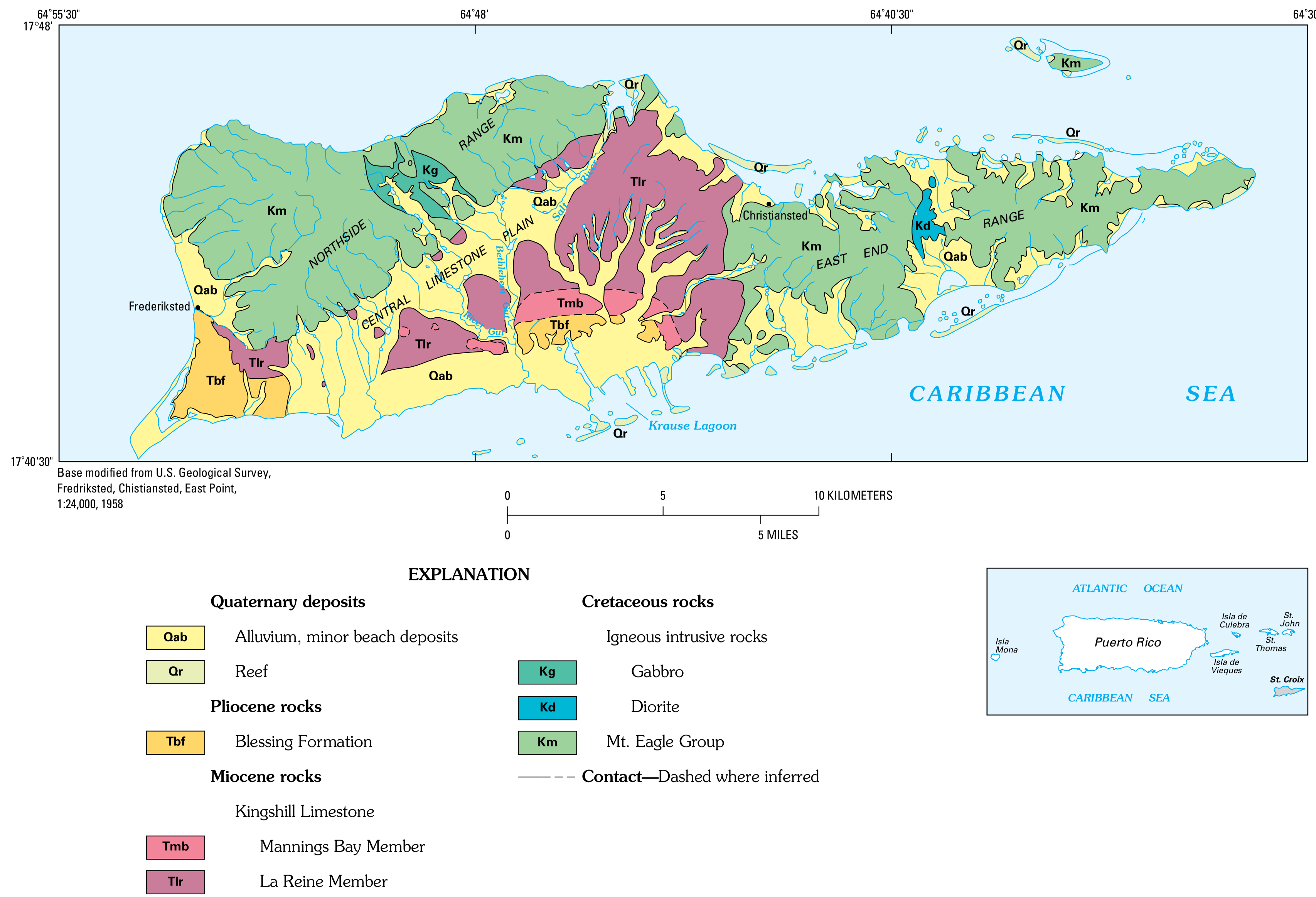


FIGURE 5.—Geology of St. Croix, U.S. Virgin Islands (modified from Whetten, 1966; Gill, 1989).

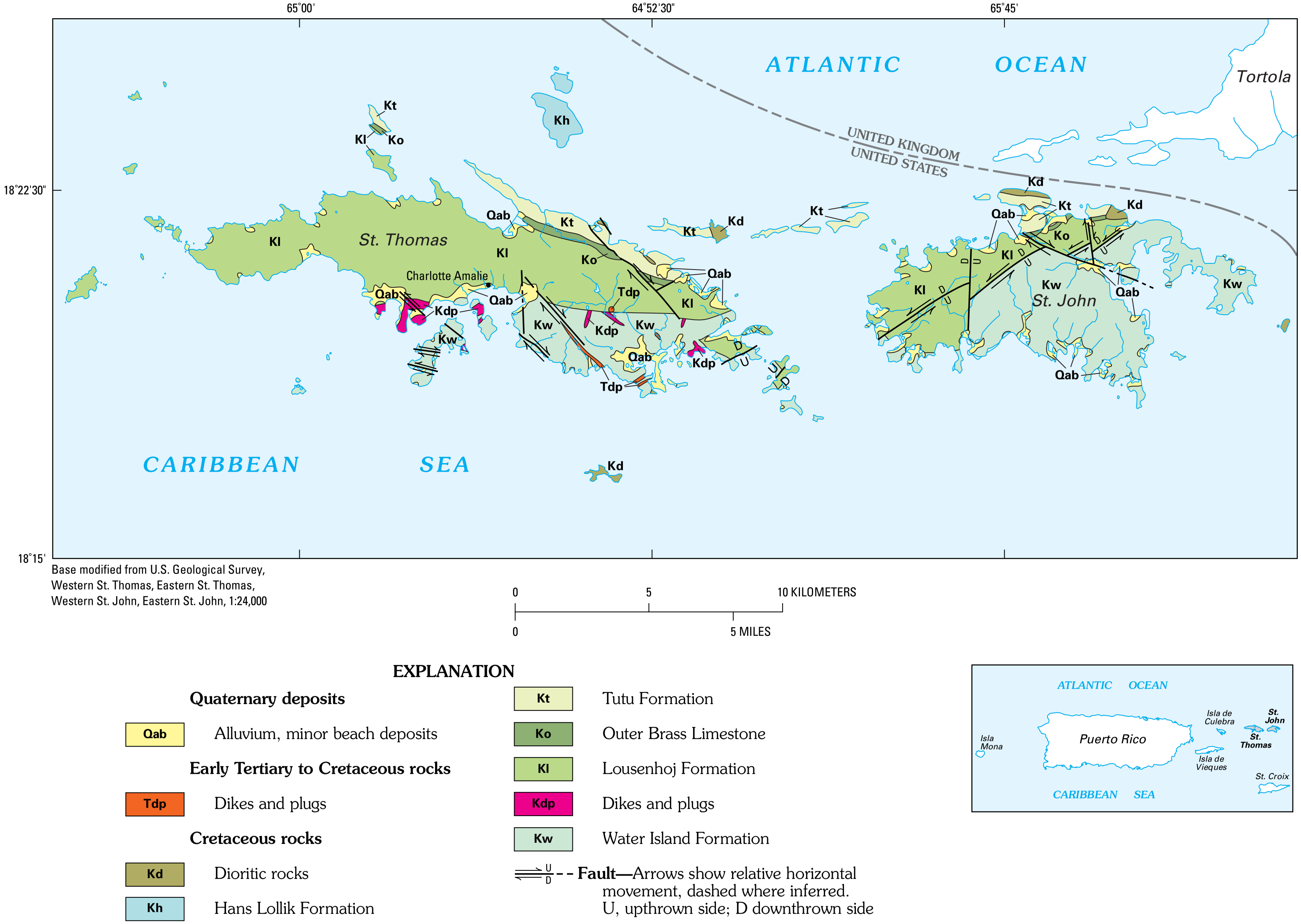


FIGURE 6.—Geology of St. Thomas and St. John, U.S. Virgin Islands (modified from Donnelly, 1966).

coastal deposits occur within several small stream valleys and within shoreline reentrants.

The St. Thomas-St. John homocline is cut by two strike-slip fault sets that strike in northwest and northeast directions. The northeast fault set parallel the orientation of the Anegada trough that lies to the south of these two islands. A third fault set strikes in a north-south direction. The striking parallelism of major stream valleys and their drainage systems with well-defined joint sets and major faults is strongly suggestive of structurally-controlled selective erosion and weathering of the bedrock (Jordan and Cosner, 1973).

PREVIOUS INVESTIGATIONS

PUERTO RICO

Some of the earliest geologic investigations in Puerto Rico were conducted by the New York Academy of Sciences; the findings of the Academy were published in a series of reports between 1919 and 1933 (Berkey, 1915, 1919; Semmes, 1919; Hodge, 1920; Mitchell, 1922; Hubbard, 1923; Fettke, 1924; and Meyerhoff, 1931, 1933). In the 1950's, the USGS initiated a mapping program of Puerto Rico and has subsequently published fifty-one 1:20,000 scale geologic quadrangle maps (1960-84) showing outcropping rock units and geologic structure. A geologic map of Puerto Rico, its offshore islands, and the Virgin Islands was published by Briggs and Ackers (1965). An updated geologic map of Puerto Rico is in preparation (R.D. Krushensky, oral commun., 1993).

Reports that describe the geology of Puerto Rico's South Coast ground-water province include Pessagno (1960, 1963), McClymonds and Ward (1966), Moussa and Seiglie (1970, 1975), Glover (1971), Monroe (1973, 1980), Krushensky and Monroe (1975, 1978, 1979), Frost and others (1983), and Erikson and others (1990). Geologic investigations of Puerto Rico's North Coast ground-water province are published in reports by Berkey (1915, 1919), Hubbard (1923), Zapp and others (1948), Bermúdez and Seiglie (1969), Monroe (1973, 1980), Seiglie and Moussa (1974, 1975, 1984), Moussa and Seiglie (1975), Meyerhoff and others (1983), and Moussa and others (1987). The geology of the East Coast, West Coast, and Interior ground-water provinces has been documented in U.S. Geological Survey geologic quadrangle maps (1960-84) and in reports by Mattson (1960, 1973). The thickness and character of alluvial deposits found in the East Coast ground-water province is described by Robison and Anders (1973), Adolphson and others (1977), and Graves (1989). The physical character of alluvial deposits in the West Coast ground-water province and Lajas Valley include work by Anderson (1977), Colón-Dieppa and Quiñones-Marquéz (1985), Díaz and Jordan (1987), and Graves (1991). Puig and Rodríguez (1993) provide data regarding the thickness of alluvial deposits in the Interior ground-water province's Caguas-Juncos Valley.

Many of the early reports (1946-76) as well as subsequent reports (1976-94) that describe the hydrogeology and hydrology of Puerto Rico's North and South Coast ground-water provinces focus principally on hydrologic conditions within local areas and did not examine conditions within the entire ground-water province. Bennett's (1976) analog model study of the South Coast ground-water province is a notable exception and the first to study an entire hydrogeologic province. Guisti and Bennett (1976), Guisti (1978), and Heisel and others (1983) followed with regional hydrogeologic and hydrologic studies of the North Coast ground-water province. Ward and others (1990), Rodríguez-Martinez (1990), Renken and Goméz-Goméz (1994), and Torres-González and others (1996) have updated the knowledge of the geology, hydrogeology, and hydrology of the north coast and information presented earlier is expanded herein. Goméz-Goméz and Heisel (1980) provide a summary appraisal of the entire U.S. Caribbean region.

Reports that describe the local hydrology and hydrogeology of the South Coast ground-water province include: McClymonds and Ward (1966), McClymonds (1967, 1972), Crooks and others (1968), Guisti (1971), Grossman and others (1972), McClymonds and Díaz (1972a, b), Heisel and Gonzáles (1979), Quiñones-Aponte (1986b, 1990), Dacosta and Gómez-Gómez (1987), Quiñones-Aponte and Gómez-Gómez (1987), Román-Mas and Ramos-Ginés (1987), Torres-Gonzáles and Gómez-Gómez (1987), Gómez-Gómez (1990), Renken, Díaz, and others (1990), Renken, Gómez-Gómez, and others (1990), Rodríguez-del-Río and Quiñones-Aponte (1990), and Quiñones-Aponte and others (1996).

Reports that address local hydrology and hydro-geology within the North Coast ground-water province include Jordan (1970, 1977), Bennett and Guisti (1972), Anderson (1976), Gómez-Gómez (1984), Torres-González and Díaz (1984), Zack and Class-Cacho (1984), Torres-González (1985), Quiñones-Aponte (1986a), Gómez-Gómez and Torres-Sierra (1988), Quiñones-Aponte and others (1989) and Torres-González and others (1996).

PUERTO RICO'S OFFSHORE ISLANDS

Few geologic reports of the island of Vieques have been published since Meyerhoff's (1927) work. A map showing the geology of Isla de Vieques was first published as part of the Briggs and Ackers (1965) map of Puerto Rico and adjacent islands. An updated map completed by Grove was published in a geochemical reconnaissance study of the island by Learned and others (1973). Hydrologic reports include those by McGuinnes (1945) and Torres-González (1989).

The geology of Isla de Culebra is described in a report by Donnelly (1959) and as part of the Briggs and Ackers (1965) map of Puerto Rico and adjacent islands. Some modifications to Donnelly's work are presented in a report by the members of the Culebra Study Group (Puerto Rico Environmental Quality Board, 1971). The hydrology of the island is described by Jordan and Gilbert (1976).

The geology of the island of Mona is described in reports by Kaye (1959), Briggs and Seiders (1972), and Aaron (1973). Isla Mona hydrology is presented in a report by Jordan (1973).

A geologic description of Isla Desecheo is presented by Seiders, Briggs, and Glover (1972). There are no hydrologic reports available for Isla Desecheo.

U.S. VIRGIN ISLANDS

Early work on the geology of St. Croix dates to the early 1800's; examples include Maclure (1817) and Hovey (1839), both of which are summarized in Cederstrom (1950). Geologic work continued into the early 20th century with contributions by Vaughan (1916,1923) and Kemp (1926) who suggested names and ages for the sedimentary units, as well as a bio-geographical relation between Puerto Rico and St. Croix. Cederstrom's (1950) report contains substantial information on the subsurface geology and ground-water conditions resulting from a federally sponsored drilling program. Test wells drilled for this program in 1938 and 1939 are the deepest on record in St. Croix, and much of our knowledge of the subsurface of St. Croix comes from this information (Cederstrom, 1950).

The first modern interpretation of the structure and sedimentology of Cretaceous age rocks on St. Croix is described by Whetten (1961, 1966). More recent interpretations of the Kingshill-Jealousy Basin were published by Frost and Bakos (1977), Multer and others (1977), Gerhard and others (1978), Lidz (1982), Gill and Hubbard (1986, 1987), Gill (1989), and Gill and others (1989).

The biostratigraphy of the Tertiary age carbonate rocks on St. Croix is presented in reports by Cushman (1946), Bold (1970), Lidz (1982, 1984), Andreieff and others (1986), and Gill (1989). Reports that deal specifically with ground-water conditions and the hydrogeology of St. Croix include Cederstrom (1950), Hendrickson (1963), Jordan (1975), Robison (1972), Black and others (1976), Geraghty and Miller (1983), Gill and Hubbard (1986,1987), Torres-González and Rodriguéz del Río (1990) and Torres-González (1990).

The geology of St. Thomas and St. John is described in a paper by Donnelly (1966). Hydrologic investigations include those by Cosner (1972) and Jordan and Cosner (1973). Graves and González (1988) constructed a map showing the September 1987 potentiometric surface of the bedrock and local alluvial deposits that make up the aquifer in eastern St. Thomas.

METHOD OF INVESTIGATION

A regional hydrogeologic system, or aquifer system, can be categorized as one of two types. The first type of regional aquifer system is one that contains a body of water-bearing strata having a wide areal distribution, an extensive set of aquifers and confining units, and acts hydrologically as a single regional system. The second type of aquifer system is one comprising independent aquifers that can be hydrologically characterized such that common principles can be established and serve as a prototype to similar hydrologic terrains (Bennett, 1979). The Caribbean Islands aquifer RASA investigation is considered to be this second type of regional system. Hydrologic features and hydrogeologic conditions presented herein could parallel other Caribbean islands or tropical island regimes elsewhere.

The tectonic and lithostratigraphic nature of sedimentary basins are studied by exploration and development geologists in an effort to assess the mineral-resource potential of a particular area. Maps and cross sections showing plate reconstructions, regional geology, facies, stratigraphy, and paleogeography all help to identify areas underlain by sedimentary strata in which geologic conditions and past depositional processes could prove favorable to the occurrence of a specific mineral resource. Sedimentary basin analysis is a useful investigative technique in that it helps identify the important geologic processes, outlines factors that control the occurrence of a mineral resource, and provides information and knowledge that can be transferrable and applicable to the study of other sedimentary basins (and aquifers or aquifer systems). This report applies basin analysis techniques to a regional hydrologic evaluation of U.S. Caribbean Island aquifers and aquifer systems. Depositional, tectonic, paleoclimatic, eustatic, and diagenetic factors are important geologic processes critical to understanding the distribution, character, and evolution of permeability and porosity within aquifers and aquifer systems of the U.S. Caribbean Islands. A hydrogeologic framework for U.S. Caribbean Island aquifers and aquifer systems is defined herein by use of cross sections, structure contour, isopach, and lithofacies maps that illustrate the spatial distribution, and physical attributes of the individual aquifers and confining units that serve as conduits or that impede the movement of ground water within the regional flow system. Geologic maps in this report are compared with transmissivity and hydraulic conductivity maps to examine and evaluate the geologic processes that influence permeability and transmissivity. The hydrologic and hydrogeologic factors are considered within the context of a regional geologic framework of the northeastern Caribbean.

The hydrogeologic framework described in this report was defined using lithologic, paleontologic, geophysical, and hydrologic data obtained from the files of the U.S. Geological Survey, published reports, and from unpublished data of non-

Survey workers. Although borehole geophysical data were collected during the course of the investigation, most records require further analysis, particularly in terms of identifying mappable marker horizons. Driller's and lithologic sample logs, in combination with hydrologic data, were used to map the attitude of beds, their thickness, and to assess their physical and hydraulic character. The majority of these records are contained within U.S. Geological Survey files.

The geologic and hydrogeologic framework of Puerto Rico's North Coast ground-water province is based largely on core data collected from 17 deep test wells drilled to depths that exceed 750 m. These deep test wells were drilled as part of a cooperative Commonwealth of Puerto Rico-U.S. Geological Survey investigation to evaluate the resource potential and to map the extent of an artesian limestone aquifer of northern Puerto Rico. Cores were collected using a reverse-air dual-tube drilling method that continuously collects core of 7.5-cm diameter. Limestone core samples considered representative of a certain bed, or sequence of beds, were selected, slabbed and thin sectioned for study at the University of New Orleans. Analysis included study of carbonate rock texture, porosity, fossil content, bedding, and identification of other possible depositional and diagenetic features. Detailed geologic and hydrologic descriptions of the cored test holes are presented in Hartley (1989), Scharlach (1990), Rodríguez-Martínez, Hartley and others (1991), Rodríguez-Martínez, Scharlach and others (1991,1992), Rodríguez-Martínez and Hartley (1994), and Rodríguez-Martínez and Scharlach (1994).

As part of the CI-RASA investigation, five deep exploration test wells were drilled and continuously cored in separate localities of the southern fan-delta plain. For the most part, detailed study was limited to the clastic part of the sequence. Core studies of the clastic sequence included study of grain size, bed thickness, and other depositional features. Lithologic core data were supplemented with auger cuttings and split-spoon samples collected from several shallow wells drilled during the tenure of the investigation. Driller's log data and other well data from more than 500 wells were used to map the thickness of alluvial deposits, map the configuration of the underlying bedrock surface and determine the percent of coarse-grained clastic detritus contained within the stratigraphic section.

In St. Croix, fourteen test holes were drilled as part of a subsurface exploration study and information derived from these wells was first outlined in Gill and Hubbard (1986, 1987), Gill (1989), and Gill and others (1989). Cross sections, structure, and isopach maps presented herein were constructed using information derived from the field studies as well as data presented by earlier workers. Split-spoon samples and cores from these test wells were supplemented with other cutting samples and lithologic descriptions from other test holes and water wells. Split-spoon and core samples were analyzed by thin section analysis, X-ray diffraction, and micropaleontological identification. Mud-rich, split-spoon samples collected below the water table were usually unlithified, and contained nearly pristine tests of benthic and planktonic foraminifera. During the later phase of the RASA project, more than 20 wells were drilled in St. Croix using the dual-tube method described previously, and the data collected provided some additional insight regarding the thickness or attitude of various geologic units, particularly the thickness of alluvium filling some of the incised paleochannels.

GEOLOGY OF THE SOUTH COAST GROUND-WATER PROVINCE OF PUERTO RICO

By Robert A. Renken[1]

Puerto Rico's South Coast ground-water province encompasses 596 km^2 between Guánica and Patillas and flanks much of the southern side of the island. The South Coast ground-water province can be physiographically separated into two distinct areas: a western area that extends eastward from Guánica to Ponce characterized by low coastal plain ridges and foothills and underlain by carbonate and clastic strata of the Juana Díaz Formation and Ponce Limestone; and an eastern area that is characterized by a low-lying, narrow fan-delta plain underlain throughout most of its 70 km extent from Ponce to Patillas by gravel, sand, and silt of Quaternary age.

Most of the South Coast ground-water province is underlain by the South Coast Tertiary Basin, a structural and depositional basin that extends from Bahía Montalva (west of Guánica) to Bahía de Rincon (Meyerhoff and others, 1983) (fig. 7). The South Coast Tertiary Basin contains a coastal plain wedge that thickens seaward and is infilled with onlapping shelf and reef tract limestone and minor clastic rocks that range from Oligocene to Miocene age (pls. 1*A*, 2*A*). Outliers of these late Tertiary rocks occur as far west as Cabo Rojo (Volckmann, 1984a) and to the east at Cerro Central Aguirre (Glover, 1971). Oligocene to Miocene age strata are exposed nearly continuously from Bahía de Montalva to Juana Díaz. Equivalent rocks extend southward beneath the Isla Caja de Muertos shelf (Trumbull and Garrison, 1973) and southeastward where they underlie unconsolidated Quaternary sediments that make up the fan-delta plain (Glover, 1971, p. 75). The structural dip of Oligocene and Miocene strata is southward at less than 30°, except where normal fault movement has locally reversed structural dip to the north (Krushensky and Monroe, 1978).

[1] U.S. Geological Survey

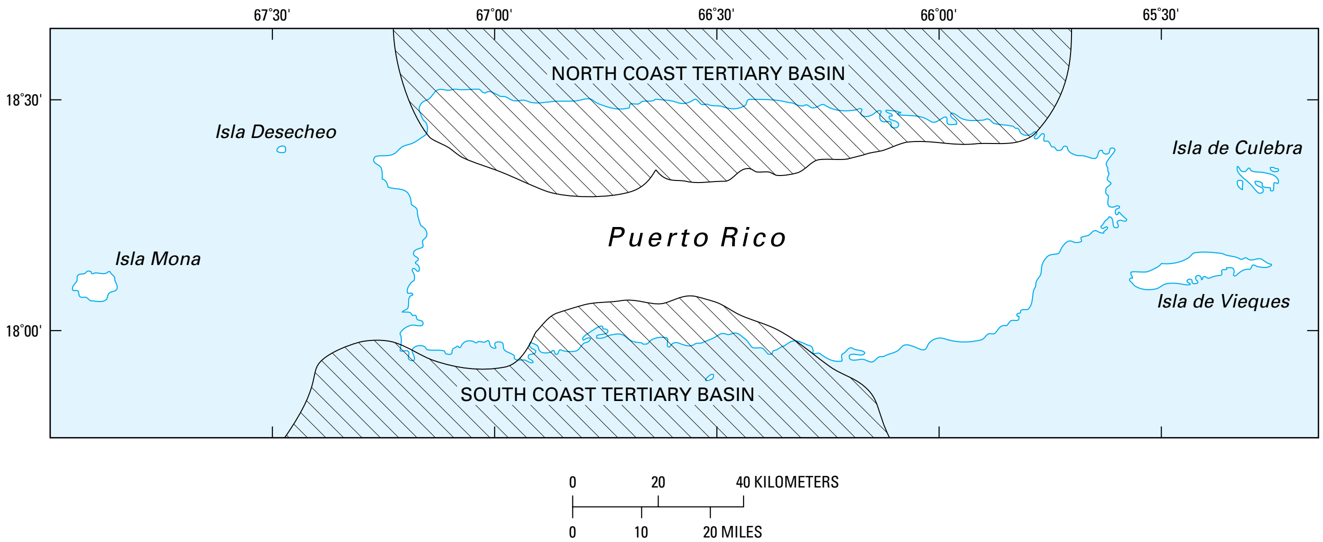


FIGURE 7.—Location of Tertiary sedimentary basins of Puerto Rico (modified from Meyerhoff and others, 1983).

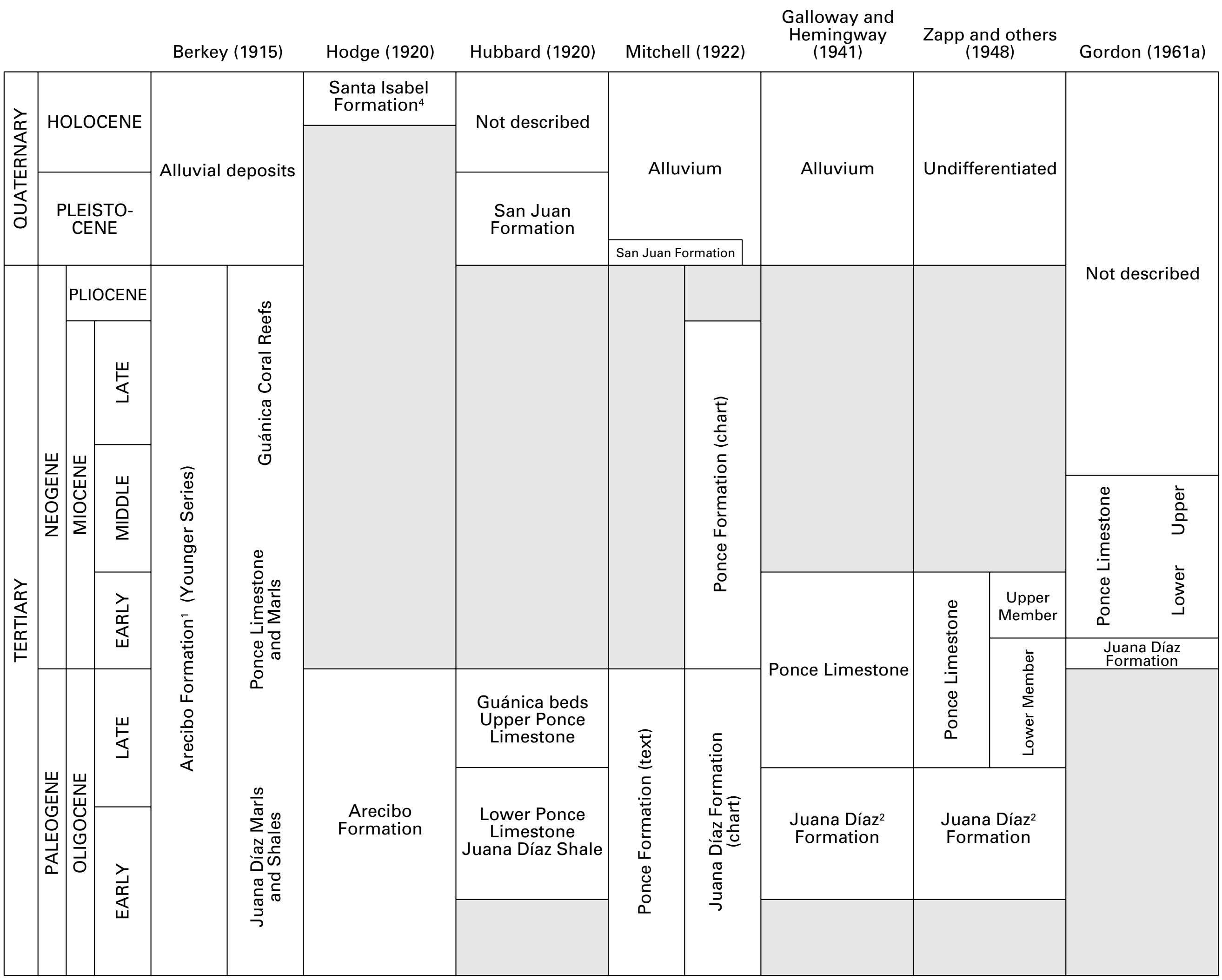
Early workers have variously characterized Quaternary age deposits of southern Puerto Rico between Ponce and Patillas as low alluvial flats (Lobeck, 1922), an alluvial coastal plain (Hodge, 1920), alluvial fans (Lobeck, 1922; Berryhill, 1960; McClymonds and Ward, 1966), alluvial lowlands or alluvial plain (Zapp and others, 1948), and Piedmont alluvial plain formed by coalescing alluvial fans (Glover, 1971, p. 77). Friedman and Saunders (1978, p. 302) characterize clastic deposits of southern Puerto Rico as "modern fans of the sea shore." In a global analysis of the tectonic and geologic settings of Holocene fan deltas, Wescott and Ethridge (1980, p. 379) were the first workers to classify Puerto Rico's fans as fan deltas; they catalogued Puerto Rico's fans as gravel-fan types that occur within island-arc collision zones. Although Wescott and Ethridge (1980) describe them as examples, they did not provide detail regarding their physical character or geologic history, nor did they conduct any field investigations (F.G. Ethridge, oral commun., 1989).

In the western part of the South Coast ground-water province, foothill and ridges are dissected by five large stream valleys of the Ríos Tallaboa, Macaná, Guayanilla, Yauco, and Loco (Gúanica valley). Each valley is underlain by moderately thick deposits of alluvium. The Ríos Macaná, Guayanilla, and Yauco flow across an 8-km-wide alluvial plain before entering the Caribbean Sea at Bahía de Guayanilla. The surface of the alluvial plain rises 10 m above sea level at its landward coastal alluvial plain edge and to an altitude of 40 m where it extends inland within the different alluvial valleys. In places, low-lying swamps and beaches separate the coastal alluvial plain from the Caribbean Sea. The fanlike morphology and the narrow coastal zone of beaches and swamps associated with the Ríos Macaná and Tallaboa valleys are geomorphically similar but less extensive than the fan-delta plain east of Ponce.

STRATIGRAPHY

Unconsolidated to lithified, clastic, and carbonate deposits of Tertiary and Quaternary age make up the principal stratigraphic units of hydrologic interest within the South Coast ground-water province. In ascending order, they are the Juana Díaz Formation (Oligocene age), Ponce Limestone (middle Miocene to Pliocene(?) age), and unnamed gravel, sand, and silt deposits of Pleistocene to Holocene age.

Stratigraphic boundaries within the Oligocene to Pliocene(?) sequence have been revised a number of times since Berkey (1915) (fig. 8) separated the Tertiary sequence into a lower clastic unit and an upper limestone unit. Later revisions to the stratigraphic sequence were made in light of subsequent studies of macrofaunal assemblages, recognition of mappable lithofacies, identification of unconformities, correlation of planktonic foraminiferal assemblages, and revisions in the age range of these foraminifera assemblages. Citing paleontologic evidence, Seiglie and Bermúdez (1969) proposed that the top of the Juana Díaz Formation be shifted upward to include limestone strata that were previously defined by Zapp and others (1948) as the lower member of the Ponce Limestone. Moussa and Seiglie (1970) later recognized five planktonic foraminiferal zones within the pre-Ponce Limestone sequence and correlated them with worldwide assemblage zones. In addition, Seiglie and Bermúdez (1969) and Moussa and Seiglie (1970, 1975) identified a minor sequence of pelagic limestone beds of early Miocene age that were exposed in several quarries between the Río Tallaboa and Ponce; noting the occurrence of overlying and



[1] Berkey (1915) suggested the Arecibo Formation may be, in part, Eocene in age

[2] Considered by Galloway and Hermingway (1914) and Zapp and others (1948) to be Middle Oligocene in age

[3] Todd and Low (1976) suggested possibility of Miocene age Juana Díaz Formation rocks in deep test holes 2 CPR and 3 CPR

[4] Hodges (1920) also described Santa Isabel Formation as a series

FIGURE 8.—Correlation chart showing stratigraphic terminology in Puerto Rico's South Coast ground-water province.

underlying unconformities, they referenced these rocks separately as the Angola limestone beds, Río Tallaboa marlstone beds, and Quarry No. 2 sandstone beds. Some of their work served as the basis for Monroe's (1980) stratigraphic revision of the Tertiary section that is currently applied by the U.S. Geological Survey. Monroe, however, included the Angola limestone, Río Tallaboa marlstone, and Quarry No. 2 sandstone beds as part of the Juana Díaz Formation, in part, due to the limited occurrence and exposure of these beds and the difficulty in reliably tracing them from outcrop (Monroe, 1980, p. 66). Presumably, the early Miocene pelagic rocks were part of a sequence that was largely removed by erosion prior to deposition of the Ponce Limestone.

As a result of a detailed investigation of coral faunal communities contained within the Oligocene and early Miocene section of southern Puerto Rico, Frost and others (1983) refined correlation of shallow- and deep-water lithofacies within the Juana Díaz Formation beyond that proposed by Moussa and Seiglie (1970); they suggested that the name, Juana Díaz Formation, be further restricted and that its usage be limited to the dominately clastic part of the section. Although no names were suggested, Frost and others (1983) proposed that it would be more appropriate to apply separate and "new" formation names to (a) reef/shelf tract and some minor slope carbonate facies now considered part of the Juana Díaz Formation and (b) the pelagic slope Angola limestone-Río Tallaboa chalk facies.

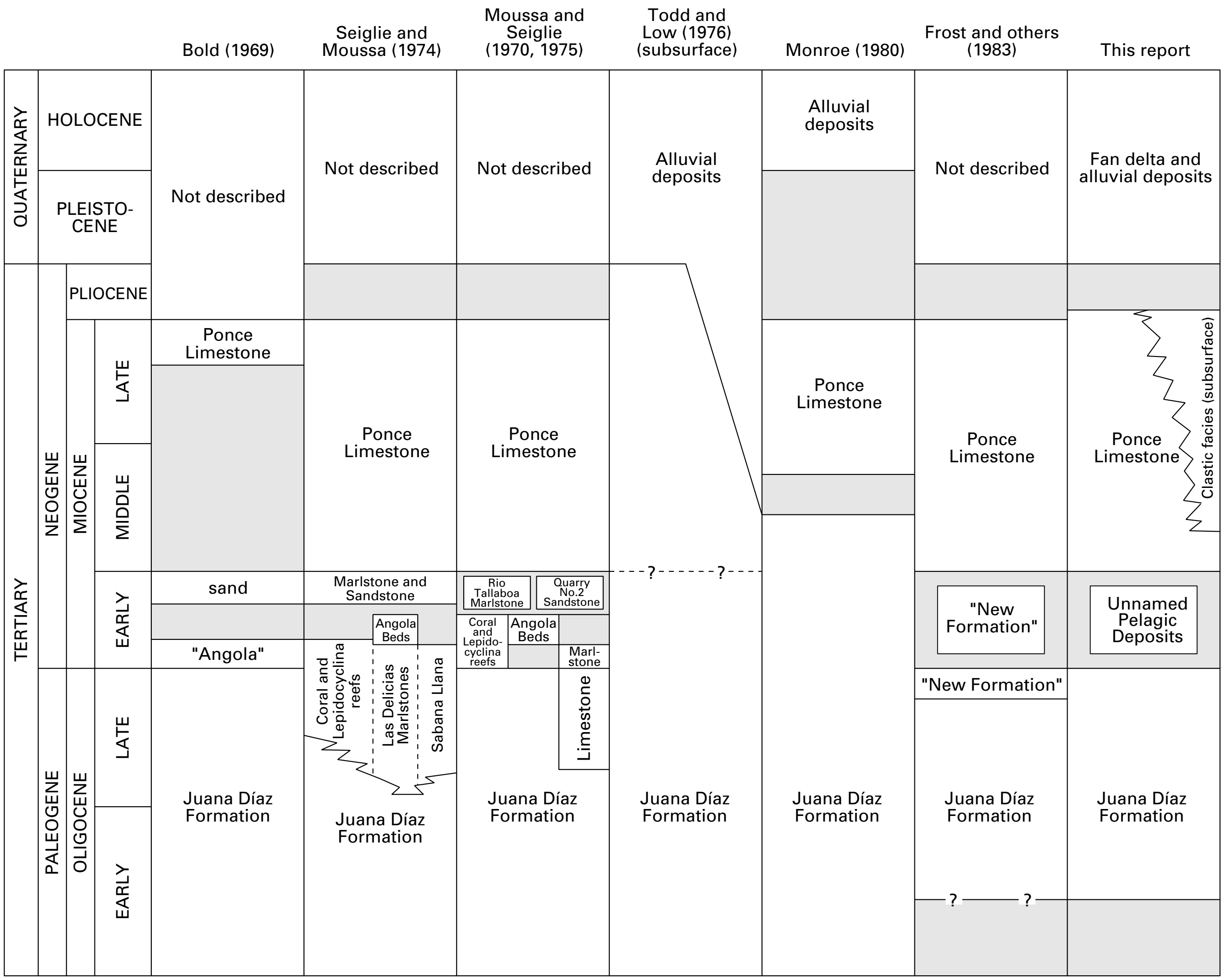


FIGURE 8.—Continued. Correlation chart showing stratigraphic terminology in Puerto Rico's South Coast ground-water province.

Glover (1971, p. 75), Todd and Low (1976, p. 2), and Meyerhoff and others (1983) tentatively extended formational contacts of the Juana Díaz Formation and Ponce Limestone to buried strata that underlie the fan-delta plain. Sparse well control and limited paleontologic data have impeded further division of the subsurface stratigraphic section.

Unconsolidated to poorly lithified boulder- to silt-size detritus of Pleistocene to Holocene age that forms the fan-delta plain east of Ponce, or infills incised valleys that lie to their north, or west, is not formally named (pls. 1*A*, 2*A*). Hodge (1920) referred these and other alluvial deposits, including alluvium of the upland Cayey valley, to his Santa Isabel Formation. The Santa Isabel terminology was never widely applied, however, even among Hodges' colleagues (Mitchell, 1922).

Current USGS usage separates the late Tertiary sequence into a lower clastic-carbonate unit of Oligocene to middle Miocene age (Juana Díaz Formation) and overlying limestone unit of Miocene age (Ponce Limestone). For purposes of this report, this author separates the Oligocene-Holocene sequence into (1) the lower clastic-carbonate Juana Díaz Formation of Oligocene age; (2) an unnamed pelagic carbonate rock sequence of early Miocene age equivalent to the Angola limestone, Río Tallaboa marlstone, and Quarry No. 2 sandstone beds of Seiglie and Bermúdez (1969) and Moussa and Seiglie (1970, 1975), and the upper "new" formation of Frost and others, (1983); (3) the Ponce limestone (carbonate and clastic facies) of middle Miocene to early Pliocene age; and (4) fan delta and alluvial deposits of Quaternary age (fig. 8). The geologic ages assigned to the Tertiary sequence are based strictly on foraminiferal assemblage zones reported by Moussa and Seiglie (1970, 1975); however, the age of these zones has been refined by Haq and others (1988) and is the zonation used in this report.

JUANA DÍAZ FORMATION

Except where covered by alluvium in major river valleys, the Juana Díaz Formation is exposed almost continuously from Bahía de Guánica to the city of Ponce. Large outliers of the Juana Díaz Formation crop out northeast and east of Ponce. Small outliers occur at Cerro de los Muertos near Santa Isabel and have been reported at Cerro Central Aguirre near Salinas (Berryhill, 1960) (pl. 1*A*).

The basal part of the Juana Díaz Formation consists of a basal clastic mudstone or facies equivalents that consist of clastic conglomerate of boulders, cobble, sand, and mudstone of possible alluvial fan or fan-delta origin (fig. 9). Deposition of the Juana Díaz Formation's conglomeratic beds probably occurred in response to uplift and increased erosion in highland areas during a comparatively low base level. Northeast and east of Ponce, basal Juana Díaz beds exhibit horizontal to parallel stratification and some beds are reported to locally contain silicified wood and fossil leaves. Some mudstone beds are burrowed and contain interbeds of sandstone and claystone that have marine fauna. Reef faunal assemblages occur throughout the finer clastic facies of the Juana Díaz Formation (Frost and others, 1983, p. 13). An angular unconformity separates the lower part of the Juana Díaz Formation from older, underlying Cretaceous and Eocene bedrock units and records pre-late Oligocene emergence and erosion in southern Puerto Rico. North of Ponce, basal conglomeratic beds of the Juana Díaz Formation are horizontally juxtaposed with Cretaceous and Eocene strata by strike-slip and normal faults (Krushensky and Monroe, 1975). In the western part of the basin, nonmarine and clastic shelf rocks of the Juana Díaz Formation grade upward (coastward) to a limestone sequence deposited within carbonate shelf (reef, forereef, deep forereef) and island-slope environments (the lower "new formation" of Frost and others, 1983). The transition in facies from terrigenous to carbonate slope deposition in the north-central part of the basin is rapid and lacks the reef facies seen to the west (Frost and others, 1983 p. 13-15) (fig. 9).

Limestone of the Juana Díaz Formation contains a rich and diverse fauna of coral, coralline algae, large benthic foraminifera, and mollusks that record alternating periods of reef growth and destruction. These phases of growth and destruction have been attributed to a combination of factors that include tectonic movement, upwelling of colder oceanic waters, and eustatic changes in sea level (Frost and others, 1983). The reef facies extends eastward from Guánica to the Río Tallaboa; farther eastward, this sequence grades to forereef and island slope deposits. Carbonate and clastic rocks of Oligocene age equivalent to the Juana Díaz Formation lie buried in the deep subsurface between Ponce and Santa Isabel (Glover, 1971). Here, shallow-water benthic foraminiferal assemblages contrast with underlying, deep-water benthic and planktonic faunal assemblages, highlighting the contact that separates sedimentary strata of the Ponce Limestone from the Juana Díaz Formation (Todd and Low, 1976). The Juana Díaz Formation here is reported to consist of silty shale with limestone, sandstone, shale and conglomerate (Glover, 1971, p. 76), and marly quartz conglomerate (Meyerhoff and others, 1983, fig. 18). The reported occurrence of quartz conglomerate beds within this buried section suggests a nearby source of terrigenous material.

At outcrop, unconformable relations mark the upper and lower contacts of the Juana Díaz Formation. A lowermost angular unconformity that separates the clastic Juana Díaz Formation from the older early Tertiary and Cretaceous rocks has been described earlier. Paleontologic evidence (Moussa and Seiglie, 1970, 1975) and an apparent erosion surface mark the unconformity separating the carbonates of the Juana Díaz Formation from overlying "pelagic carbonate deposits" of early Miocene age. This unconformity suggests a second major period of emergence immediately followed deposition of the Juana Díaz Formation.

Sparse well data, structural tilting, and complex fault relations make it difficult to assess formation thickness. The Juana Díaz Formation may range from 200 to more than 700 m thick where it crops out or lies buried in the subsurface between Guayanilla and Santa Isabel (Todd and Low, 1976; Monroe, 1980) (fig. 9). The Juana Díaz Formation is probably thickest in the Río Tallaboa-Playa de Ponce area (400 to more than 700 m thick) and thins to 200 m thick or less on the eastern and western margin of the basin. Clastic beds that make up the lower part of the formation range from 100 to 420 m thick, whereas the estimated thickness of the limestone facies varies from 150 m to more than 600 m.

Three planktonic foraminiferal zones, the *Globigerina ampliapertura, Globorotalia opima opima* and *Globigerina ciperoensis* Zones, have been identified within the Juana Díaz Formation (Moussa and Seiglie, 1970). Frost and others (1983, p. 18) correlate clastic mudstones that make up the basal part of the formation in the Guayanilla area with the *Globigerina ampliapertura* zone contained in beds northwest of the city of Juana Díaz, placing this part of the section in the middle part of the early Oligocene. Moussa and Seiglie (1970) and Frost and others (1983) correlate the shallow-shelf carbonate rocks that make up the upper part of the formation in the west with deep-water carbonate rocks of the north-central part of the basin which contain planktonic foraminifera assigned to the *Globorotalia opima opima* Zone. Accordingly, this part of the section is late-early to early-late Oligocene (Haq and others, 1988). There appears to be some difference of opinion between Moussa and Seiglie (1970) and Frost and others (1983) as to the correlation of shallow-water limestone beds near Guanica in the western edge of the basin with slope chalk beds near Guayanilla containing faunal assemblages assigned to the *Globigerina ciperoensis* Zone of late Oligocene age. Moussa and Seiglie (1970) show the

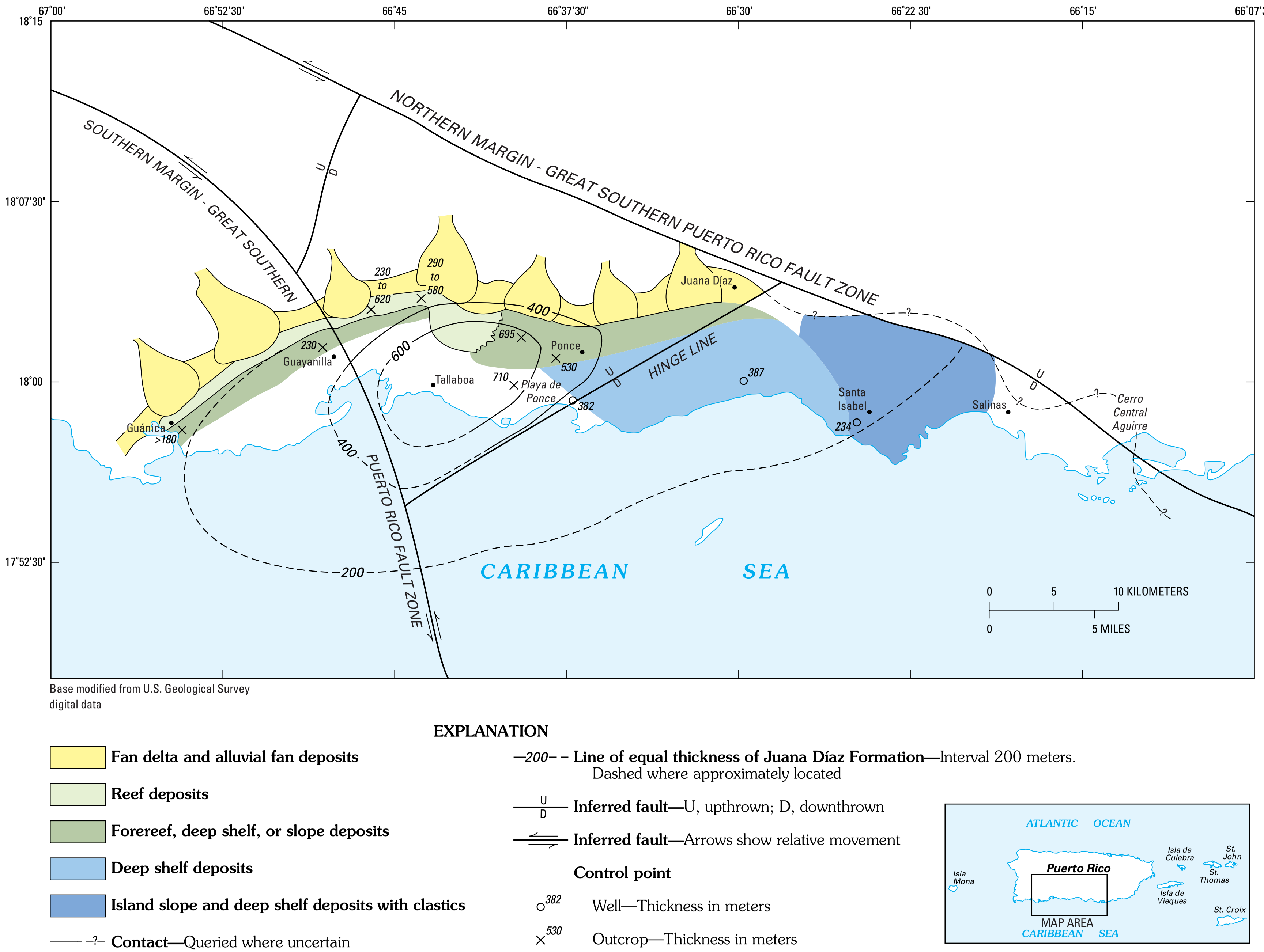


FIGURE 9.—Major facies and thickness of the Juana Díaz Formation, south-central Puerto Rico (distribution of western facies from Frost and others, 1983).

limestones as being correlative, whereas Frost and others (1983) did not identify coeval shallow-water equivalents.

UNNAMED PELAGIC CARBONATE ROCKS

An unnamed carbonate-rock sequence of early Miocene age unconformably overlies the Juana Díaz Formation and crops out in restricted localities of the north-central part of the basin. These strata include the Angola limestone or island-slope chalk beds of Seiglie and Bermúdez (1969), the pelagic Río Tallaboa marlstone of Moussa and Seiglie (1970), and the upper "new formation" of Frost and others (1983) (fig. 8). Chalk and marlstone beds deposited within an island-slope environment crop out in restricted localities between Guayanilla and Ponce (Moussa and Seiglie, 1970, p. 1894) and contain planktonic foraminifera assigned to the *Globorotalia kugleri* Zone. Moussa and Seiglie (1970) suggest that shallow-water reef and *Lepidocyclina undosa* (large benthic foraminifera) forereef strata in the north-central part of the basin are, at least in part, correlative with the chalky "Angola beds" of early Miocene age. However, Frost and others (1983) do not show these shallow-water limestone beds as correlative. The Río Tallaboa marlstone beds, bedded *Globergina* ooze (sandstone at Quarry No. 2), and other equivalent interbedded marlstone and claystone beds crop out only in a few exposures between Ponce and Río Macaná. These beds contain planktonic foraminifera of the *Globigerinatella insueta* Zone, suggesting these rocks are late-early Miocene in age (Haq and others, 1988). Moussa and Seiglie (1970) imply an unconformity separates the Angola and Río Tallaboa beds and their equivalents, whereas Frost and others (1983, p. 62) suggest continuous deposition within the early Miocene sequence. Taken together, these early Miocene strata are the lenticular remnant of a bathyal sequence that was deposited almost until the end of the early Miocene. If rocks equivalent to these bathyal deposits lie buried beneath the fan-delta plain, they were not described by Todd and Low (1976).

PONCE LIMESTONE

The Ponce Limestone unconformably overlies the unnamed carbonate-rock sequence previously described and, where this sequence is missing, the Ponce unconformably overlies the Juana Díaz Formation. The Ponce Limestone consists largely of yellowish-orange, soft to moderately hard, fossiliferous limestone and crops out nearly continuously as a narrow band that extends from Bahía Montalva to the Río Pastillo (pls. 1*A*, 2*A*). Outliers of the Ponce Limestone are also exposed north and northeast of the city of Ponce and in the southwestern part of the island between Punta Aguila to Isla Cueva, and unconformably overlie early Tertiary bedrock units on Isla Caja de Muertos.

Outcropping strata of the Ponce Limestone contain an abundant marine fauna; molds of gastropods, pelecypods, coral heads, and large foraminifera are indicative of deposition in shallow-water lagoon and back-reef environments. The large foraminifera, *Lepidocyclina undosa* and the ahermatypic "deep sea" coral *Flabellum* are reported within the Ponce Limestone (Monroe, 1980, p. 78). Such fauna reflect deeper shelf environments also contained within the Ponce Limestone sequence. Minor clastic beds equivalent to the Ponce Limestone crop out near Ponce and are considered indicative of deposition in nearshore environments.

Clastic beds equivalent to the Ponce Limestone are buried beneath the fan-delta plain between Playa de Ponce and Santa Isabel (see discussion below). Cutting samples collected from the Kewannee oil wells show that shallow-water beds of the Ponce Limestone grades west to east from a shallow-water facies to terrigenous sand, gravel, and mudstone interbedded with some limestone (Glover, 1971; Todd and Low, 1976, p. 2; Meyerhoff and others, 1983).

On the basis of stratigraphic position and planktonic foraminiferal data collected from the underlying unnamed island-slope sequence described previously, Moussa and Seiglie (1975) suggest that the lower part of Ponce Limestone is probably middle Miocene age. Frost and others (1983, p. 10-11) correlate coral faunal assemblages within the lower Ponce Limestone with the *Globorotalia foshi* Zone of middle Miocene age. Bold (1969) studied the ostracod fauna within the upper part of the Ponce Limestone and correlated faunal assemblages with the *Globorotalia margaritae* planktonic foraminiferal zone. The age of this zone was revised (Haq and others, 1988) and is currently considered to extend from latest Miocene to early Pliocene time. Therefore, the Ponce Limestone may range in age from middle Miocene with the uppermost unconformity recording post-early Pliocene emergence and erosion.

A brackish and nearshore marine, benthonic foraminiferal fauna constitute the *Amphistegina angulata-Elphidium lens* marker horizon identified from Kewannee oil well cutting samples. This fauna is also reported to occur within outcropping rocks of the Ponce Limestone (Seiglie and Moussa, 1974, p. 257) and is considered to be middle Miocene. Todd and Low (1976, p. 2) showed that the clastic mudstone strata that lie deeply buried in the Playa de Ponce to Santa Isabel area are stratigraphically equivalent to the Ponce Limestone.

Structural complexity and sparse well control limits accurate thickness estimates of the Ponce Limestone. The limestone facies and equivalent clastic strata appear to be thickest (300 to more than 400 m) (fig. 10) in the Ponce and Santa Isabel area. The Ponce Limestone has been estimated to be as much as 850 m thick in the Río Tallaboa area (Monroe, 1980, p. 81), a thickness estimate that seems to be inconsistent with regional trends in the area between Ponce and Guayanilla (fig. 10). Perhaps, complex fault relations and vegetative

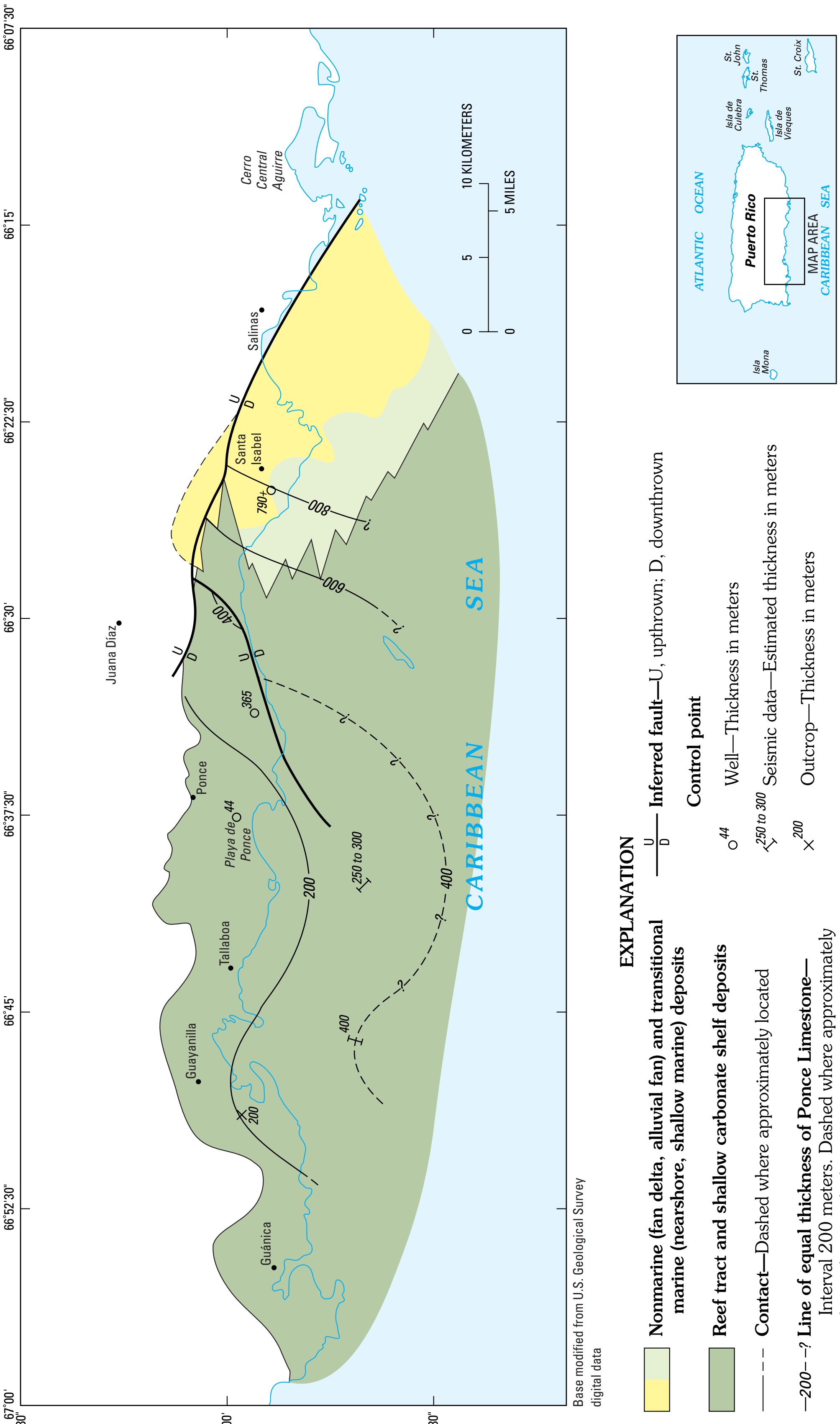


FIGURE 10.—Major facies and thickness of the Ponce Limestone and equivalent beds, south-central Puerto Rico.

cover obscured geologic relations and contributed, as suggested by Frost and others (1983, p. 24), to what they considered to be an overestimate by Monroe of the thickness of the Ponce. Middle to upper Miocene deposits of the Ponce Limestone, however, are thickest between Ponce and Santa Isabel and are associated with clastic deposition (alluvial fan or fan delta) in a subsiding basin.

A shallow-water and possibly some deeper shelf carbonate paleoenvironments prevailed in much of the western basin during middle to late Miocene time. During the early Pliocene, relative sea level continued to decline and resulted in subaerial exposure of the late Miocene and early Pliocene carbonate-clastic shelf. It is not known if the Pliocene hiatus that marks the top of the Ponce Limestone is restricted to rocks that crop out or if the unconformity extends eastward to the clastic facies that underlies the fan-delta plain. Deposition of alluvial-fan or fan-delta deposits may have continued during the Pliocene in response to a low base level in the eastern part of the basin.

SUBSURFACE STRATIGRAPHIC RELATIONS

Stratigraphic and structural relations of Oligocene to Quaternary lithologic units are complex where they lie buried beneath the southern fan-delta plain. The relations are illustrated in sections *A–A´* and *B–B´* (figs. 11, 12). A paleontologic marker horizon (the *Amphistegina angulata-Elphidium lens* benthic zone) found within the Ponce Limestone sequence shows important age-related clastic-carbonate relations. This marker horizon occurs in limestone and clastic facies and verifies equivalent age of deposits and a facies change in deposition in the eastern part of the basin. The subsurface contact separating the Ponce Limestone and underlying Juana Díaz Formation is recognized by an abrupt faunal change from varied and abundant assemblage of planktonic foraminifera of Oligocene age to overlying shallow-water benthic foraminifera of Miocene age (Todd and Low, 1976). Unnamed pelagic strata of early Miocene age (Angola limestone and Río Tallaboa marlstone) that crop out between Guayanilla and Tallaboa were not reported within the subsurface sequence located between Ponce and Santa Isabel (Todd and Low, 1976). The subsurface contact between the carbonate facies of the Ponce Limestone and overlying clastic fan-delta deposits of Quaternary age is readily identified in wells located in the western part of the fan-delta plain; however, this contact is difficult to recognize in the central part of the fan-delta plain where buried carbonate rocks of the Ponce Limestone grade eastward to a nearshore, brackish marine, and nonmarine sequence of clastic and minor interbedded limestone beds. Here, clastic deposits of Miocene to Pliocene (?) age underlie clastic deposits of Quaternary age. Similar difficulties were encountered during the present investigation when studying driller's log descriptions of wells located in areas where fan-delta and valley-fill deposits directly overlie conglomeratic beds of the Juana Díaz Formation. For the most part, these wells are located on the northern margin of the fan-delta plain and in the Tallaboa-Guánica area. In general, the contact between Cretaceous-Tertiary bedrock units and overlying strata can be easily identified in well cuttings, cores, and geophysical log data.

Sections *A–A´* and *B–B´* illustrate an important structural feature of Puerto Rico's south coast. An inferred high-angle fault vertically juxtaposes the Ponce Limestone and coeval clastic beds with bedrock of Cretaceous and Tertiary age. The carbonate-clastic facies change within the Ponce Limestone and its clastic equivalents are shown to be the same age, but basinal subsidence helps explain a large increase in thickness of the Miocene section.

PLEISTOCENE TO HOLOCENE FAN-DELTA AND ALLUVIAL DEPOSITS

Four large and seven smaller fan deltas coalesce to form the low-lying fan-delta plain between Ponce and Patillas (fig. 13). Bordered to the north by the Cordillera Central, the insular drainage divide lies less than 24 km north of the Caribbean coastline. High-gradient streams that flow southward and transport bedload deposits of boulders, cobbles, sand, and silt during upper flow regimes have incised deep mountain and foothill valleys. The altitude of most of the fan deltas located between Ponce and Patillas do not exceed 50 m above sea level at their apex, except for the Capitanejo fan that rises to 80 m above sea level (pl. 1*A*). The surface of the different fans slopes coastward at a gradient that varies from 25 m/km within the apex or proximal upland channel to 2 m/km near the coast. From fan apex to shoreline, fan radii average nearly 10 km; all of the fan deltas east of Ponce contain a well-developed, semi-radial, subaerial morphology. However, bedrock hills protrude the fan-delta plain in several localities, more commonly where deposits thin against the foothills. One of the larger bedrock hills is at Central Aguirre, located adjacent to the Caribbean Sea. Cerro Central Aguirre is the only locality within the fan-delta plain where pre-Miocene strata have been reported to crop out along the coast (Berryhill, 1960; Glover, 1971).

West of Ponce in the Tallaboa to Guánica area, five major valleys contain moderately thick gravel, sand, and silt deposits and separate an otherwise continuous outcropping belt of Oligocene to Pliocene (?) rocks that make up the Juana Díaz Formation and Ponce Limestone (pl. 2). These alluvial-filled valleys extend coastward where three river valleys, the Ríos Guayanilla, Macaná, and Yauco, combine to form a more extensive low-lying plain (fig. 14). Although the extent of this plain is considerably smaller than the fan-delta plain described above, fan-like topography of the coalesced lower valleys and plain parallels similar features seen to the east. Similar features are present in the Guánica and Tallaboa valleys.

By definition, a fan delta is an alluvial fan that progrades into a standing body of water from an adjacent highland (Holmes, 1965). Fan deltas are characterized by their semiradial or fan-like shape in plain view, concave-upward radial and convex-upward cross-fan profiles, and the relatively narrow space that they occupy between a highland mountain front and the nearby water body (Wescott and Ethridge, 1980; McPherson and others, 1987). Fan deltas contain subaerial and subaqueous depositional components that are separated by a narrow transitional marine coastal zone of beach, mangrove swamps, and tidal flats. Sedimentary strata deposited within the subaerial component are dominated by streamflow, sheetflow, and gravity depositional processes. The subaqueous part of the fan-delta system lies offshore and is subject to marine shelf and slope depositional processes.

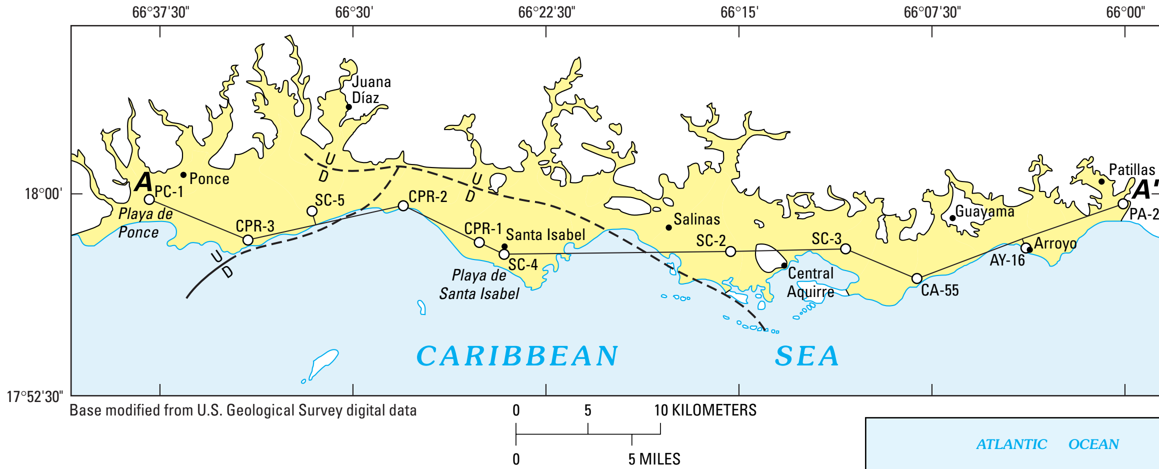
The fan-delta plain between Ponce and Patillas and the alluviated valley-fan-delta plain between Tallaboa and Guánica is bordered to the north by steep, southward-facing foothill and mountain slopes of the Cordillera Central, and to the south by the Caribbean Sea. The subaqueous part of the fan-delta system of Puerto Rico lies offshore where it forms the upper sediments of the Muertos insular shelf. Quaternary deposits that make up the bulk of the fan-delta plain consist almost entirely of subaerial deposits, but include some transitional, marine deposits.

The arcuate-cuspate coastline morphology of much of the south coast (Kaye, 1959a) is the result of the interaction of wave energy, longshore current, and detritus carried to the coast by streams (Hayes and Michel, 1982). Present-day streams and floodflow conditions apparently are not of significant magnitude or sufficient frequency to maintain the lobate form that typifies active fan deltas such as the Yallahs fan delta of Jamaica (Wescott and Ethridge, 1980). The lobate Río Guayanilla fan delta, is located within the protected confines of Bahía Guayanilla, is a notable exception. The apparent reduction in wave energy and lessened longshore currents within this embayed area is the principal factor controlling the shape of the coastline in the vicinity of Río Guayanilla. The supply of sediment from the river system that feeds an adjoining fan delta, that of the Río Yauco, has sufficient magnitude, in combination with low wave energy and minimal longshore currents, to allow the development of a small progradational delta at the mouth of the river.

Subaerial parts of southern Puerto Rico's fan deltas are separated from the Caribbean Sea by a narrow marginal marine zone of supratidal or salty scrub flats, marsh and mangrove swamps, and beach deposits. Fan-delta coastal zones are largely characterized by broad sand and gravel beaches. Mangroves, marshes, and tidal flats are mostly restricted to those areas protected by offshore, fringing reefs. The most extensive area of mangroves, marshes, and tidal flats is along the Salinas fan-delta margin. Spits partially enclose Bahía de Jobos and Bahía de Guayanilla. The compound spit at Bahía de Jobos shelters expansive mangrove swamps that rim the bay adjacent to the Salinas fan delta. The beach here and along the southern edge of the Playa de Salinas consists, at least in part, of skeletal carbonate sand. The occurrence of carbonate sand is largely restricted to the lee of fringing reefs that extend from Punta Ola Grande to Playa de Salinas. Fringing reefs are also the principal source of carbonate sand supplying an elongate compound spit at Punta Pozuelo. Carbonate sand beaches bordering the fan-delta plain are unusual in southern Puerto Rico, however. The Playa de Salinas to Punta Ola Grande area represents the only place where the transitional beach zone is dominated by, or contains a large component of, carbonate detritus.

Major streams that traverse the 70-km wide fan-delta plain and alluviated valley-fan delta areas to the west generally display a straight channel morphology, drain one fan, and mostly extend in a southwestward direction from the fan apex. The floor of stream channels traverse the southern alluviated valleys and fan-delta plain slope at a gradient of 2 to 8 m/km near the coast and higher inland gradients of 8 to 18 m/km. The coastward slope of streams draining the large coastal fan-delta plain near Ponce is 1 to 6 m/km. The Portugúes-Bucana and Capitanejo fans are drained by two, relatively straight streams. These streams develop a sinuous to meandering pattern as they extend coastward, except where they have been channelized. Flood control channelization efforts, such as that developed for the Bucana-Portugúes-Cerillos flood control and reservoir project have altered depositional conditions within the fan-delta plain. Prior to these changes, the confining channel of many streams altered to a distributary system in the distal fan area allowing surface water to spread out as sheetflow onto the coastal lowlands (Mitchell, 1922, p. 236).

Streamflow within the fan-delta plain is minimal except during flood events. For example, streamflow within the landward parts of the fan-delta plain usually is less than 1.0 cubic meters per second (m^3/s) 90 percent of the time (Quiñones and others, 1984) and the midstream reach is often dry. The distal stream channel can contain standing water, the result of upward ground-water discharge or equilibrium with the ground-water table. Intense storm precipitation that can last several days occasionally results in floodflow that is widespread and catastrophic. In 1985, Puerto Rico was affected by a stationary tropical depression that produced more than 580 millimeters (mm) of rainfall in 24 hours and caused extensive flooding over much of the southern part of the island (Quiñones and Johnson, 1987) (fig. 15). Surface-water records show that flooding has been more extensive and widespread in the western half of the South Coast ground-



EXPLANATION

Rocks of Miocene to Quaternary age

Unconsolidated clastic sediments—Boulder- to silt- or clay-size clastic detritus deposited under subaerial conditions, mostly during Pleistocene to Holocene time

Unconsolidated to poorly consolidated sediments—Boulder- to silt- or clay-size detritus, minor limestone and marl deposited under subaerial, nearshore, and shallow marine conditions. Deeply buried sediments may be as old as Miocene age and are equivalent to the Ponce Limestone. Uppermost deposits are Pleistocene and/or Holocene in age

Limestone—Consists of limestone with brackish- to shallow-marine fauna. Considered equivalent to Ponce Limestone

Rocks of Oligocene age

Limestone-shale sequence—Consists of deep-water limestone, silty shale, marly conglomerate dominated by planktonic and deep-water benthic foraminfera. Considered equivalent to the Juana Díaz Formation

Rocks of Cretaceous to early Tertiary age

Bedrock—Consists of bedded, lithified sequence of conglomeratic sandstone, siltstone, volcanic and igneous rocks, and minor limestone

Line showing approximate position of freshwater-saline water interface

Line showing top of *Amphistegina Angulata-Elphidum* lens fauna—Considered to be a Miocene stratigraphic datum (Todd and Low, 1976)

U D **Fault—**U, upthrown side; D, downthrown side. Dashed where inferred

A A' **Line of section**

SC-5 **Control point**

Well name abbreviations

SC	South Coast
CPR	Kewanee Interamerican Oil Company—Commonwealth of Puerto Rico
PC	Punta Cuchara
CA	Central Aquirre
AY	Arroyo
PA	Patilla
SI	Santa Isabel

FIGURE 11.—Section *A–A′* across southern Puerto Rico's fan-delta plain.

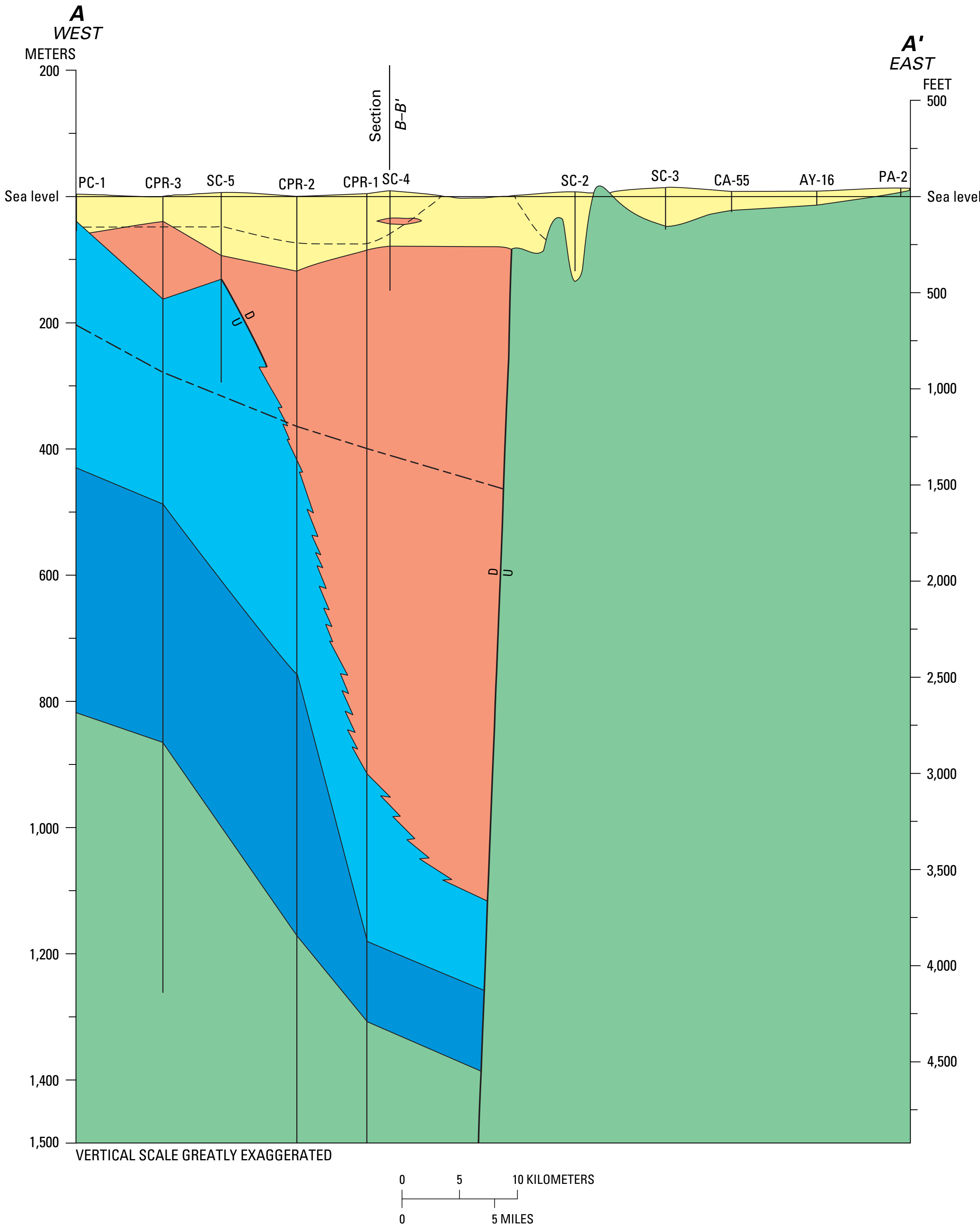
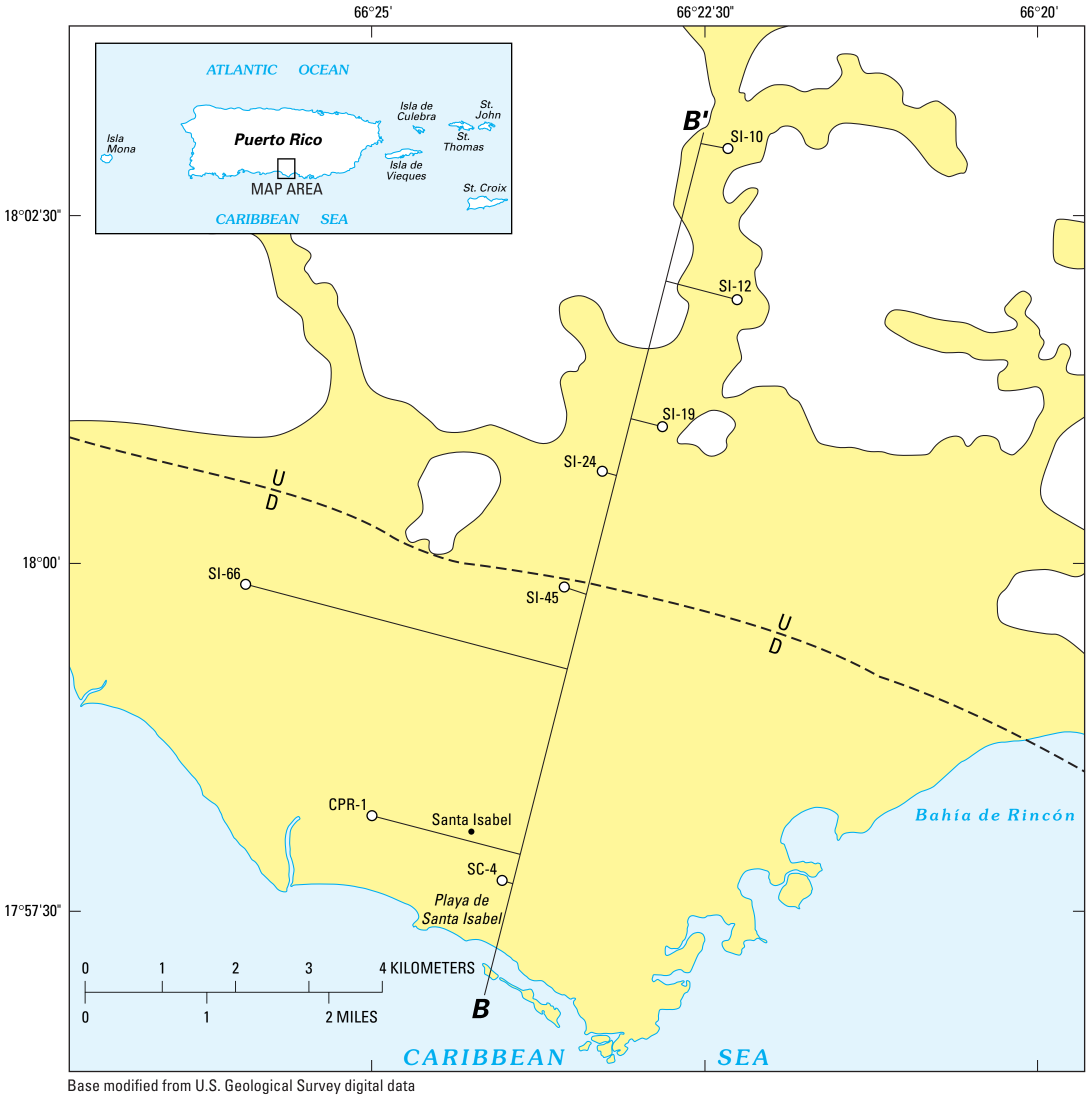


FIGURE 11—Continued. Section *A–A′* across southern Puerto Rico's fan-delta plain.



EXPLANATION

Rocks of Miocene to Quaternary age

Unconsolidated clastic sediments—Boulder- to silt- or clay-size clastic detritus deposited under subaerial conditions, mostly during Pleistocene to Holocene time

Unconsolidated to poorly consolidated sediments—Boulder- to silt- or clay-size detritus, minor limestone and marl deposited under subaerial, nearshore, and shallow marine conditions. Deeply buried sediments may be as old as Miocene age and are equivalent to the Ponce Limestone. Uppermost deposits are Pleistocene and/or Holocene in age

Limestone—Consists of limestone with brackish- to shallow-marine fauna. Considered equivalent to Ponce Limestone

Rocks of Cretaceous to early Tertiary age

Bedrock—Consists of bedded, lithified sequence of conglomeratic sandstone, siltstone, volcanic and igneous rocks, and minor limestone

Well lithology

Sand-size or larger
Silt-size or smaller
Limestone, limey clay, or marl
Bedrock

Line showing approximate position of freshwater-saline water interface

Line showing top of *Amphistegina Angulata-Elphidum* lens fauna—Considered to be a Miocene stratigraphic datum (Todd and Low, 1976)

U D **Fault**—U, upthrown side; D, downthrown side. Dashed where infered

B B' **Line of section**

SC-4 **Control point**—Well name abbreviations on figure 11

FIGURE 12.—Section *B–B′* down the axis of the Coamo fan delta, south-central Puerto Rico.

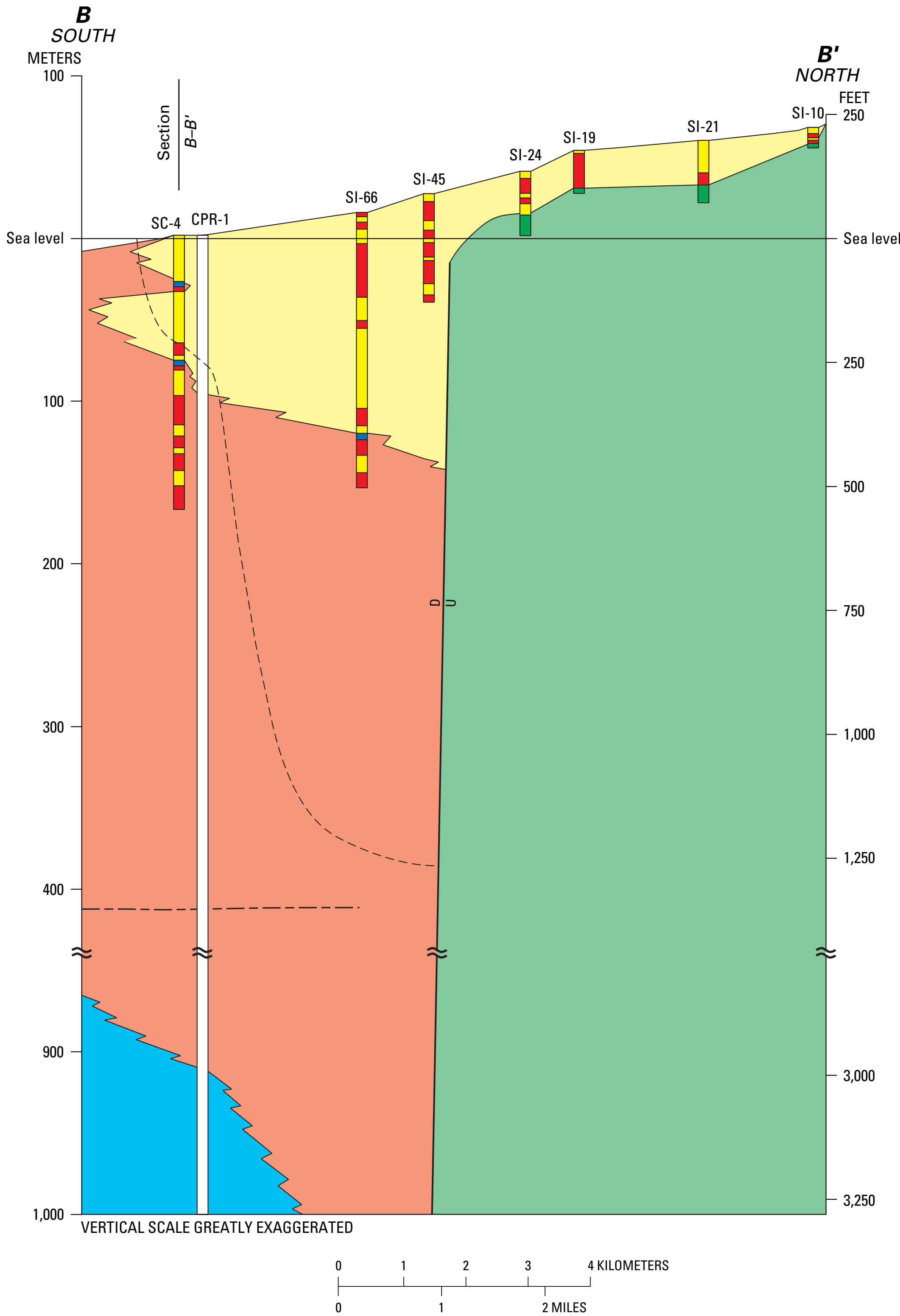


FIGURE 12—Continued. Section *B–B′* down the axis of the Coamo fan delta, south-central Puerto Rico.

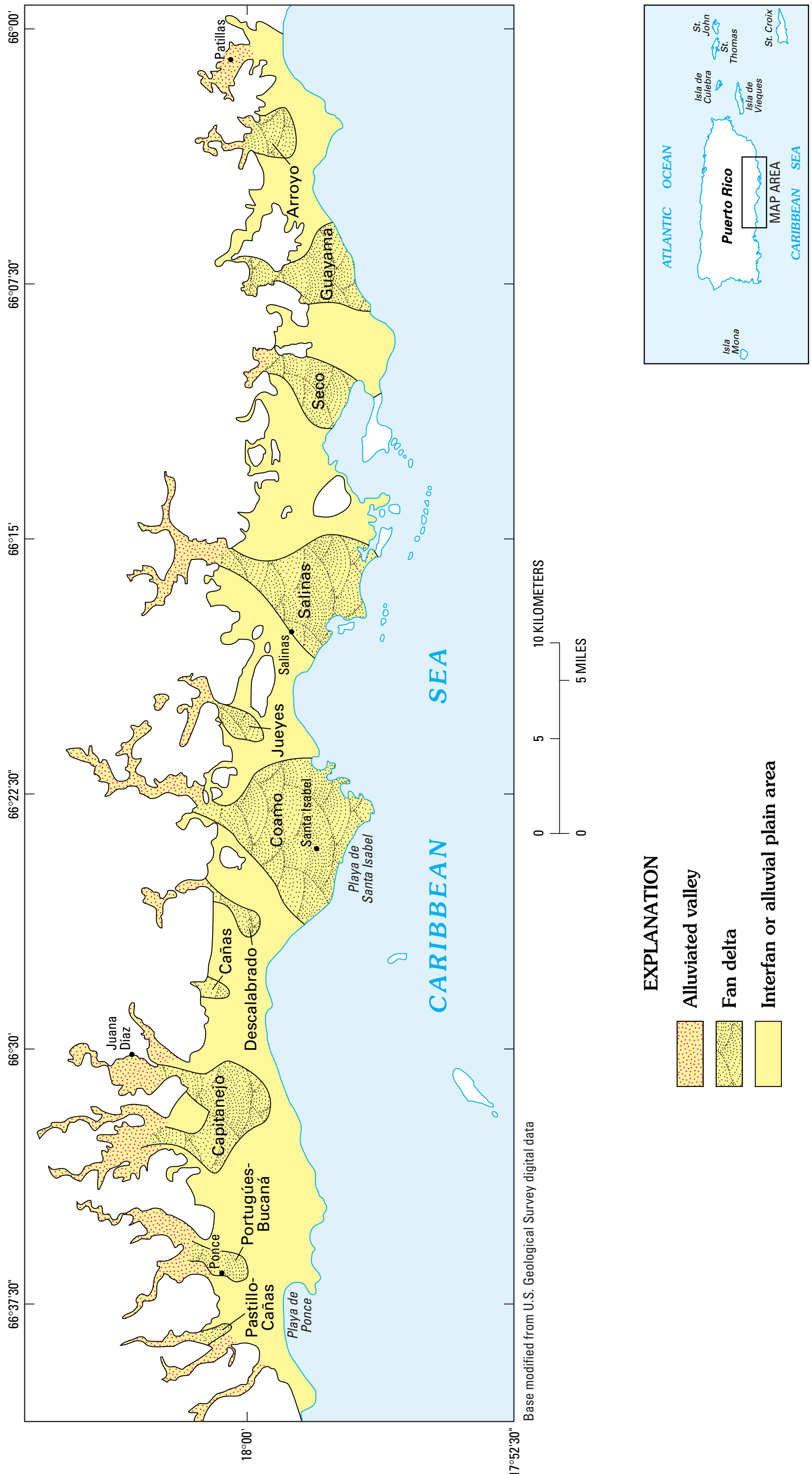


FIGURE 13.—Location and extent of fan deltas of southern Puerto Rico.

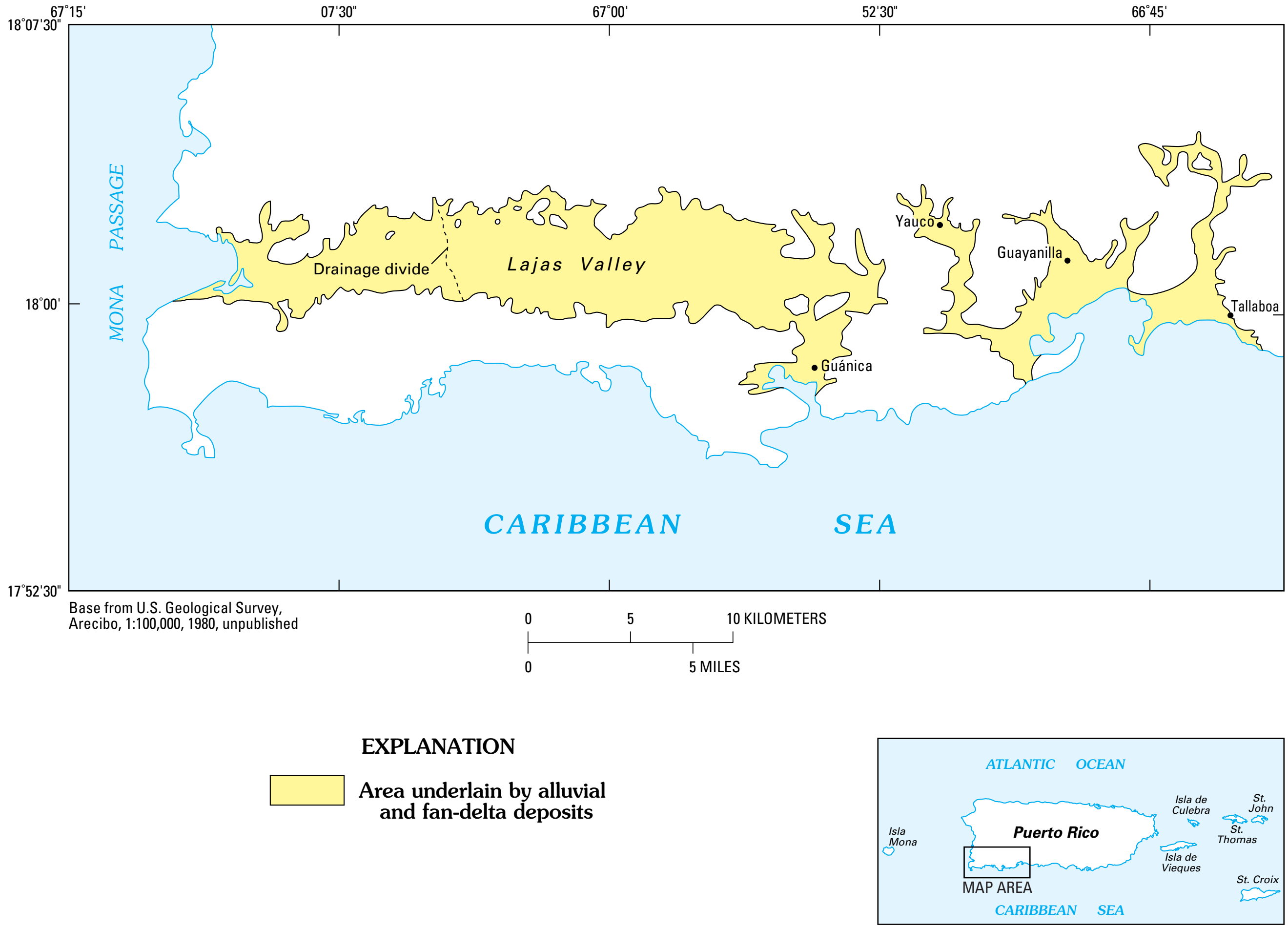


FIGURE 14.—Location of principal alluviated valleys and small, restricted fan-delta plains in the western half of Puerto Rico's south coast.

water province than in the eastern half. Widespread, catastrophic flooding of the western fan-delta plain is reported to have occurred six times between 1899 and 1985; extensive flooding of the Río Tallaboa Valley has occurred at least four times between 1928 and 1975 (Johnson, 1981).

The subaqueous component of Puerto Rico's modern-day fan-delta plain lies offshore and within the Isla Caja de Muertos shelf area. Bathymetric data indicates a semi-radial fan-like morphology of the fan-delta plain that extends to depths of 10 m (pl. 1*A*). Uppermost deposits within the subaqueous part of the fan-delta system are made up of inner shelf deposits. Inner shelf deposits grade seaward to outer shelf and shelf slope deposits; all of these shelf deposits are considered to be an active part of the fan-delta depositional system. The inner shelf extends from the shoreline to water depths of 20 to 30 m and can be separated into nearshore, shelf platform, and shelf basin areas (Beach and Trumbull, 1981). Nearshore deposits lie within the turbid coastline and are made-up of terrigenous fine sand. The shelf platform zone consists of a layer of gravel- to silt-size bioclastic detritus that is underlain by a cemented hardground surface. Live, recurved fringing reefs of intergrown coral and coral-algae lie offshore of the Coamo and Salinas fan deltas. These reefs function as a source of carbonate sand that form carbonate banks or cays on their leeward side. A bathymetric and structural shelf basin lies south of Playa de Ponce. In this area, longshore currents have carried fine terrigenous detritus from the nearshore zone and moved them farther downslope than elsewhere along the coastline. An outer shelf area lies seaward of the fringing reefs and is covered with biogenic sand and gravel; brown-stained sediment (Beach and Trumbull, 1981) suggests that this outer shelf was subject to subaerial exposure. Drowned reefs that border the outer shelf slope rim and may record a lower, relict sea stand.

Although terrigenous fine sand and mud cover inner-bay areas of Bahía de Tallaboa, Guayanilla, and Guánica, the fan-like nearshore bathymetry seen east of Ponce is not present in these shallow marine areas. Biogenic silt covers much of the outlying shallow shelf platform and hard-bottom areas are generally covered by coral and coralline algae. Patch reefs

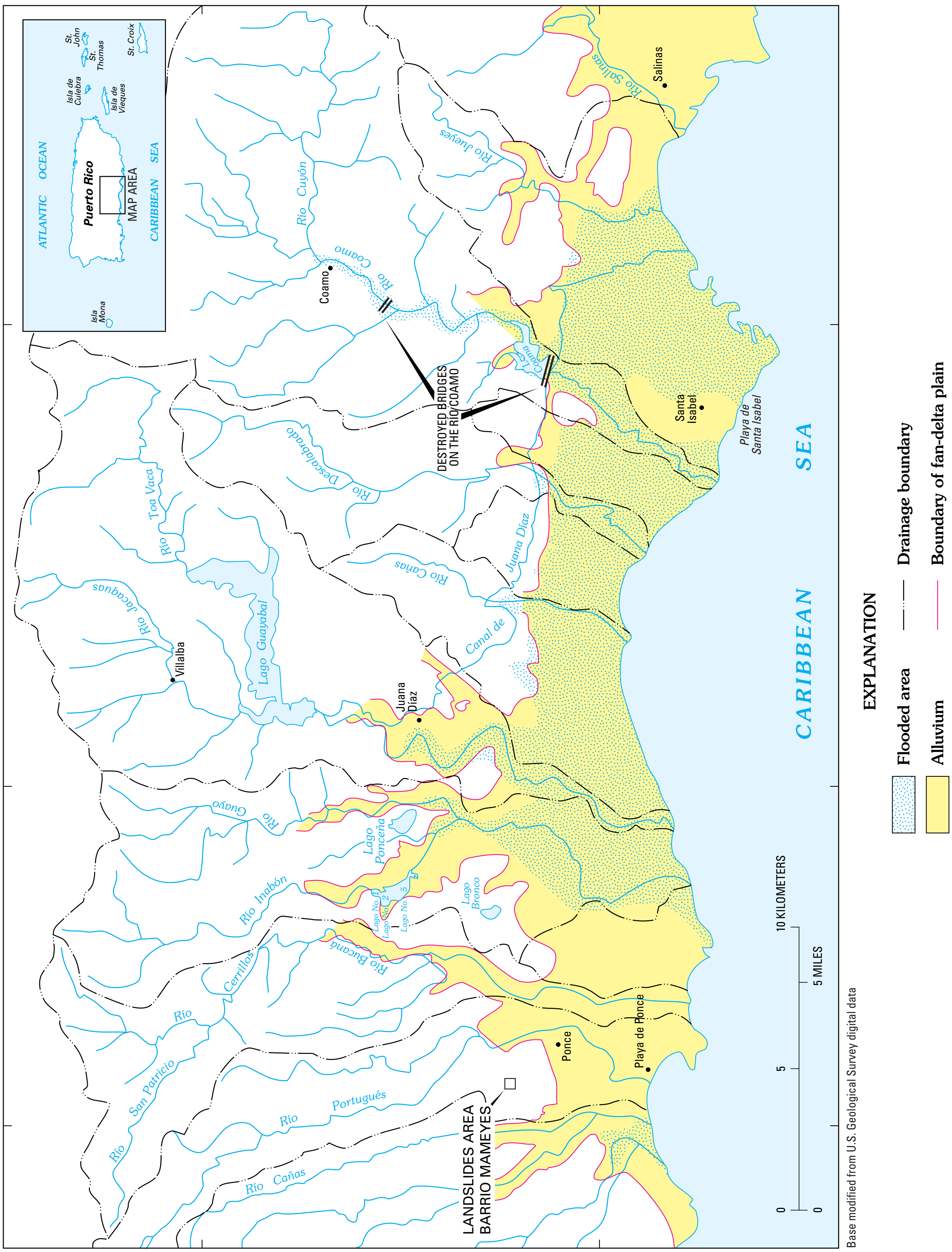


FIGURE 15.—Areas flooded in the central part of the southern plain during the October 6–7, 1985 flood (modified from Quiñones and Johnson, 1981).

and leeward sandy cays are present within the inner bay areas (indicating limited influx of terrigenous sediment) and in the outlying shallow shelf platform areas.

Configuration of Basal Quaternary Contact and Thickness of Deposits

Driller's logs and other well data for more than 500 wells were used to estimate the thickness of fan-delta and alluvial valley deposits and map the configuration of the underlying bedrock surfaces (pls. 1*B*, 1*C*, 2*B*). Of these wells, many do not reach underlying bedrock that is generally described by drillers as "hard, blue, or gray rock." These shallow well data are considered useful data control points because they indicate a minimum depth a well must be drilled in order to penetrate the underlying bedrock surface. Some wells drilled in the eastern half of the fan-delta plain penetrate a sequence of weathered clay, silty clay, or silty limestone reported on driller's logs as "tosca." Tosca has been previously interpreted as a weathered bedrock zone of highly variable thickness that overlies unweathered bedrock (McClymonds and Ward, 1966). Ramos-Ginés (1994) reports that alluvial deposits in the Río Majada and Río Lapa area are underlain by a 3 to 24 m-thick zone of highly weathered volcanic rocks which are, in turn, underlain by partly weathered and unweathered bedrock. Test borings drilled in the Central Aguirre area reportedly penetrated a weathered bedrock zone of 3 to 15 m thick (Weston Geophysical Research, 1967). Graves (1994) describes a 1 to 33 m-thick regolith or saprolite zone in the Aguirre area that preserves original rock structure. Driller's log data suggest that, in some places, the weathered bedrock zone is as much as 18 to 24 m thick. Core samples collected from the SC 3 well drilled during this study show gravel, sand, or silt deposits lying immediately above partly weathered bedrock; a saprolitic zone of weathered clay, silty clay, or silty limestone was not observed. In the western part of the fan-delta plain near Ponce and in valley-fill areas between the Río Tallaboa and Guánica, many wells are reported to bottom in "white, gray, or blue clay or limestone." On the basis of lithofacies maps shown for Oligocene and Miocene strata, it seems likely that wells drilled in the western part of the fan-delta plain and in the valley-fill areas to the west have penetrated a carbonate facies within either the Juana Díaz Formation or the Ponce Limestone. However, some "limestone" beds could consist of caliche rather than Oligocene to Miocene bedrock. Poorly developed soil caliche has been observed elsewhere within the fan-delta plain at isolated exposures and the occurrence of caliche in the subsurface is consistent with semiarid environmental conditions during the Pleistocene. In the Central Aguirre area, drillers' log descriptions of cutting samples report the occurrence of "white clay" contained within the interbedded sequence of sand, gravel, silt, and clay deposits.

Fan-delta deposits usually do not exceed 10 to 30 m in thickness where they are found within the proximal part of the fan or within inland alluvial channels that extend landward from the fan apex (pl. 1*B*). The thickness of the Holocene to Pleistocene fan-delta sequence east of Ponce increases from a featheredge at its landward margin to 80 to 100 m in most coastal areas. Where the sequence overlies the structural basin between Playa de Ponce and Bahía de Rincon, it can locally thicken to more than 400 m; the actual thickness of Quaternary deposits within this basin is poorly known because of sparse control and the lack of age-diagnostic faunal assemblages. Between Bahía de Jobos and Patillas, Fan-delta deposits usually are less than 40 m-thick. The thickness of unconsolidated alluvium within all fan-delta/valley-fill areas west of Ponce is greatest near the coast, and reportedly in excess of 45 m in some coastal areas.

In offshore areas west of Ponce, deposits of Quaternary age that underlie the Isla Caja de Muertos shelf are estimated to average 150 m thick, but these deposits progressively thin along the flanks of submarine canyons that border and incise the insular shelf (Trumbull and Garrison, 1973). The thickness of Quaternary deposits that lie in the eastern offshore areas of the South Coast ground-water province is not known.

The valleys of the Ríos Tallaboa, Guayanilla, Macaná, Yauco, and Loco-Guánica are incised into bedrock units of the Juana Díaz Formation and Ponce Limestone to depths as much as 45 m below sea level (pl. 2*B*). A period of subaerial exposure and fluvial downcutting (late Pliocene(?) to early Pleistocene) of the Muertos shelf is also reflected by canyon bathymetry within the Bahía de Guayanilla and Bahía de Guánica. The confluence of the Ríos Macaná, Guayanilla, and possibly Yauco was located beneath Bahía de Guayanilla during lower sea stands. Bathymetric data in the Punta Verraco area may indicate a different drainage pattern for the Río Yauco; this river discharges across the dune deposits west of Punta Verraco during extreme floods. Canyon development south of the dunes suggests a southward drainage direction. A delta formed at the mouth of the Río Yauco has covered much of the canyon that incises the Bahía de Guayanilla, visible to the east. In any case, these three rivers combine to form a larger river system that may have extended farther southward on to the Isla Caja de Muertos shelf (Trumbull and Garrison, 1973).

Lithofacies

A seacliff exposure located in the Central Machete-Puerto Arroyo area extends 2.5 km along the Caribbean Sea and represents the only extensive cross-profile fan in the South Coast ground-water province. An extensive cutbank exposure occurs on both sides of the Río Coamo channel south of Paso Seco and shows a longitudinal section of a fan for approximately 5 km downstream. Other cutbank exposures within the fan-delta plain are poorly preserved because the unlithified nature of deposits promotes sloughing. Subaerially-deposited silt represents the best preserved lithofacies, in large part because it is better lithified and can support a nearly vertical exposure face. Exposures located within the fan-delta plain are limited to sediments deposited under subaerial conditions.

Subaerial fan-delta deposits include thick to very thick, crudely-stratified, clast-supported, and rare open-framework conglomerates; horizontal and planar cross-stratified boulders, cobbles, pebbles; and sand, and thickly bedded to massive silt. All of these different subaerial facies usually occur within thick, horizontal to subhorizontal beds; however, conglomeratic beds also occur as channel-fill deposits.

Conglomeratic sediments range in size from fine sand to boulders and usually fine-upward, but sometimes gradationally coarsen upward, or show no discernible vertical change in grain size. Some sequences interpreted to be coarsening-upward could be the result of poor definition between thinner, discrete conglomerate beds. Up-current imbrication of cobbles and boulders within conglomeratic beds is poorly to well-exhibited. Conglomerates of boulder- to pebble-size material are usually thickly bedded, clast-supported, and contain a sandy matrix. The lower contact of coarse-grained beds usually is abrupt and suggestive of a predepositional phase of channel scouring. These conglomerate beds are interpreted to have been deposited in a braided stream as part of migrating channel bars.

An example of an exhumed conglomeratic channel-fill sequence is visible at the coastal sea cliff exposure near Central Machete-Puerto Arroyo (fig. 16). This channel sequence ranges from 10 to 30 m wide and is 1 to 4 m thick. The channel-fill consists of a clast-supported, cobble- and boulder-conglomerate with a sandy to pebbly matrix; the sequence exhibits large-scale, low-angle crossbeds that were possibly associated with channel bar migration and gradual channel aggradation. The channel conglomerate overlies and downcuts a massive silt bed. Rare open-channel fill conglomerates have been seen along a cutbank exposure of the Río Nigua at Salinas. The conglomeratic stream deposits are probably associated with deposition during high flow conditions in which most fine sediment is carried away in suspension. Smaller pebbles and sand were deposited during lower flow regimes and filled only the uppermost pore space.

Bedded coarse-grained deposits of fine to coarse sand and pebbles, with minor cobbles, are dominated by horizontal and planar crossbedding. Sandy and pebbly, planar cross-bedded deposits are interpreted as being associated with migrating alluvial bedforms. Horizontal or parallel crossbeds within the sand and pebble lithofacies and are attributed to deposition within an upper flow regime. Rust (1972) concluded that migrating longitudinal bars form poorly defined horizontal beds possibly due to transport in planar sheets under high-flow. A few, poorly preserved, large-scale trough beds of fine to coarse sand and pebbly sand, probably associated with braided-stream deposition, have been observed at the Central Machete-Puerto Arroyo sea cliff exposure and in a cutbank exposure along the upland channel fan-head reach of the Río Coamo near the city of Coamo.

Silt beds were largely deposited under sheet flow conditions in which flood waters spread outside the confines of an incised alluvial channel. Bedded silt deposits are often massive and tend to be blocky, especially where large pieces have sloughed off the incised channel walls, as in the Río Coamo south of Paso Seco. Horizontal bedding features present within the silt facies are not everywhere evident, partly due to the quality of preservation within the section at most exposures. At the Río Coamo exposure south of Paso Seco, very thin, discontinuous lenses of sand and pebbles (less than a few cm) separate discrete horizontal beds. The uppermost contact that separates massive silt beds from overlying coarse-grained sand, pebbles, cobble, and boulder-bedded deposits is abrupt, erosional, and, in many places, shows evidence of fluvial scouring.

Poorly-preserved paleosols were seen in a few locations and represent periods of nondeposition and subaerial exposure. Paleosols are represented by the occurrence of calcium carbonate deposits contained within the bedded fan-delta sequence. Calcification generally occurs in subhumid to arid regions where there is insufficient precipitation to drive soil water to the water table. Calcium carbonate, carried into solution from the A soil horizon, is reprecipitated in the B soil horizon. Calcium carbonate deposits have been observed at a road cut into the coastal terrace north of Bahía de Rincón, west of Las Ochenta, and within the streambed of the Río Coamo near Paso Seco. The reported occurrence of white “tosca” in driller’s well log reports, often underlain by sand and gravel deposits, can be interpreted as paleosol-related calcium carbonate.

Vertical Profile

Well-to-well correlation of discrete subsurface cobble, sand, and silt beds that underlie the fan-delta plain is impossible because of the lack of continuity of coarse- and fine-grained strata, lack of correlable marker beds, and poor geophysical-log control. Core samples were continuously collected from test wells drilled using the reverse-air dual-tube drilling method previously described. Two wells (SC 4 and SC 5) are located within the Ponce Basin; a third well (SC 2) was drilled northeast of the basin but within the distal part of the Salinas fan delta. Due to the unconsolidated nature of coarse-grained fan-delta deposits, crossbed current structures were destroyed and many bed-to-bed contacts were “blurred” by coring operations; however, progressive changes in grain

FIGURE 16.—Southward-facing seacliff exposure at Central Machete-Puerto Arroyo in the South Coast ground-water province, Puerto Rico, showing an exhumed channel within Quaternary fan-delta plain.

size and bed thickness could, for the most part, be observed (pl. 3).

The analysis of sedimentary cyclicity, as defined by progressive changes in grain size, bed thickness, and their interpreted depositional process, has been shown to be a viable approach to evaluate alluvial fan depositional systems and their short-term and long-term depositional behavior (Heward, 1978; Steel and Aasheim, 1978; Gloppen and Steel, 1981; Steel, 1988). One purpose of this analysis is to identify cyclic patterns of deposition within the vertical sequence that, at first glance, appear to be part of a chaotic distribution of coarse-grained and fine-grained sediments. Recognition of such cyclicity was used to aid well-to-well correlation between the different cored test holes in this study (pl. 3) and to suggest how the fan-delta sequence might be separated into regionally-extensive water-bearing units.

Three scales of cyclic deposition were identified. Smallest-scale cyclicity (less than 1 m to 20 m) is associated with discrete coarse- and fine-grained beds and largely characterized by a progressive-upward change in grain size within a discrete bed. An intermediate-scale of cyclic deposition (15 to 70 m) was recognized by progressive changes in bed thickness. Some cycles were separated by the occurrence of limestone or limy marl; limestone and limy marl strata were considered to represent the initial phase in a new cycle of deposition. Coarse- (gravel- and sand-size detritus) and fine-grained (silt-size detritus) beds were grouped as an intermediate-scale cycle if bed thickness appeared to progressively increase or progressively decrease. The largest scale (400 to 500 m) of cyclicity referred to overall changes in bed thickness that occurred within the entire gravel, sand, and silt section that was penetrated by drilling.

In general, most individual beds of coarse-grained sediment either fine-upward or coarsen-upward; in some instances, they do not exhibit any obvious change in grain size. Fining-upward bed cycles are the most common vertical change in lithology, and they usually consist of a basal conglomerate with a sandy matrix, fining upward to coarse to fine sand. Whereas the lower silt-to-sand contact is distinct and sharp, the upper sand-to-silt contact ranged from sharp to gradational. Bedded units of cobble- to sand-size detritus range from 1 to 20 m thick with thickest coarse-grained beds more commonly seen within the upper part of the section.

Thin lenses of sand, used to separate discrete silt beds at outcrop, were not easily recognized in cored samples. Small-scale fining-upward cycles probably formed in response to flood deposition, such as aggradation or lateral accretion within channels. Small-scale coarsening-upward cycles are either associated with channel bar migration or are the result of poor definition between thinner, discrete coarse-grained beds. Silt bed thickness varies from less than 1 to 20 m; thickest silt beds are generally present within the deep subsurface. Silt beds are associated with low-energy sheetflow deposition in areas away from major trunk streams, in distal parts of the fan, or in interfan areas. Some or many of these beds do not represent a single flood, but are probably the result of the stacking of deposits from several floods.

Four separate, intermediate-scale depositional cycles that range from 30 to 50 m thick can be delineated within the vertical section penetrated by test wells SC 4 (near Santa Isabel) and SC 5 (near Boca Chica, Playa de Ponce). Two intermediate-scale depositional cycles were identified within the fan-delta section penetrated by SC 2 (Salinas fan delta) and range from 15 to 70 m thick. Coarsening-upward cycles, characterized by upward-thickening of coarse-grained beds and upward-thinning of fine-grained beds, dominate the cored section of SC 4 and SC 5. Thin marl, limy clay, and limestone beds separate several of the depositional cycles and can indicate a minor period of marine onlap prior to continued fan outbuilding. Fining-upward cycles, recognized by the upward-thinning of coarse-grained beds, and the thickening-upward of fine-grained beds, dominate the SC 2 core. Only one intermediate-scale cycle (SC 4 well) displays a gradual coarsening upward followed by a fining-upward change contained within a single cycle.

Unlike grain size variations (small-scale cyclically) that occur within discrete beds and reflect short-term depositional (stream and floodflow) events, intermediate- and large-scale cyclicity probably reflect overall progradational (or aggradational) and retrogradational fan activity. This fan activity was controlled by a complex interaction of eustasy, climate, and tectonics. The specific role of these contributory factors is considered later.

Large-scale cyclicity, or the progressive change in bed thickness throughout the entire penetrated section, differs through the fan-delta plain. The SC 5 core shows an overall coarsening-upward. The SC 4 core exhibits a similar coarsening-upward pattern in the lower two-thirds of the section, but appears to fine-upward near the top of the section. The SC 2 core exhibits a third pattern, in which the fan-delta section appears to fine-upward.

Sand and Gravel Percentage

Sand and gravel percentage maps show the spatial distribution of coarse- and fine-grained lithofacies within the fan-delta plain. Sand and gravel percentage data are mostly based on lithologic descriptions provided in drillers' reports. The majority of wells located in the South Coast ground-water province and used as part of this analysis, were drilled prior to 1980 mostly using a cable-tool percussion method. Drillers' lithologic descriptions provided information concerning the type of lithologic material, their sample depth and the thickness of discrete beds of gravel, sand, silt and clay. The amount of gravel plus sand at a given locality is expressed as a percent of the total sedimentary section. The writer assumed that the sand and gravel calculated for a partial sequence could be assigned as being representative of the entire undrilled section. However, most coastal area wells are shallow and do not penetrate deeper parts of section; the character of these deeply-buried sediments is poorly known. Accordingly, the percent of coarse-grained detritus is likely over- or underestimated in these areas. Therefore, the areal distribution is intended to illustrate the areal prevalence of coarse-grained deposits in context of the conceptual depositional model previously described.

A lithofacies map for the fan-delta plain shows that sand and gravel deposits were concentrated as lobes and separated from one another by interlobe areas of fine-grained detritus (pl. 1*D*). The relative size of the different fan-delta lobes can reflect differences in drainage basin size, topographic relief, elevation, stream gradients, and possibly the type of rock that underlies feeder basins. The Capitanejo, Coamo, Salinas, and Guamani fan deltas contain large concentrations of coarse detritus that extend considerably downfan. Small lobes are associated with the Ríos Pastillo-Cañas, Cañas at Juana Díaz, Descalabrado, and Jueyes; the Portugués-Bucaná, Seco, and Arroyo sand and gravel lobe are moderate in size.

The percentage of gravel plus sand in the different fan deltas decreases in a downfan and downflow direction. The percent lithofacies map indicates that highest concentrations of coarse-grained (sand and gravel) sediment occur in proximal fan areas or within fluvial channels that reach inland where flows are restricted and velocities are the greatest. Within the proximal parts of the Salinas, Coamo, and Capitanejo fan deltas, sand and gravel deposits exceed 40 percent of the entire section. Within the Río Cerrillos, one of two streams that drains proximal parts of the Portugués-Bucaná fan at Ponce, the percent of sand and gravel exceeds 60 percent. High sand and gravel percentages are also present within the Río Jacaguas alluvial valley, one of two feeder streams to the Capitanejo fan delta. High concentrations of sand and gravel are locally found within the upland channel of the Coamo fan delta.

Where channeled, surface water spreads out and covers the midfan floodplain, floodwaters diminish in depth and velocity, and coarse detritus is deposited as a lobe. In midfan areas, the amount of coarse material diminishes to 20 to 40 percent of the sedimentary section. As floodwaters extend downfan, their bedload consists primarily of silt and clay. In these downfan areas, the coarse fraction can represent less than 20 percent of the fan-delta distal sequence.

The size, extent, and amount of sand and gravel within the Salinas and Guamani fan-delta lobes suggest that distal subaerial fan-delta deposits lie buried in the offshore subsurface. Well cuttings collected from a well in the Playa de Salinas area indicate that subaerial deposits are buried beneath mud and sand deposited within a transitional marine environment. Conversely, an erosional coastal marine scarp marks the point where Holocene sea level rise has truncated the seaward part of the Guamani fan delta.

Finger-like projections of coarse-grained detritus extend southeast and southwest from the main channel and Salinas fan-delta lobe; similar features extend from the Arroyo and Jueyes fan delta. They are interpreted as paleostream channels that fed fan segments that lie farther offshore and were active during a lower sea level. Perhaps, these paleochannels initially formed during a phase of fan incision and sea level decline, and later aggraded during a eustatic rise.

The distribution of sand and gravel in the Capitanejo fan-delta area is more complex than elsewhere within the fan-delta plain. The lithofacies pattern here suggests that the Río Inabon and Río Jacaguas fed separate fan deltas that coalesced and now make up a single fan. To the south of the Portugués-Bucaná fan, a buried sequence of fine, dark gray sand and minor shell debris lies at depths less than 10 to 15 m below land surface. The lateral extent of this sequence suggests that it forms a narrow strip trending in an east-west direction that parallels the modern-day coastline in the Playa de Ponce area. These sandy beds are, in turn, underlain by dark gray to blue organic clay and shell debris. Similar clay beds buried in the subsurface also occur in a landward direction. Given their proximity to a prograding beach that can be mapped at land surface, it is likely that these beds were part of a former beach and marsh area which bordered the coast.

It is difficult to characterize the distribution of coarse-grained detritus within fan-delta/valley-fill areas between Tallaboa and Guánica because of sparse well control (pl. 2*C*). It appears that sand plus gravel-size detritus is concentrated within the narrower confines of inland incised-valley channels. Sand and gravel within the Guánica (Río Loco) and Río Yauco Valleys ranges from less than 25 to more than 75 percent of the vertical section (pl. 2*C*). In the Río Tallaboa area, sand and gravel is present in more than 60 percent of the section in the valley-fill area immediately north of the coastward low-lying fan-delta plain; the amount of coarse-grained material diminishes to less than 20 percent within the fan-delta plain south of the channelized area.

THE SOUTH COAST TERTIARY BASIN: CONTROLS ON CLASTIC DEPOSITION

As discussed above, a significant part of the Oligocene to Pliocene (?) sedimentary sequence and nearly the entire Quaternary sequence that lies onshore consists of clastic coarse-grained detrital sediments that were deposited as part of a series of fan deltas or alluvial fans. A principal physiographic requisite to fan-delta or alluvial-fan deposition is the co-occurrence of a highland area that immediately adjoins a lowland area (Denny, 1967, p. 83). Puerto Rico's Cordillera Central highland area has served as the source for abundant coarse-grained detritus throughout Oligocene to Quaternary time. As rivers exit the highland and streamflow moves outside the confines of the channel and onto the fan surface there is an abrupt reduction in stream competence, which results in deposition of bedload material.

Structural setting and associated tectonic movement is a second factor considered important as a control to fan-delta and alluvial-fan deposition. Accordingly, tectonics is often emphasized in the fan-delta and alluvial-fan literature. Wescott and Ethridge (1980) catalogued modern and ancient fan deltas within a tectonic-physiographic classification scheme. They observed that fan deltas are, in part, recognized by their close association and proximity to relatively young, high-relief mountains that are commonly fault-bound on the proximal margins of the fan deltas. Tectonic movement can increase the gradient of streams, rejuvenate nearby highland sources of clastic detritus (Blissenbach, 1954), shift sites of deposition (Crowell, 1974), and control patterns of fan growth (Heward, 1978). Tectonic movement provides the initial relief required for the formation of fans; continued movement creates basinal conditions that are well-suited to the continued accumulation and preservation of detritus.

Although the role of tectonically-induced base level change should not be underestimated, other factors must also be considered. Fan formation can occur in response to rapid rates of eustatic sea level rise. Sea level rise is often accompanied by a eustatically-related change in climate (McGowen, 1970; Soegaard, 1990). A world-wide acceleration of fan growth occurred in response to sea level rise and climate change during the Quaternary (Nilsen, 1982).

STRUCTURAL FEATURES AND EVIDENCE OF TECTONIC MOVEMENT IN THE SOUTH COAST GROUND-WATER PROVINCE

The Great Southern Puerto Rico fault zone is a principal structural feature on the southern side of the island and contains a wide variety of fault structures. The fault zone is formed by parallel to subparallel sinistral faults that strike northwest and extend diagonally across the south-central part of Puerto Rico. Glover (1971) postulated a fault zone extending westward to the central-west coastline, separating the central and southwestern blocks of the island. However, Glover's thoughts on the subject were made prior to much of the needed mapping of western Puerto Rico, and the proposal of such a continuous fault zone has been questioned; detailed delineation of a southwestern block is not possible because of the widespread cover of younger Cretaceous and Tertiary rocks and pervasive normal and strike-slip faults (Krushensky, written commun., 1994). Oceanic rocks that lie southwest of the fault zone were emplaced by an abducting plate during the middle Eocene or even later (Krushensky and Schellekens, written commun., 1994).

Gravity (Glover, 1971, p. 84) and seismic data (Garrison, 1969) indicate that the Great Southern Puerto Rico fault zone extends beneath the fan-delta plain and the Isla Caja de Muertos shelf, possibly forming the south wall of the Whiting Basin (Western Geophysical Company of America, 1974). As many as 12 northwest striking sinistral faults have been mapped in the insular highland areas west of Coamo (pls. 1*A*, 1*E*). The Santo Domingo, San Patricio, Paraiso, and Río Jueyes faults, and the splay fault, Río Cañas Abajo, form the northern margin of the fault zone. The Bartolomei, Lago Garzas, Portugués, and Machuelo sinistral faults form the southwestern margin of the fault zone in an area west of the fan-delta plain. Northwest of Ponce, the width of the fault zone that lies between the northernmost (San Patricio) and southernmost (Bartolomei) sinistral faults is more than 9-km wide. An interpretative structure map of the bedrock surface that underlies the fan-delta plain (discussion follows) suggests the Great Southern Puerto Rico fault zone narrows to a width of 3 km. However, coastward parts of the fan-delta plain possibly conceal a much wider zone, but control given by wells is lacking. The strike of the fault zone varies from N 54° W to N 55° W where it crosses the Cordillera Central to the northwest and west of Ponce (Glover, 1971; Krushensky and Monroe, 1975, 1978, 1979) to N 75° W where it underlies the fan-delta plain.

Low-angle thrust faults mapped within the fault zone occur only within a narrow belt of Eocene to Paleocene age rocks located in the highland areas immediately north of the fan-delta plain and between the Ríos Coamo and Jacaguas (Glover and Mattson, 1973). These faults have been interpreted as (1) northward-moving gravity slide plates (Glover, 1971), (2) southward-moving gravity glide plates (Krushensky and Monroe, 1975), (3) part of a transgressive flower structure (Erickson and others, 1990), or (4) formed by compressional thrust movement that preceded sinistral movement (Erickson and others, 1990). High-angle cross faults that strike northwest have been mapped throughout the highland areas north and northwest of Ponce, the majority of which do not crosscut sinistral faults. West and north of Ponce, normal faults strike east-west and vertically displace the Juana Díaz Formation and the Ponce Limestone.

Glover (1971) thought first sinistral movement occurred during the Early Cretaceous, with later episodes of movement occurring during Maestrichtian and Eocene time. McIntyre (1971, 1975) suggests that inception of the Great Southern Puerto Rico fault zone was a post-middle Eocene event. Krushensky and Monroe (1975, 1978) constrained sinistral movement to Eocene to Oligocene time with horizontal movement continuing along the Lago Garzas and Bartolomei faults as late as the early Miocene. Sinistral movement along the Lago Garzas and Bartolomei faults could possibly correspond with the development of the large structural and depositional basin that underlies the fan-delta plain between Ponce and Santa Isabel (figs. 9, 10, and discussion below). Other faults strike east-west, have a normal slip component, and displace rocks of the Ponce Limestone and Juana Díaz Formation that are exposed west and north of Ponce. These latter faults probably postdate sinistral movement.

Whereas rapid rates of denudation by fluvial erosion and mass wastage processes help mask structural relations in many parts of Puerto Rico, other lines of geomorphic evidence support ancient and more recent structural movement. For example, closely aligned karstic features in the North Coast limestone ground-water province nearly parallel joint and fracture patterns of older, underlying volcaniclastic rocks (Tobisch and Turner, 1971). Fault control of mountain areas has also been inferred by the apparent alignment of faults with linear valleys and scarps (Kaye, 1959a, p. 51; Pease, 1968; Rodgers, 1977; M'Gonigle, 1978). North of the Salinas fan-delta, streams parallel fractures, joints, and faults (Berryhill and Glover, 1960) and in highland areas of the Cordillera Central, streams often exhibit a drainage pattern that seems to parallel the orientation of faults within the Great Southern Puerto Rico fault zone. Snow (1993) has noted fault control along some segments of several drainage divides in the interior mountains. Recent tectonic movement within the Ponce Basin is suggested by linear bathymetric scarps that conform with the position of Bajo Tasmanian fault zone and Caja de Muertos Fault (Garrison, 1969). Seaward tilting of the Isla Caja de Muertos shelf during Quaternary time has caused the drowning of some reefs (Beach and Trumbull, 1981).

The configuration of the bedrock surface that underlies Puerto Rico's southern fan-delta plain (pl. 1*B*) appears to parallel structural and geomorphic features in the highland areas. The distinctive pattern of bedrock low and high areas that underlie the eastern half of the fan-delta plain ("buried valleys and ridges" of McClymonds and Ward, 1966) suggests that fault movement or fracturing, or both, controlled pre-Quaternary paleotopography in southern Puerto Rico. Bedrock low areas probably correspond to sites that have been subject to greater rates of mechanical and chemical subaerial erosion. However, differential rates of pre-fan erosion could have resulted in topographic inversion; that is, structural and paleotopographic "highs and lows" do not necessarily correspond.

It is suggested here that the pattern of buried bedrock highs and lows are relict features of a braided sinistral fault system. Horst and graben fault blocks, formed by movement along the Great Southern Puerto Rico fault zone, were subjected to subaerial erosion, then buried and preserved as a series of paleotopographic ridges and valleys. The position and extent of these buried faults were largely *inferred* by the sharp breaks in bedrock slope (compare pls. 1*B* and 1*E*). Most inferred fracture or faults strike northwest, northeast, or east-west.

A distinctive change in bedrock slope caused by faulting occurs in the western half of the fan-delta plain (pls. 1*B*, 1*E*). Two faults border the margins of a large graben and delimit the landward border of the Ponce Basin. The west-northwest oriented fault (N 70° W to N 80° W) is remarkably linear and extends 21 km as a single trace from Aguilita to Bahía de Rincón exhibiting dip-slip movement to the south. Rocks of Miocene to Oligocene age have been vertically displaced by as much as 50 m near Aguilita but more than 200 m where the fault crosses the Bahía de Rincon coastline. This northwest fault trace is well-aligned with the sinistral Portugués fault, but concealed by unfaulted strata of the Juana Díaz Formation and Ponce Limestone that crop out near Ponce. Sinistral movement changing to down-to-the-south and southwest normal movement also occurs along the San Patricio fault, horizontally juxtaposing rocks of Oligocene and early Tertiary age (Krushensky and Monroe, 1975). If outcrop relations are correctly illustrated (Krushensky and Monroe, 1975), latest horizontal movement along this buried hinge line occurred prior to, with latest movement during, Oligocene time. The throughgoing linearity and steeply vertical nature of this northwest-oriented buried hinge line, and its parallel alignment with other northwest-oriented, sinistral faults suggests it too was a former sinistral fault. Perhaps, this fault contained a normal component or was reactivated by normal movement. Sinistral movement along the Bartolomei fault, located southwest of the Portugués fault, could have occurred during early Miocene time (Krushensky and Monroe, 1978), but on the basis of available well data its extension beneath the fan-delta plain can not be demonstrated.

A second set of lineaments that underlie the fan-delta plain strike N 40° E to N 60° E and parallel some faults mapped in the highland areas north of the fan-delta plain (Glover, 1971; Krushensky and Monroe, 1975, 1978, 1979) as well as several other faults that displace rocks beneath the Isla Caja de Muertos shelf (Garrison, 1969; Beach and Trumbull, 1981). It is impossible to accurately determine crosscutting relations between various faults that underlie the fan-delta plain; some northeast-oriented faults probably formed in response to sinistral movement, whereas others could reflect a later phase of normal movement. For example, a buried northeast-striking fault trace (pl. 1*E*) is shown near Aguilita to truncate a northwest-oriented hinge line that together delimit the landward margin of the Ponce Basin. This suggests that movement of the northeast-striking fault trace postdates movement along the northwest hinge line.

The third buried fault or lineament orientation located south of Ponce also exhibits down-to-the-south normal movement. These east-west buried faults parallel other normal faults that displace the Juana Díaz Formation and Ponce Limestone west of the fan-delta plain (Krushensky and Monroe, 1975, 1978, 1979). These east-west buried faults also parallel normal faults that have been mapped offshore along the Isla Caja de Muertos shelf (Garrison, 1969; Western Geophysical Company of America, 1974; Meyerhoff and others, 1983).

A strike-slip structural model is postulated here to explain Oligocene depositional patterns (fig. 9) and is partly based on the fault pattern inferred for the buried part of the Great Southern Puerto Rico fault zone that lies east and southeast of Ponce. Two southeast-striking sinistral faults, assumed to be coincident with northeastern and southwestern margins of the fault zone, diverge and form a large wedge-shaped basin. Uplift and convergence of the two sinistral faults at their wedge-tip coincides with areas containing conglomeratic detritus of the basal Juana Díaz Formation. Carbonate rocks, thickest between Ponce and Bahía de Guánica, form a northeast-southwest oriented band. The thickest reef deposits accumulated along a shelf hinge line, formed along a fault striking northeast-southwest with down-to-the-southeast normal movement. Deep-water deposition occurred to the southeast within a subsiding basin. Fault and outcrop relations indicate last sinistral movement within the Great Southern Puerto Rico fault zone occurred along the Lago Garzas-Bartolomei faults during early Miocene time (Krushensky and Monroe, 1978).

Strike-slip movement was succeeded by normal fault movement during middle to late Miocene time, possibly along a former sinistral fault. Subsidence or uplift, or both, in the Ponce-Santa Isabel area was substantial. The clastic and minor limestone sequence that infills the large graben structure from Santa Isabel eastward exceeds 800 m in thickness (fig. 11). Denning (1955) estimated that as much as 1,100 m of vertical displacement occurred along one of two faults that form the Ponce Basin, a graben structure identified in Isla Caja de Muertos shelf bathymetry (Beach and Trumbull, 1981). Post-early Pliocene movement can be inferred by the occurrence of normal faults which displace the Ponce Limestone and locally reverse the southward-dip of beds to the north.

Elevated marine terrace data collected in the northwestern part of Puerto Rico show that the island was subject to slow insular uplift during the Quaternary. As much as 50 to 90 m of insular uplift has occurred since the onset of the Pleistocene (Taggart and Joyce, 1990, Taggart, 1992). If Moore's (1982) eustatic curves correctly depict present seas at their highest level in the last 120,000 years, Taggart and Joyce's (1990) assumption of an average rate of uplift (.03 to .05 mm/yr) might not be correct, nor can this assumed average rate be applied to the south coast. A relict marine shoreline near

Bahía de Rincón lies 2 to 3 m above sea level. A late Holocene uplift rate of 1.8 mm/yr (Geomatrix Consultants, 1988) or episodic movement on the south coast is suggested if one can correctly correlate the Bahía de Rincon relict shoreline with the 1,500 to 3,000 year-old marine terrace in northwestern Puerto Rico.

CHANGES IN BASE LEVEL: ITS RECORD IN THE STRATIGRAPHIC SEQUENCE

Clastic, basal conglomeratic deposits of the Juana Díaz Formation, considered coeval with the planktonic foraminifera zone, *Globergerina ampliapertura* (Moussa and Seiglie, 1970; Frost and others, 1983), were deposited during early Oligocene time. Conglomeratic alluvial-fan or fan-delta deposits were probably deposited in direct response to a low base level. If eustatically high seas prevailed during early Oligocene time (Haq and others, 1988), deposition of conglomeratic fan-delta deposits probably reflect tectonic movement (lowering base level), possibly associated with sinistral movement along the Great Southern Puerto Rico fault zone (fig. 17). Limestone strata of the Guánica and Peñuelas area are considered coeval with the *Globergina opima opima* Zone and exhibit periods of reef growth interrupted by episodes of reef destruction; destructive events have been attributed to tectonic uplift or subsidence of the shelf margin, or both (Frost and others, 1983, p. 39). The influx of clastics and rapid subsidence in the Ponce-Juana Díaz area during late-early Oligocene time is indicated by a deep shelf facies of sandy shale and minor limestone beds that directly overlie conglomeratic beds.

Moussa and Seiglie (1970) correlated shallow-water limestone strata in areas west of Río Tallaboa with the *Globergerina ciperoensis ciperoensis* Zone, whereas Frost and others (1983) believed that reef deposition in the western part of the basin terminated by this time. Pelagic mudstone and turbidite beds overlie reef-shelf deposits in the Guayanilla area indicating rapid shift from shallow marine, reef-shelf deposition to deep water, pelagic deposition. Subsidence within the basin probably continued to control pelagic conditions as global sea level was relatively low during late Oligocene (Haq and others, 1988). An erosion surface and unconformity spans most, if not all, of the *Globergerina ciperoensis ciperoensis* Zone (Frost and others, 1983, p. 58, 61, 76) and separates the slope facies of late Oligocene age from overlying slope chalk beds ("Angola limestone" and "Río Tallaboa marlstone" of Moussa and Seiglie, 1970, 1975) of early Miocene age. Frost and others (1983, p. 61) believed this unconformity reflected uplift and subaerial erosion during the latest Oligocene that was followed by subsidence and flooding in the early Miocene. Submarine erosion or a submarine gravity slide of the late Oligocene slope might be an alternative explanation to the occurrence of "slope-on-slope" deposits. If the basin experienced a fluctuation in relative sea level greater than 100 m, one might expect deposition of a reef or shallow shelf sequence that would separate the two different slope sequences. An erosive submarine event would eliminate the need for a 100 m or greater eustatic or tectonic change in base level to explain the late Oligocene-early Miocene hiatus.

Bathyal submergence and deposition of the island slope carbonate rocks is recorded during earliest Miocene time (*Globergerina kugleri* Zone), a period of high global sea levels. Moussa and Seiglie (1970, p. 1893) implied an unconformity separated the chalky unnamed pelagic deposits into two separate units ("Angola Limestone" and "Tallaboa marlstone"), whereas Frost and others (1983, p. 62) indicate that submergence probably continued without interruption throughout early Miocene time. Uplift and a period of subaerial erosion are suggested by an unconformity that spans the early-middle Miocene. This hiatus separates uppermost island-slope pelagic chalk beds from overlying strata of the Ponce Limestone (Moussa and Seiglie, 1970; Frost and others, 1983).

The Ponce Limestone consists of a shallow-water carbonate sequence that was largely deposited during middle early Miocene to early Pliocene time. The Ponce Limestone grades eastward to a conglomeratic facies that underlies the western part of the fan-delta plain. This clastic facies could be, in part, equivalent to paralic crossbedded sand and gravelly channel-fill deposits (Monroe, 1980, p. 73; Moussa and Seiglie, 1975, p. 166) that crop out in a restricted area west of Ponce. Shallow-water and some deeper shelf environments contained within the Ponce Limestone sequence indicate that basin subsidence could have, at times, exceeded eustatic decline. The more than 500-m thick clastic sequence of Miocene age near Santa Isabel indicates this area was subject to a rapid rate of subsidence or uplift, or both, in the adjoining highland areas.

Moussa and Seiglie (1975, p. 168) and Frost and others (1983, p. 10) consider lower beds of the Ponce Limestone to be early middle Miocene age. Frost and others (1983) correlate coral assemblages contained within these strata with *Globorotalia fohsi fohsi* Zone of early middle Miocene age. Bold (1969) correlated uppermost strata of the Ponce "Formation" with the *Globorotalia margaritae* Zone on the basis of ostacode and bethonic foraminiferal assemblages. Under current USGS usage (Monroe (1980, p. 82), the Ponce Limestone is considered to be late Miocene in age. However, the *Globorotalia margaritae* foraminiferal zone is currently considered to range from latest Miocene to early Pliocene age (Haq and others, 1988). Therefore, uppermost beds of the Ponce could be younger than the late Miocene age suggested by Monroe (1980). The unconformity that marks the upper surface of the Ponce Limestone probably spans late Pliocene time, a period of subaerial exposure, declining sea levels, and possibly tectonic uplift.

In summary, changes in base level during Oligocene to early Pliocene time and clastic-carbonate deposition appear

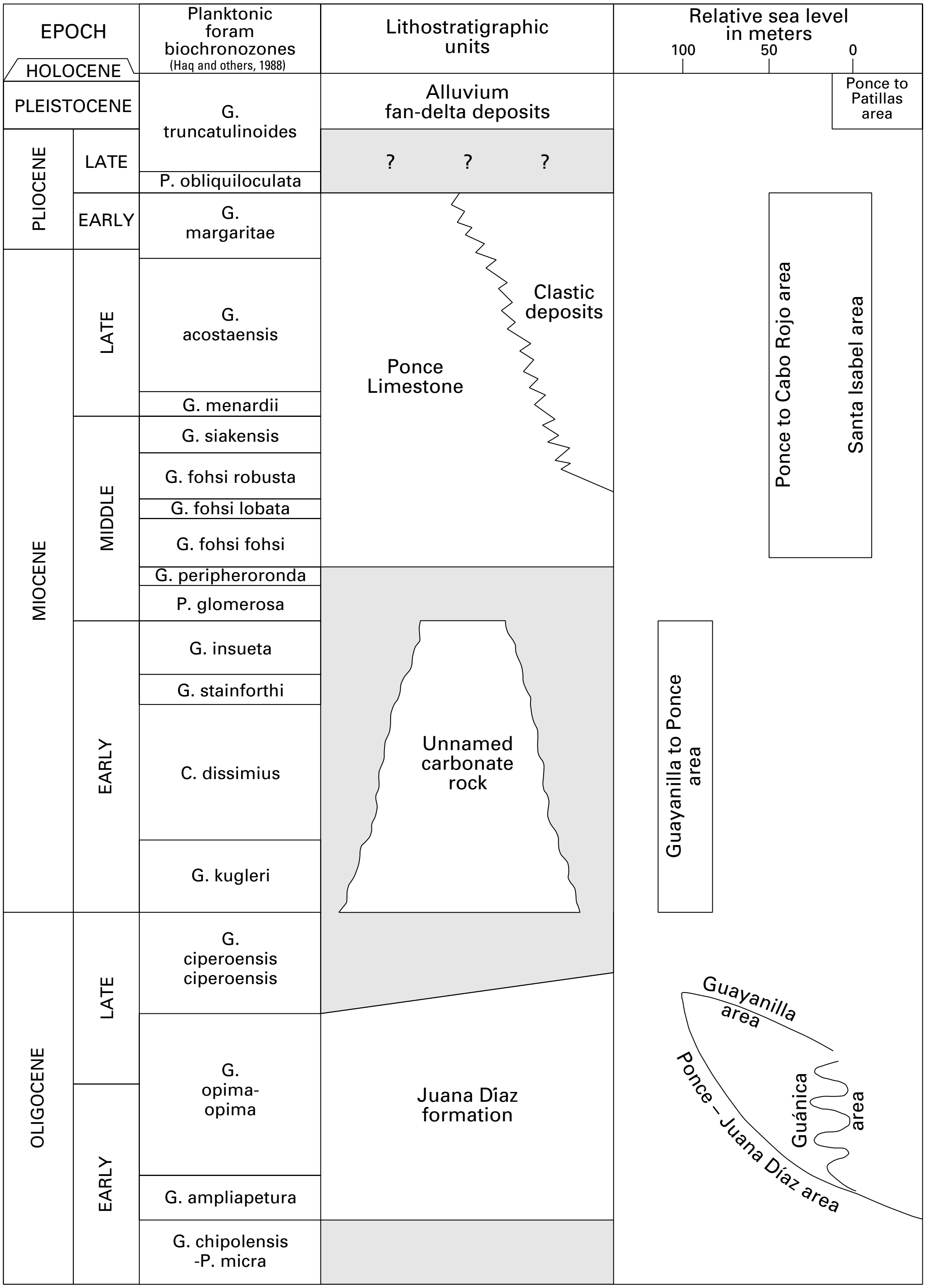


FIGURE 17.—Chart of major biochronozones and lithostratigraphic units of late Tertiary and Quaternary age in the South Coast ground-water province and estimates of relative sea level.

to have been controlled by tectonic movement and eustacy. Of the two variables, however, tectonic movement seems to represent a more important factor in terms of late Tertiary clastic and carbonate deposition.

Change in eustatic base level was the primary control on coarse-grained clastic deposition in southern Puerto Rico during the Quaternary with tectonic movement playing a secondary role. Sea level rose as much as 130 m during the last glacial maxima (18,000 years before present [yr BP]) (Chappell and Shackleton, 1986; Fairbanks, 1989) with eustatic variations of similar magnitude occurring during the early Pleistocene and Pliocene time (Haq and others, 1988).

Study of the Pleistocene (?) to Holocene vertical sequence as seen at outcrop and on the basis of deep well control (pl. 3) provides considerable insight regarding short- and long-term depositional behavior of the South Coast fan deltas. Small-scale fining- and coarsening-upward cycles that occur within individual beds, or a series of beds (1 to 20 m thick), are probably related to specific short-term hydrologic events. Longer-term depositional behavior is probably related to fluctuations in base level; these changes are exhibited within the intermediate (15 to 70 m) and large-scale (400 to 500 m) cycles. To understand the relation between intermediate-scale and large-scale depositional cycles within the South Coast fan-delta plain, one must assume that eustatic change in base level during Quaternary occurred at a greater frequency and was larger in magnitude than base level change associated with tectonic movement.

The stacked series of intermediate-scale, coarsening-upward (aggradation) and fining-upward (retrogradation) cycles defined within three continuously-cored, deep test wells (pl. 3) reflect fan-delta deposition in response to the relative change in base level. This change in relative base level includes two principal components, change in base level due to eustacy and change in base level due to tectonics. Tectonic base level change is further complicated in that it includes uplift and subsidence that, in some cases, could have occurred simultaneously within different parts of the fan-delta plain. This eustatic-tectonic balance could explain markedly different depositional responses within the western and eastern parts of the fan-delta plain, namely, aggradation that occurs within landward parts of the slowly subsiding Ponce Basin area, and retrogradation that occurs on the adjoining, structural block to the east that is slowly being uplifted. Two deep wells (SC 4 and SC 5) that penetrate the western half of the fan-delta plain lie well within the Ponce basin; the easternmost well (SC 2) is located in the upthrown side of a fault block that defines the northeastern side of the basin. If intermediate-scale depositional cycles of the Capitanejo, Portugués-Bucaná, Coamo, and Salinas fans are correctly correlated, it is apparent that fans located in the western part of the south coast actively aggraded or even prograded during sea level rise. This eustatically-induced sedimentation process, characterized by the intermediate-scale, thickening upward of coarse-grained beds, is analogous to deposition that occurs in a reservoir following closure of a dam (Leopold and others, 1964, p. 259). The locus of coarse-grained deposition during lowstand periods probably remained in close proximity to the mountain front or fault line, or both, during each successive lowstand period. Conversely, the eastern part of the fan-delta plain was slowly being uplifted, and the Salinas fan (and other eastern fans) were gradually being abandoned as the locus of coarse-grained deposition shifted seaward. This is supported by a progressive, upward-decrease in the thickness of coarse-grained beds (pl. 3) and a lithofacies map (pl. 1*D*) that indicates buried channels fed fan segments that were probably located in offshore areas. Although large-scale depositional cycles within the Ponce Basin parallel intermediate-scale behavior, this 400 to 500 m scale probably reflects the long-term structural movement; namely, subsidence within the Ponce Basin. Alternately, long-term cyclicity (fining upward) on the eastern edge of the basin suggests gradual fan abandonment as the highland structural block was slowly uplifted.

Two geomorphic features of the fan-delta plain that further illustrate the relation between Quaternary eustacy and uplift include multilevel fan-head terraces and the raised relict shoreline at Bahía de Rincón. The raised shoreline may reflect a lower base level that existed during the late Holocene eustatic rise in sea level. If uplift along the south coast was at a slower rate than eustatic rise, the presence of 1,500- to 3,000-year-old relict shoreline seems, at first glance, contradictory. A possible explanation is that base level along the south coast of Puerto Rico has lowered due to an increase in the rate of uplift approximately 1,500 to 3,000 years ago. An alternative explanation is that the rate of uplift did not significantly increase, but could have exceeded the rate of sea level rise. The rate of eustatic change is sinusoidal and as seas approach their interglacial maxima, the rate of change diminishes. Another possible explanation is that Holocene eustatic sea level has been higher than the present level (Stapor and Matthews, 1983; Shackleton, 1987; Stapor and others, 1991; Taggart, 1992), a view not considered to be resolved by all workers (Kidson, 1982; Lajoie, 1986, p. 102; Bloom and Yonekura, 1990, p. 111).

Fan-head terraces (pl. 1*A*) are interpreted to record short-term fluctuations in sea level. Fan-head trenches probably were incised during interglacial highstands; diminished source area relief was accompanied by an interglacial wet climate, increased vegetation cover that stabilized slopes, and a reduction in fluvial bedload. Multiple terrace levels within apex of different fan-deltas reflect different episodes of interglacial fan-head incision.

Bathymetric data provide additional insight to the change in Quaternary eustatic base level. Fringing reefs separate a relatively shallow, inner shelf and a deeper, outer shelf. A submerged reef borders the Isla Caja de Muertos shelf and slope edge and records a relict lowstand (Beach and Trumbull, 1991). Submerged early Holocene or late Pleistocene reefs located on the shelf edge are common to other eastern Caribbean islands; during later stages of Holocene sea-level rise, reefs were adjacent to deep ocean water but were unable to keep pace with the rising sea level (Macintyre, 1972) (fig. 18). Fan-like nearshore bathymetry and sand percentage data also indicate that these fans extended further seaward and that the Caribbean Sea has subsequently transgressed coastward parts of Puerto Rico's fan-delta plain. Terrigenous deposition has not kept pace with the eustatic rise in sea level, despite pulses of sediment resulting from episodic, catastrophic floods. Thus, it appears that fan deltas of southern Puerto Rico have entered a period of relative quiescence (fig. 19). Wave energy, longshore currents, and carbonate sedimentation are the principal processes operating during sea-level highstands; these processes have reshaped the coastline morphology and promoted the longshore transport of coarse-grained detritus. Beach progradation in the Playa de Ponce area is the direct result of longshore transport of clastic detritus deposited within a slowly subsiding basin. The buildup of carbonate-dominated detritus on the inner Isla Caja de Muertos shelf occurred largely in response to the Holocene rise in sea level combined with lessened fan activity, clastic sediment input, and sediment stress.

CLIMATE

Climate represents the third factor influencing coarse-grained deposition on the south coast. Temporal and spatial variability of moisture and temperature in the Caribbean and Central America region during Pleistocene and Holocene time has been the subject of considerable study and speculation (Douglas and Spencer, 1985). It is theorized that the southern Caribbean-South American region experienced a significant reduction in rainfall (Damuth and Fairbridge, 1970) and an expansion of coastal land areas during glacial lowstands. These dry periods alternated with humid, interglacial periods accompanied by a reduction in land area (Tricart, 1985). A similar reduction in rainfall has also been reported along the western and southern (Tricart, 1985) Caribbean region during the most recent glacial lowstand (18,000 yrs BP) (Street-Perrott and others, 1985). Eustatic lowstand periods within northernmost South America were accompanied by fewer tropical storms and easterly rains, and cooler, drier winds (Damuth and Fairbanks, 1970). It seems plausible that the rain shadow effect caused by Puerto Rico's central highlands and leeward aridity could have been further accentuated.

In Puerto Rico, evidence for Pleistocene climate change is supported by the occurrence of eolianite deposits that are preserved on the northern coastal margin. Coastal sand dunes were active during glacial lowstands on an expanded inner shelf covered by sand and exposed to cool, dry wind. Discrete eolianite beds are separated by paleosols that developed during the wet, interglacial periods subject to milder winds, warmer temperatures, and humid conditions that enhanced dune stabilization by vegetation (Kaye, 1959a). Quaternary climate change in Puerto Rico's westernmost satellite island, Isla Mona, has been inferred on the basis of cemented red residuum and the solution development of caverns (Kaye, 1959b, p. 173). Cemented red residuum indicates the island was subjected to a glacial period of greater aridity or smaller average rate of precipitation. Remnants of the residuum occur on cavern walls and suggest that the caves, once filled with guano, formed earlier in response to greater precipitation and meteroric dissolution, presumably during an interglacial Pleistocene highstand.

The type and distribution of vegetation on the leeward side of Puerto Rico during sea level lowstands is unknown. Assuming Puerto Rico experienced a period of tropical aridity during glacial lowstands, vegetative cover on the fan-delta plain and lower mountain slopes could have been comparatively sparse. It also seems likely that a dry forest, common to lower foothill slopes in Puerto Rico before colonial deforestation, could have extended even further upslope and was accompanied by a reduction in the size of mountain rain forests.

Fan deposition is likely during periods of high runoff and sediment yield. In southern Puerto Rico, such conditions correspond to the period of time immediately following a glacial maximum. If vegetation was sparse, it could not effectively protect the steep mountain slopes from erosion of chemically-weakened saprolitic soil. These soils formed during more humid, interglacial periods were subject to mechanical erosion as precipitation increased in response to a change from a dry, glacial to wetter, interglacial climate. Following geomorphic models proposed by Schumm (1968) and Street-Perrott and others (1985), the transition period phase to greater humidity and more frequent rainfall during eustatic recovery probably represented the most effective period of runoff and sediment yield in southern Puerto Rico. As the recovery period continued, the increased amount and frequency of rainfall was accompanied by an expansion of vegetative cover that helped reduce the sediment yield to streams and eventually resulted in fan-head dissection.

GEOLOGY OF THE WEST COAST GROUND-WATER PROVINCE OF PUERTO RICO

Located in the southeastern part of the island (pl. 2), Lajas valley forms a broad (6 km), elongate (35 m), lowland valley whose floor rises no more than 50 m above sea level. The Sierra Bermeja Mountains border the southern side of the val-

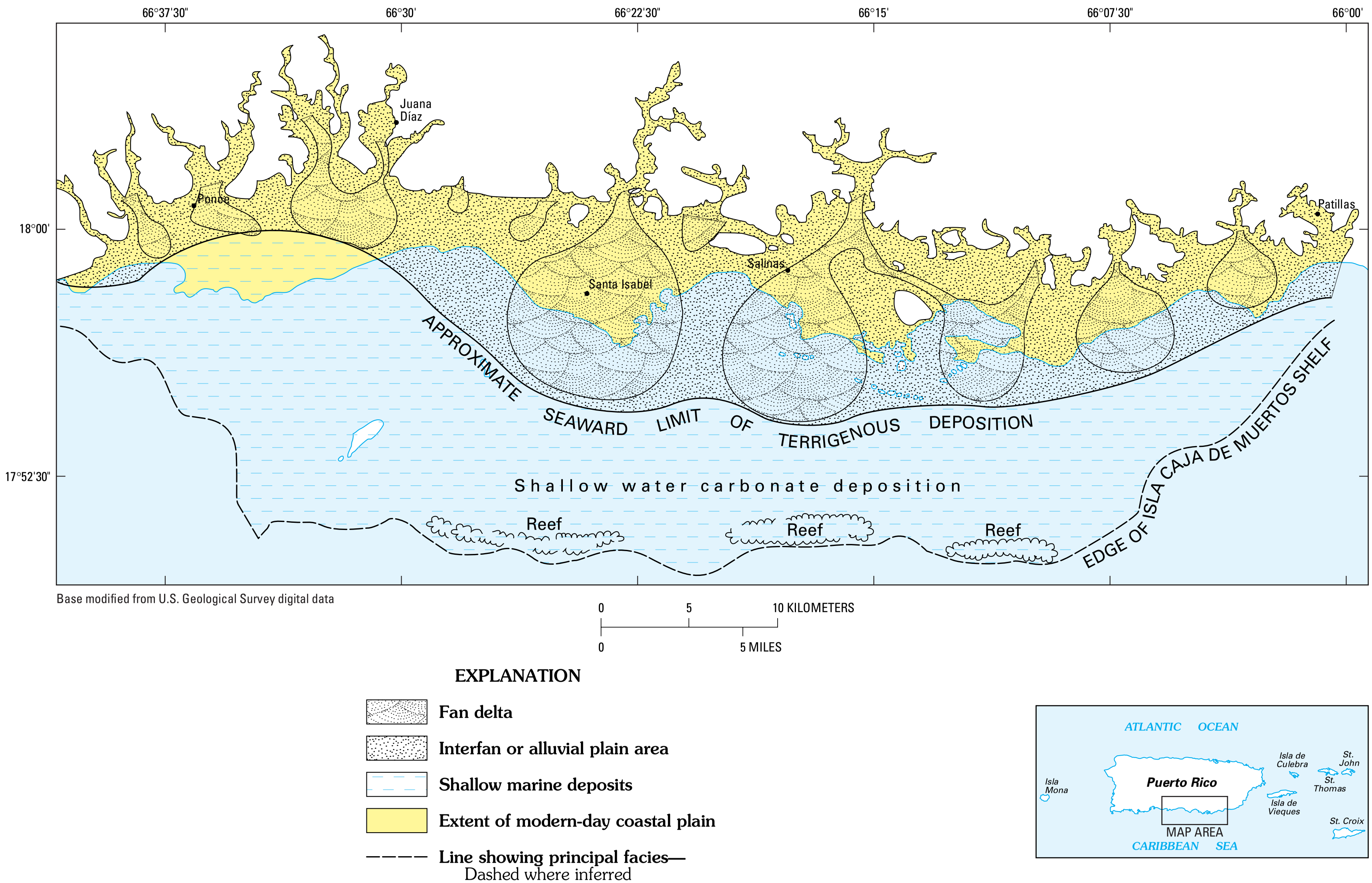


FIGURE 18.—Fan-delta deposition in south-central Puerto Rico during late Pleistocene-early Holocene sea level rise.

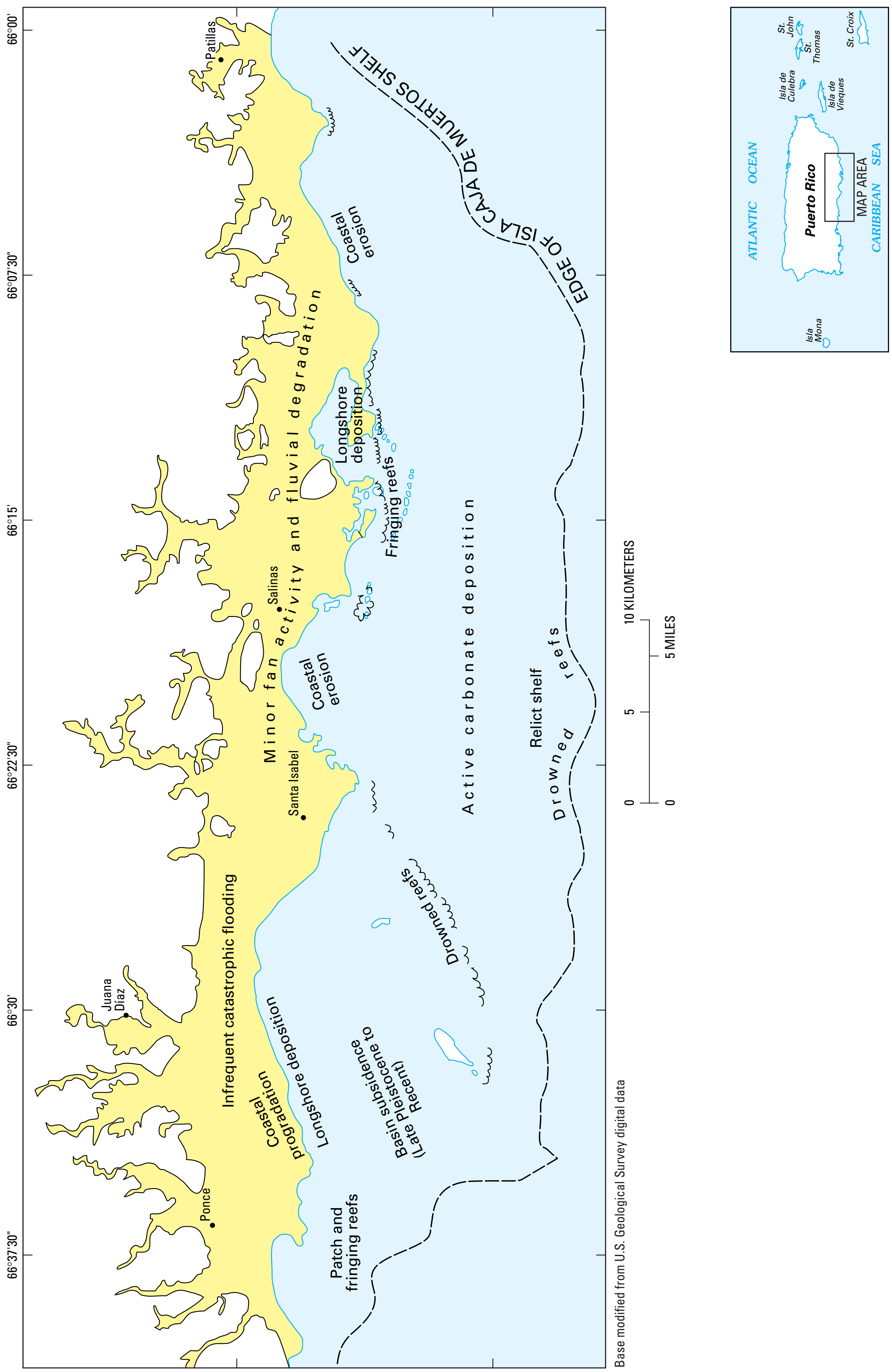


FIGURE 19.—Physical processes within the fan-delta plain of south-central Puerto Rico following the last Holocene transgression.

ley and form a low foothill ridge with a maximum altitude of 246 m; the northern side of the valley is flanked by dissected hills and ridges that rise to altitudes of 200 m. Lajas Valley, open at its eastern and western ends, drains to Guánica valley and Bahía de Boqueron, respectively. Ephermeral streams drain from the north and south and once fed three large lagoons. The two easternmost lagoons have been drained for agricultural purposes, while Laguna Cartegena in the western part of the valley is maintained as a wildlife refuge.

Upland areas adjacent to Lajas Valley are underlain by Cretaceous and Tertiary volcanic and volcaniclastic bedrock and minor limestone beds, Cretaceous to Jurassic serpentinite, amphibolite, and siliceous chert. However, the distribution and character of bedrock units that underlie the clayey alluvium of the central valley is poorly known, largely due to scattered well control. Limestone strata that represent potential aquifers underlie the central part of the valley and are possibly equivalent to irregularly-distributed sequences of Cretaceous limestone strata exposed along nearby foothills. West of Laguna Cartegena, clayey alluvium overlies a carbonate-clastic sequence that could be equivalent to nearby outliers of the Juana Díaz Formation and Ponce Limestone.

Alluvial deposits of Lajas valley range are 60 to 90 m thick and consist mostly of clayey silt, interspersed with stringers of sand. Deposits of sand and gravel are restricted largely to several small alluvial fans located on the perimeter of the valley. Clayey silt underlying the central part of the valley is distal fan or lacustrine in origin.

The Añasco Valley (39 km^2) (figs. 2, 3) and the Guanajibo Valley (34 km^2) are among the largest alluvial valleys of the West Coast ground-water province. The Añasco Valley, drained by two streams, is formed by a low-lying alluvial plain having a maximum altitude of 15 m above sea level and is surrounded on three sides by hills and mountains. The east-southeast trending Guanajibo alluvial valley lies south of the Añasco Valley and north of Lajas Valley. The 22-km-long valley is 1 to 4.5 km wide and is drained principally by Río Guanajibo. Two small alluvial fans border the north side of the valley, formed and fed by tributary streams.

The vertical sequence of stratigraphic units within the Guanajibo and Añasco Valleys suggest that both contain a similar geology. In both valley areas unconsolidated alluvial to marginal marine deposits are underlain by clay and limestone of Pleistocene(?) age that, in turn, unconformably overlie volcaniclastic bedrock. Alluvial deposits in the Añasco Valley consist of clay, minor sand, and occasional channel gravel; clastic nonmarine deposits grade coastward to beach, dune and marsh deposits of clay, silt, sand and skeletal carbonate debris. Alluvial deposits are locally 45 m thick with coarse-grained detritus forming 15 to 30 m-thick beds. A 75 m-thick zone of hard, dense clay interlayered with 15 m-thick, soft limestone beds of Pleistocene(?) age underlies alluvial deposits of the Añasco Valley; the underlying bedrock floor occurs at depths of 100 m below sea level (Díaz and Jordan, 1987). In the Guanajibo Valley, alluvial deposits consist of sand, gravel, and clay reported to be, in some places, 30 m thick. An approximately 50 m-thick limestone unit of Pleistocene(?) age separates alluvial deposits, and unconformably overlies volcaniclastic and volcanic bedrock.

GEOLOGY OF THE EAST COAST GROUND-WATER PROVINCE OF PUERTO RICO

Ridges and mountains of Puerto Rico's East Coast ground-water province (figs. 2, 3) are flanked by a discontinuous plain of alluvial fan fanglomerates and floodplain alluvium that infill several incised stream valleys and grade coastward to lagoonal, swamp, and beach deposits. These valleys are, in turn, underlain by Cretaceous volcaniclastics and Tertiary intrusive and extrusive volcanic rocks akin to the adjoining highlands. The alignment of the alluvial lowland areas and intervening highland ridges indicates that bedrock topography is probably structurally-controlled. Upland stream linearity, trellis or rectilinear drainage patterns, shape of the alluviated valleys, and the configuration of buried bedrock surfaces all strongly reflect joint and fault control.

Alluvial floodplain deposits of unconsolidated, poorly sorted to moderately well-sorted, thick bedded sand, gravel, and clay form a 35-m-thick Piedmont plain in the Río Fajardo valley (Briggs and Aguilar-Cortes, 1980). Sandy lime mud and organic clay deposited within a mangrove swamp and pebbly, coarse to fine-grained carbonate and terrigenous sand separate alluvial plain deposits from Sonda de Vieques. Twenty-five m-thick fanglomerate deposits of poorly- to well-sorted, clay to boulder-size detritus dominates much of the coastal area between the Río Fajardo floodplain and Naguabo (M'Gonigle, 1978).

The Humacao-Naguabo alluvial area encompasses approximately 39 km^2 (figs. 2, 3). Infilled with clay, silt, and sand deposits, the Humacao alluvial valley is formed as a broad triangular-shaped valley and plain that widens coastward. Fanglomerate deposits fringe the edge of the valley with coastal marsh and beach deposits lining the coastline. The thickness of alluvial deposits can exceed 50 m near the coast (Graves, 1989).

The Yabucoa Valley (31 km^2) is a broad, 23-km-wide by 33-km-long valley incised into the granodiorite of the San Lorenzo Batholith (figs. 2, 3). Boulder- to clay-size alluvial fan fanglomerates dominate the landward margin of the valley, but in the central part of the valley these sediments grade to alluvial plain deposits of stratified, poorly consolidated sand, silt, clay, with scattered pebbles and boulders. The thickness of the alluvial deposits is reported to be as much as 100 m, but usually averages less than 50 m near the coast (Robison and Anders, 1973; Rodgers, 1977). The Río Maunabo alluvial valley (8 km^2) (figs. 2, 3) is also incised into the granodioritic rocks of the San Lorenzo Batholith and most valley fill consists of fanglomerate and alluvial plain deposits of clay- to boulder-size detritus. The thickness of these deposits can locally exceed 60 m (Adolphson and others, 1977).

GEOLOGY OF THE INTERIOR GROUND-WATER PROVINCE OF PUERTO RICO

The Interior ground-water province of Puerto Rico forms the bedrock core of the island and is underlain by a deformed and faulted sequence of volcanic, volcaniclastic, plutonic, and sedimentary rocks of Jurassic to early Tertiary age (fig. 3). Two large batholiths of granodiorite of Late Cretaceous-early Tertiary age occur in the eastern and western parts of the Interior ground-water province. Volcanic, volcaniclastic, and other sedimentary rocks that underlie the eastern half of the Interior ground-water province are mostly Early and Late Cretaceous in age. Except for the Bermeja Complex, volcanic and sedimentary rocks in the western half of the Interior ground-water province mostly range in age from Late Cretaceous to Eocene age. The oldest rocks identified in Puerto Rico are part of the ophiolitic Bermeja Complex in southwestern Puerto Rico and range from Jurassic to Cretaceous age. Primary porosity of the rocks of the Interior ground-water province was destroyed by processes of compaction, diagenesis, and tectonic movement. Consolidated rocks of the Interior ground-water province do not represent a regionally important source of water. However, they are capable of yielding small amounts of water to wells and function as a local source of water through fractures, joints, faults and the weathered-bedrock mantle that lies within the upper 15 to 90 m of the surface.

Alluvium is the principal aquifer in Puerto Rico's Interior ground-water province, as it is along the coast. The most extensive deposits are present within the 91 km^2 Caguas-Juncos Valley in the east-central part of the island. Located within the upper part of the Río Grande de Loiza Basin, the alluvial valley is divided into two subareas (Puig and Rodríguez, 1993); the circular Caguas Valley with a 6.4 km diameter lies immediately southwest of the narrow, 0.8- to 2.4-km-wide, elongate Juncos Valley that extends east-west 19 km (fig. 20).

Alluvial deposits within the Caguas-Juncos Valley consist of boulder- to clay-size detritus and range from 10 to 50 m in thickness (Puig and Rodríguez, 1993). The thickness of the clay and silt-dominated deposits of the Caguas Valley increase in the center of the basin, locally exceeding 50 m; alluvial deposits within the Juncos Valley are dominated by sand-size or coarser detritus with a reported thickness that can locally exceed 50 m.

GEOLOGY OF THE NORTH COAST GROUND-WATER PROVINCE OF PUERTO RICO

BY W.C. WARD[1], R.A. SCHARLACH[2], AND J.R. HARTLEY[3]

INTRODUCTION

The North Coast ground-water province of Puerto Rico is underlain by a homoclinal wedge of rocks that infill the North Coast Tertiary Basin. The geology of the middle and upper Tertiary rocks of northern Puerto Rico is known mostly from several studies of the outcrop belt (Hubbard, 1923; Meyerhoff, 1933; Zapp and others, 1948; Monroe, 1973, 1980; Seiglie and Moussa, 1984). Until recently, however, there was little information on the regional stratigraphic framework of subsurface Tertiary rocks underlying the northern coastal plain. Before 1986, only a few deep wells provided data on subsurface Tertiary stratigraphy of northern Puerto Rico (Briggs, 1961; Seiglie and Moussa 1984). In 1986, an extensive core-drilling program was initiated, providing new data on the stratigraphy and depositional history of Oligocene and Miocene sedimentary rocks of Puerto Rico's North Coast Tertiary Basin (Hartley, 1989; Scharlach, 1990) (fig. 7). Much of the geologic and hydrologic core data collected between 1986 and 1989 are described in a series of reports (Hartley, 1989; Scharlach, 1990; Rodríguez-Martínez, Hartley, and Torres-González, 1991; Rodríguez-Martínez, Scharlach, and Torres-González, 1991, 1992; Rodríguez-Martínez and Hartley, 1994; Rodríguez-Martínez and Scharlach, 1994; Todd, 1996). Core recovery from all these wells (fig. 21) was about 85 percent of the total footage drilled, resulting in nearly 9,000 m of core of Tertiary rocks. These new subsurface data are the primary focus of this section.

GEOLOGIC SETTING OF NORTH COAST TERTIARY BASIN

The northern coastal plain of Puerto Rico is underlain by as much as 2,000 m of carbonate and siliciclastic sedimentary rock, which accumulated in the North Coast Tertiary Basin (fig. 7) during Oligocene to Pliocene time (Briggs, 1961; Monroe, 1973, 1980; Meyerhoff, 1975; Meyerhoff and others, 1983; Seiglie and Moussa, 1984; Hartley, 1989; Larue, 1990;

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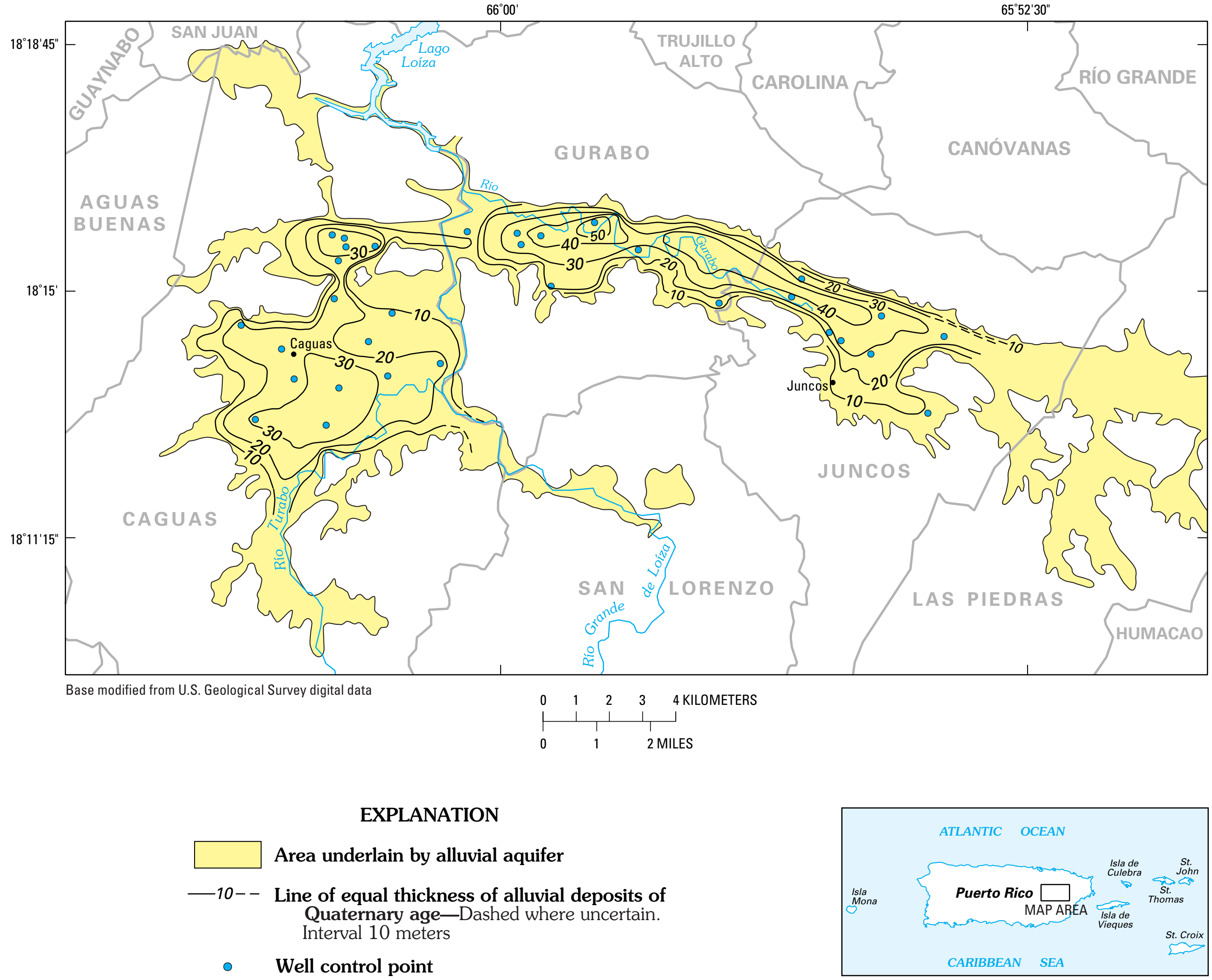

FIGURE 20.—Thickness of the Caguas-Juncos alluvial valley aquifer (modified from Puig and Rodríguez, 1993).

and Scharlach, 1990). These sedimentary rocks rest on a basement of folded and faulted Cretaceous and lower Tertiary sedimentary and igneous rocks (Monroe, 1980; Larue, 1991; Montgomery, 1998).

Maximum drilled thickness of the Oligocene-Pliocene section is 1,701 m in the CPR-4 well 8 km east of Arecibo (Briggs, 1961). Meyerhoff and others (1983) estimate maximum onshore thickness of 1,905 m and offshore thickness of 2,500 to 3,500 m. Maximum thickness of the onshore Oligocene-Pliocene section occurs under the northwestern coastline between Aguadilla and the Rio Grande de Arecibo (fig. 3; pl. 4). Under the eastern part of the northern coastal plain, the Oligocene-Pliocene section is less than 750 m and thins to less than 100 m over paleohighs in the basement complex.

Oligocene-Pliocene sedimentary rocks of the northern coastal plain strike generally east-west and dip gently toward the north (fig. 3; pl. 4). Projections from outcrop altitudes (Monroe, 1980) to correlative points in the core holes show that the regional dip is 2 to 4 degrees northward. Dips of 4 to 5 degrees (locally up to 10 degrees) were measured across the southern part of the Oligocene-Pliocene outcrop belt and 1 to 3 degrees across the northern part (Monroe, 1963a, b, 1967, 1969a, b, 1971; Berryhill, 1965; Briggs, 1965, 1968; Nelson and Monroe, 1966; Nelson, 1967a, b; Nelson and Tobisch, 1968; Tobisch and Turner, 1971). Geologic maps of these areas show only a few minor faults which displace Oligocene-Pliocene rocks (Berryhill, 1965; Monroe, 1969a). Regional faults which disrupt the regional homoclinal dip are unknown, although Briggs (1961) postulated a down-to-the-north fault with as much as 150 m of displacement, trending generally east-west from the mouth of the Río Grande de Arecibo to the mouth of the Río Cibuco. Briggs (1961) based the presence of

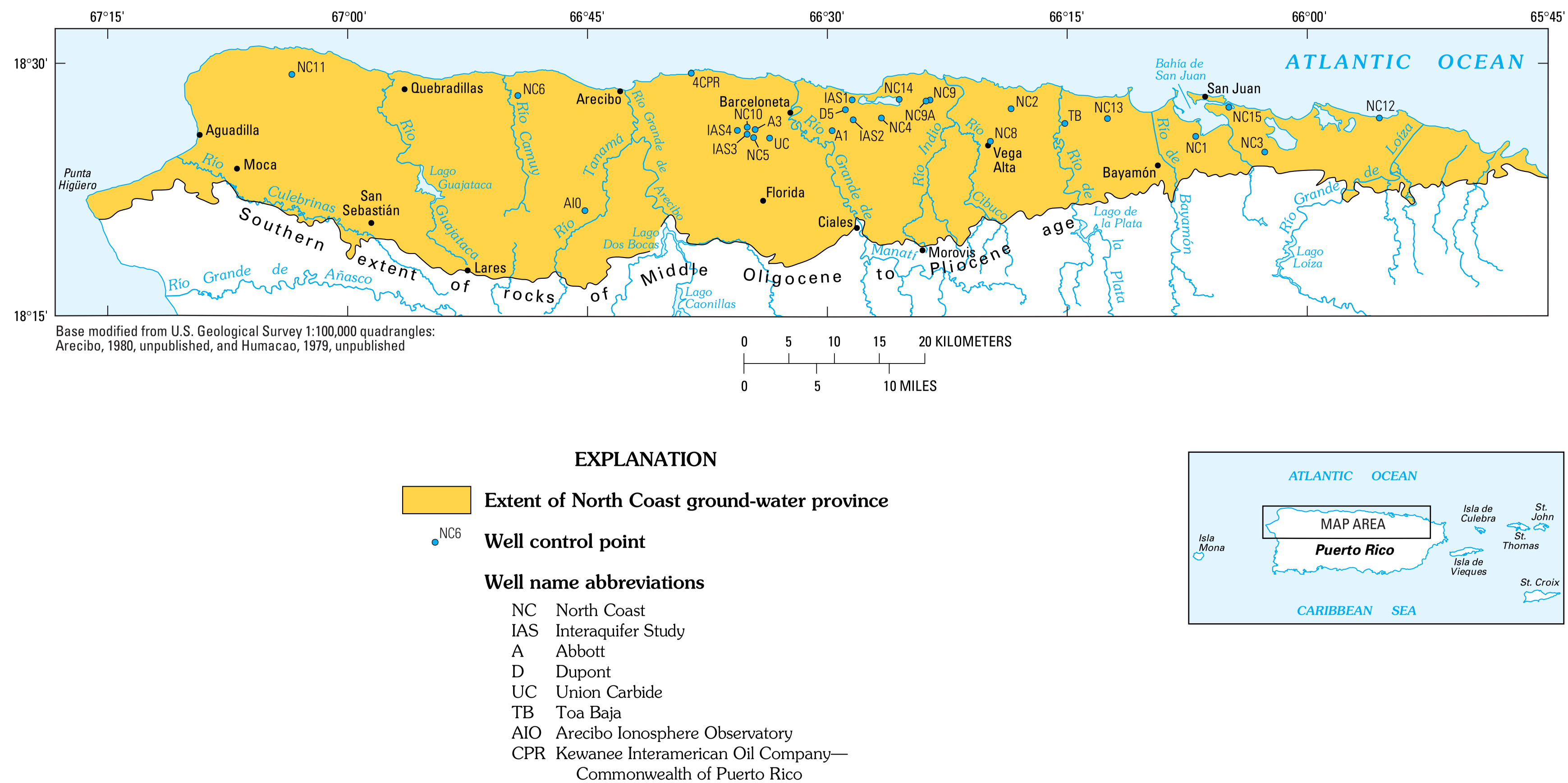

FIGURE 21.—Location of cored test holes and other wells that penetrate Tertiary rocks beneath the North Coast ground-water province of Puerto Rico.

this fault, in part, on “anomalous” geomorphic (low-lying land and swamps) and hydrologic features (presence of coastal springs) and, in part, on the dip of strata that crop out (more steeply dipping beds lie to the south). Seismic data collected in the area failed to support the “Briggs Fault” (Western Geophysical Company of America and Fugro, Inc., 1973) and the springs near the coast can be explained in terms of regional flow, ground-water discharge patterns, and the distribution of hydraulic conductivity within the upper aquifer (Renken and Gómez-Gómez, 1994; Renken, Gómez-Gómez, and Rodríguez-Martínez, this volume).

STRATIGRAPHY

Lower and upper Tertiary sedimentary rocks of northern Puerto Rico comprise two major lithologic units: (1) a relatively thin basal section of siliciclastic sedimentary rocks of “middle” to late Oligocene age and (2) a thick upper section of predominantly carbonate rocks of late Oligocene to middle Miocene age (pl. 4). The boundary between these major units is conformable and diachronous. In the central part of the North Coast Tertiary Basin between the Río Guajataca and Río Grande de Manatí, the upper section is divided into a lower unit of carbonate rocks, a middle unit of mixed carbonate and siliciclastic rocks, and an upper unit of carbonate rocks. Toward the western and eastern margins of the basin, the lower carbonate unit passes laterally into mixed carbonate-siliciclastic rocks. Uppermost Miocene-Pliocene limestone unconformably overlies middle Miocene limestone on the northwestern coastal plain (pl. 4).

METHODS OF CORRELATION

For the most part, the ages attributed to the various rock units are those already established by earlier workers, and no attempt will be made to further document or justify the ages used. General ages of the lithologic units described here (pl. 4; fig. 22) are known from paleontological studies (Gordon, 1961b; Bold, 1965; Bermúdez and Seiglie, 1969; Seiglie, 1978; Frost and others, 1983; Seiglie and Moussa, 1984; Montgomery and others, 1991), but biostratigraphic data are few for precise correlation of time-equivalent units. For this study, preliminary biostratigraphic correlation for some lithologic units is done with planktonic foraminifers identified by P. McLaughlin (Exxon, written commun., 1991) and A. Melillo (Chevron, written commun., 1992), but most of the cored Tertiary rocks contain predominantly benthonic foraminifers (C. Young, University of New Orleans, written commun., 1989).

In the absence of sufficient biostratigraphic control, an attempt is made to establish relative time equivalency by correlating sedimentary cycles that resulted from third-order sea-level fluctuations (Seiglie and Moussa, 1984; Scharlach and others, 1989; and Scharlach, 1990). This will be attempted by establishing the sequence-stratigraphic framework of the Oligocene-Miocene sedimentary rocks of the northern coastal plain.

LITHOSTRATIGRAPHIC NOMENCLATURE

For the most part, stratigraphic names used here for units of the middle and upper Tertiary section follow the nomenclature currently used by the U.S. Geological Survey (MacLachlan and others, 1992). These rocks are divided into six widespread lithostratigraphic units and four less-extensive units (pl. 4; fig. 22). The major stratigraphic divisions are, in ascending order: the San Sebastián Formation, the Lares Limestone, the Cibao Formation, the Aguada (Los Puertos) Limestone, the Aymamón Limestone, and the Quebradillas Limestone. In the west-central part of the basin, the Montebello Limestone Member is the lower part of the Cibao Formation, and in the east-central basin, the mudstone unit and Río Indio and Quebrada Arenas Limestones occupy this stratigraphic position (pl. 4). On the eastern side of the basin, the Lares Limestone and Cibao Formation interfinger with the Mucarabones Sand. Most of these stratigraphic subdivisions were established from outcrop studies, particularly Hubbard (1923), Zapp and others (1948), and Monroe (1973) as summarized in Monroe (1980). The mudstone unit was recognized from subsurface studies by Seiglie and Moussa (1984).

Some recent workers use other names for units above the Cibao Formation. “Aguada Limestone” (Zapp and others, 1948) is essentially the same section previously named “Los Puertos Limestone” by Hubbard (1920), although the type locality of the Aguada (Zapp and others, 1948) is within the Cibao outcrop. To deal with this problem, Monroe (1968) established a reference section for the Aguada limestone, which Moussa and Seiglie (1975) considered to be contrary to the Code of Stratigraphic Nomenclature (American Commission on Stratigraphic Nomenclature, 1961, 1970). Although the name “Los Puertos Limestone” has priority over “Aguada Limestone” (Moussa and Seiglie, 1975; Meyerhoff, 1975), “Aguada (Los Puertos) Limestone” is used here to be more consistent with USGS usage. Nomenclatural difficulties associated with the geologic name “Los Puertos” are further complicated because the same name has been applied (Glover and Mattson, 1967) and is currently used (MacLachlan and others, 1992; Krushensky and Schellekens, written commun., 1994) to describe rocks of Paleocene age located in Puerto Rico’s central interior on the leeward side of the island. The “Aymamón Limestone” (Zapp and others, 1948) is essentially equivalent to the “Moca Limestone” of Meyerhoff and others (1983). In addition, the uppermost unit called “Camuy Formation” by Monroe (1963b) was redefined as the “Quebradillas Limestone” by Moussa and Seiglie

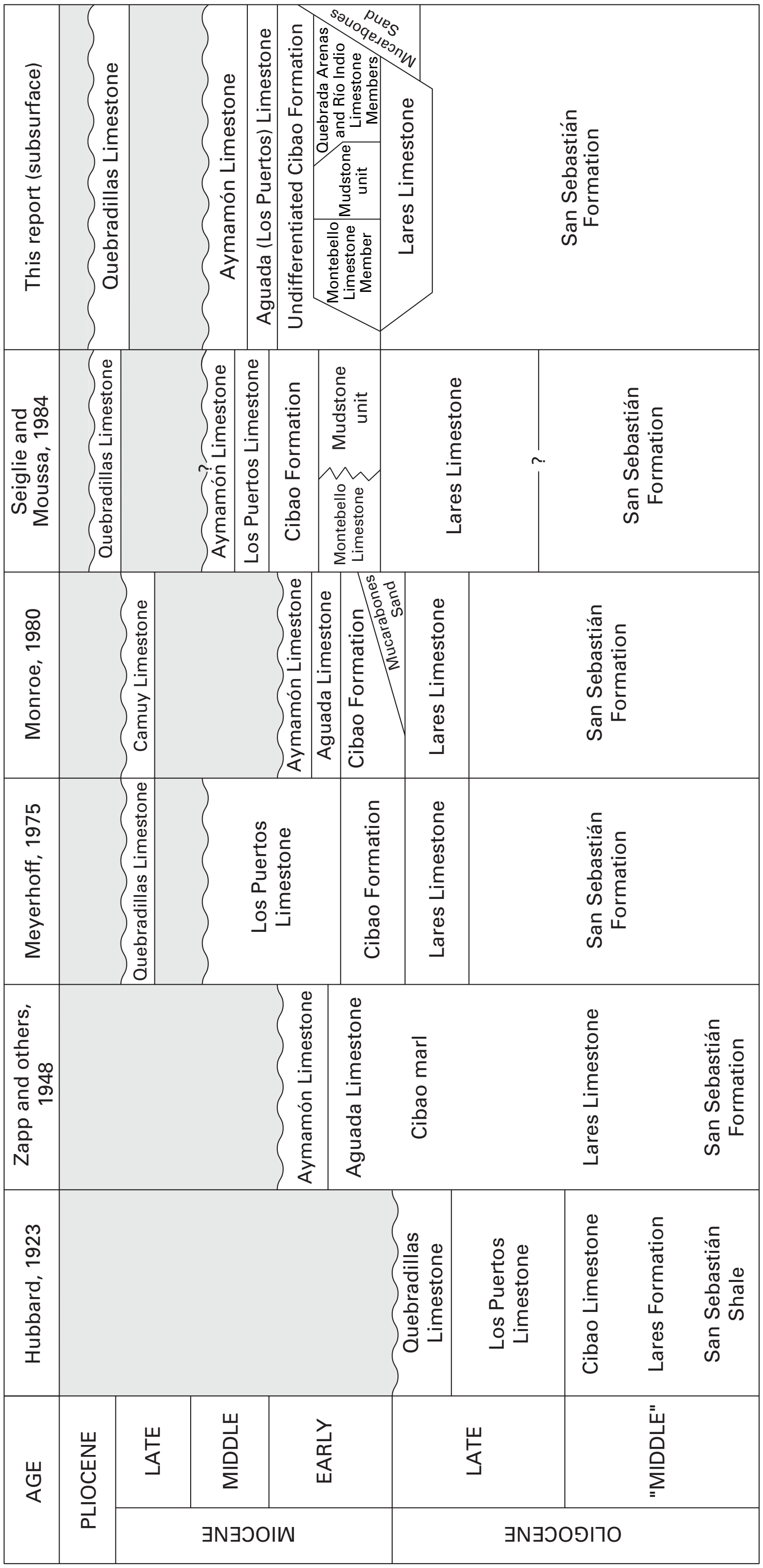

FIGURE 22.—Stratigraphic nomenclature and ages for Oligocene, Miocene, and Pliocene sedimentary rocks of the North Coast Tertiary Basin.

(1975), who used the name originally applied to the upper Tertiary section by Hubbard (1920).

SAN SEBASTIÁN FORMATION ("MIDDLE" TO UPPER OLIGOCENE)

Outcrop

As mapped by Meyerhoff (1933), Zapp and others (1948), and Monroe (1980), the predominantly siliciclastic San Sebastián Formation rests unconformably on basement rocks across most of the North Coast Tertiary Basin, but is locally absent over paleohighs, where basement rock is overlain by younger units. The thickness of this formation is highly variable, reflecting both the irregular paleotopography and the paralic depositional system. The average outcrop thickness between San Juan and the town of San Sebastián is about 70 m, but it is as thick as 150 m west of San Sebastián (Monroe, 1980).

The San Sebastián Formation is divided into three members (Meyerhoff and others, 1983). The basal part consists of yellow-brown to red-brown sandstone, conglomerate, and mudstone (Monroe, 1980; Meyerhoff and others, 1983; Frost and others, 1983). A middle unit comprises varicolored sandstone and mudstone, locally interbedded with lignite, and the upper San Sebastián Formation is gray and greenish-gray fossiliferous glauconitic mudstone, sandstone, and marl with fossiliferous limestone. The upper 30 m of the San Sebastián Formation just north of the town of Lares consists of at least five depositional cycles of carbonaceous mudstone and fine sandstone, fossiliferous siltstone and sandstone, and thin layers of skeletal packstone and wackestone (Frost and others, 1983).

Subsurface

Five test wells (NC 2, 5, 8, 11, and 13; fig 21) were drilled into the San Sebastián Formation, but none penetrated the entire thickness. There is, therefore, little control on the subsurface thickness of this formation except in two downdip wells. The Kewanee Interamerican oil-test well, 4 CPR, drilled near Arecibo in 1960 encountered 494 m of predominantly siliciclastic rocks unconformably overlying "basement" rock (Briggs, 1961). In addition, the Toa Baja test well (TB) drilled about 16 km west of San Juan in 1990 penetrated about 75 m of siliciclastic sand and mudstone above Paleogene volcaniclastic sedimentary rocks (Larue, 1990).

Under the northwestern corner of the coastal plain (NC 11), the upper 82 m of the San Sebastián Formation is predominantly olive-green mudstone and greenish-gray marl with red-brown mudstone, thin black carbonaceous mudstone, and skeletal wackestone-packstone containing miliolids, mollusks, ostracodes, and some red algae and echinoids (Hartley, 1989). Sandy mudstone and thinly bedded fine sandstone are common in the upper half of this section. The San Sebastián in this area is conformably overlain by limestone and marl of Cibao-like lithology.

In the west-central basin, the upper 65 m of San Sebastián Formation penetrated by NC 5 (fig. 21; pl. 4) is greenish-gray partly fossiliferous mudstone with red-brown mudstone and thin black carbonaceous mudstone in the lower part and yellow-gray glauconitic skeletal wackestone, packstone, and grainstone in the upper part (Hartley, 1989). Mollusks and benthic foraminifers are the predominant fossils in the lower part of this section, with *Lepidocyclina, Hetrostegina,* mollusks, red algae, bryozoans, echinoids, and a few corals in the upper glauconitic layers (Hartley, 1989). Downdip from NC 5 in the 4 CPR well (fig. 21), the upper 175 m of the San Sebastián Formation (as defined in this report; pl. 4) is pinkish- to orangish-gray sandy marl, calcareous claystone, and "punky" limestone (Briggs, 1961). The lower 320 m, which is the "San Sebastián Formation" of Briggs (1961), consists of olive-gray pyritic calcareous mudstone and thin sandstone with volcanic-rock fragments. This unit also includes thin highly carbonaceous claystone layers and, in the lower 30 m, sandstones and pebble conglomerates rich in volcanic-rock fragments. The middle two-thirds of this "San Sebastián" section is rich in planktonic foraminifers (*Globigerina*), which decline in abundance toward the top and toward the base of the unit (Gordon, 1961b). Pale-yellow-brown clay at the base of the section likely represents a paleosol developed on the volcaniclastic sandstone and siltstone of Eocene(?) age (Briggs, 1961). This downdip "San Sebastián" probably is older than the San Sebastián at the outcrop and that penetrated by the NC core tests. More likely, the updip San Sebastián is age-equivalent to the 175 m of sandstone, calcareous mudstone, and clayey limestone with inner-shelf foraminifers that Briggs (1961) included in the basal Lares Limestone.

About 120 m of the San Sebastián Formation was penetrated by NC 8 in the east-central part of the basin (pl. 4). The lower half of this section is variably colored nonfossiliferous claystone and siltstone grading up-ward into olive-green calcareous claystone with oyster fragments, high-spired gastropods, bivalves, and carbonaceous matter (Scharlach, 1990). The upper half of the San Sebastián in NC 8 is made up of three depositional sequences, which grade upward from calcareous claystone to alternating layers of clay and silty marl and finally to glauconitic muddy wackestone and packstone. Species diversity increases upward in this sequence from mostly mollusks and miliolids at the base to red algae, echinoids, oysters, pecten, green algae, and various benthic foraminifers including *Lepidocyclina* sp., *Heterostegina* sp., and *Miogysina* sp. in upper parts of the unit. Downdip from NC 8, the 45 m of upper San Sebastián cored in NC 2 is similar to that in NC 8. Farther eastward, the NC 13 well (fig. 21; pl. 4) recovered 26 m of San Sebastián composed of a lower unit that is like the lower claystone of NC 8. This unit is overlain by a coarsening-upward unit of fossiliferous fine to coarse quartz and lithic sandstone, which is overlain by clayey marl with bryozoans and *Lepidocyclina* sp. (Scharlach, 1990).

LARES LIMESTONE (UPPER OLIGOCENE TO LOWER MIOCENE)

Outcrop

Across the central and west-central outcrop belt (fig. 3), the siliciclastic beds of San Sebastián Formation grade upward into carbonate rocks of the Lares Limestone (pl. 4). According to Monroe (1980, p. 23), the Lares Limestone at outcrop has a fairly constant thickness of approximately 270 m, but thickens to more than 310 m east of the town of Lares. Projections from the outcrop map (Monroe, 1980) to the cored test wells, however, indicate that the thickness of the Lares generally is 75 to 150 m where it crops out (fig. 3; pl. 3). Frost and others (1983) measured 95 m of Lares Limestone in a new highway cut just north of the town of Lares.

The Lares Limestone thins and pinches out in the western and eastern margins of the outcrop belt. West of the town of San Sebastián, the Lares Limestone interfingers with siliciclastic rocks of San Sebastián lithology, and the limestone pinches out a few miles east of Aguadilla (Monroe, 1980). In the westernmost area of Lares outcrop, Monroe (1980) divided the Lares Limestone into three parts: a lower unit of about 25 m of oyster-bearing marl passing upward to fossiliferous limestone with abundant coral heads, a middle member of 40 to 80 m of “chalk” and calcareous clay containing abundant oysters and a few corals, and an upper unit of 30 m of fossiliferous limestone with common corals interbedded with “chalk” and calcareous clay. Toward the eastern part of the basin, Lares Limestone interfingers with and onlaps the Mucarabones Sand. Lares lithology is unknown east of the Río de la Plata (Monroe, 1980).

In the Lares Limestone exposed along Highway 129 north of the town of Lares (figs. 3, 21), Frost and others (1983) described wackestone and packstone with abundant large foraminifers and finger corals (*Porites* sp.) as well as reef limestone containing several species of corals and red algae. This section records three cycles of reef growth during Lares deposition. Frost and others (1983) noted two angular discontinuities within the lower 15 m of the Lares at about the same stratigraphic position where Monroe (1980, fig. 13, p. 22) pictures an apparent angular discontinuity northeast of Morovis in the eastern part of the basin (Frost and others, 1983).

Subsurface

Entire sections of Lares Limestone were cored in North Coast test wells located in the eastern and east-central part of the basin (wells NC 2, 5, 8, and 13; fig. 21). In addition, the entire thickness was penetrated in wells IAS 1, 4 CPR, PREPA Toa Baja (TB), and probably in the well drilled at the Arebico Ionosphere Observatory (AIO) (fig. 21). Wells NC 4, 6, and 9A, IAS 4, Abbott 3 (A3), Dupont 5 (D5), and Union Carbide 1 (UC) bottomed in the Lares Limestone. Wells NC 1, 3, 12, and 15 were drilled east of the eastern margin of Lares lithology, and NC 11 probably was drilled beyond the western limit of this formation.

Lares Limestone probably is thickest in the central part of the basin between the Río Cibuco and Río Grande de Arecibo (fig. 23). Estimations of subsurface thickness between the Río Grande de Arecibo and Río Grande de Manatí (fig. 23) are tenuous because of the difficulty in distinguishing the Lares Limestone from the overlying Montebello Limestone and in the northwestern area (NC 6 and NC 11), from the overlying Cibao Formation.

Between the Río Grande de Arecibo and Río de la Plata, the Lares Limestone can be subdivided into three major units. The lower Lares is characterized by several cycles of olive-gray and greenish-gray skeletal wackestone passing upward into skeletal packstone and lesser grainstone. Upper parts of these cyclic sequences commonly are rich in rhodolites, the large benthic foraminifer *Lepidocyclina* sp., or the branching coral *Porites* sp. Other common skeletal constituents of the lower Lares are bivalves including oysters, codiacean and dasyclad green algae, and benthic foraminifers *Heterostegina* sp. and *Amphistegina* sp. Some lowermost wackestones are clayey and glauconitic. The upper part of the lower Lares is dolomitic.

The middle part of the Lares comprises a few shoaling-upward sequences of greenish-gray and yellowish-gray burrowed skeletal wackestone-packstone grading upward to red-algae/large-foraminifer/mollusk packstone or grainstone and thin patch-reef limestones containing *Porites* sp., *Montastrea* sp., and *Goniastrea* sp. (identified by S.H. Frost, UNOCAL, written commun., 1991). Test well NC 9A penetrated thicker coral-bearing units made up of *Alveopora chiapeneca, Porites panamensis, Montastrea* sp. cf. *M. altissima, Acropora* sp. cf. *A. saludensis,* and *Astreopora*(?) sp. (corals identified by S. H. Frost, UNOCAL, written commun., 1991). The middle unit also contains oysters and the bivalve *Kuphus* sp. Many coral- and rhodolite-rich layers are dolomitized.

The lithology of the upper Lares Limestone varies from place to place. In the eastern part of the basin, between the Río Cibuco and Río de la Plata near wells NC 2 and NC 8 (fig. 21), the upper Lares passes upward from lithology similar to the middle unit to yellowish-gray partly dolomitic clayey wackestone and packstone with soritid and miliolid foraminifers. Between the Río Grande de Manatí and Río Cibuco, the upper Lares is composed of skeletal wackestone and packstone with corals, red algae, and planktonic foraminifers interbedded with clayey wackestone, silt, and fine sandstone. In the area between the Río Grande de Arecibo

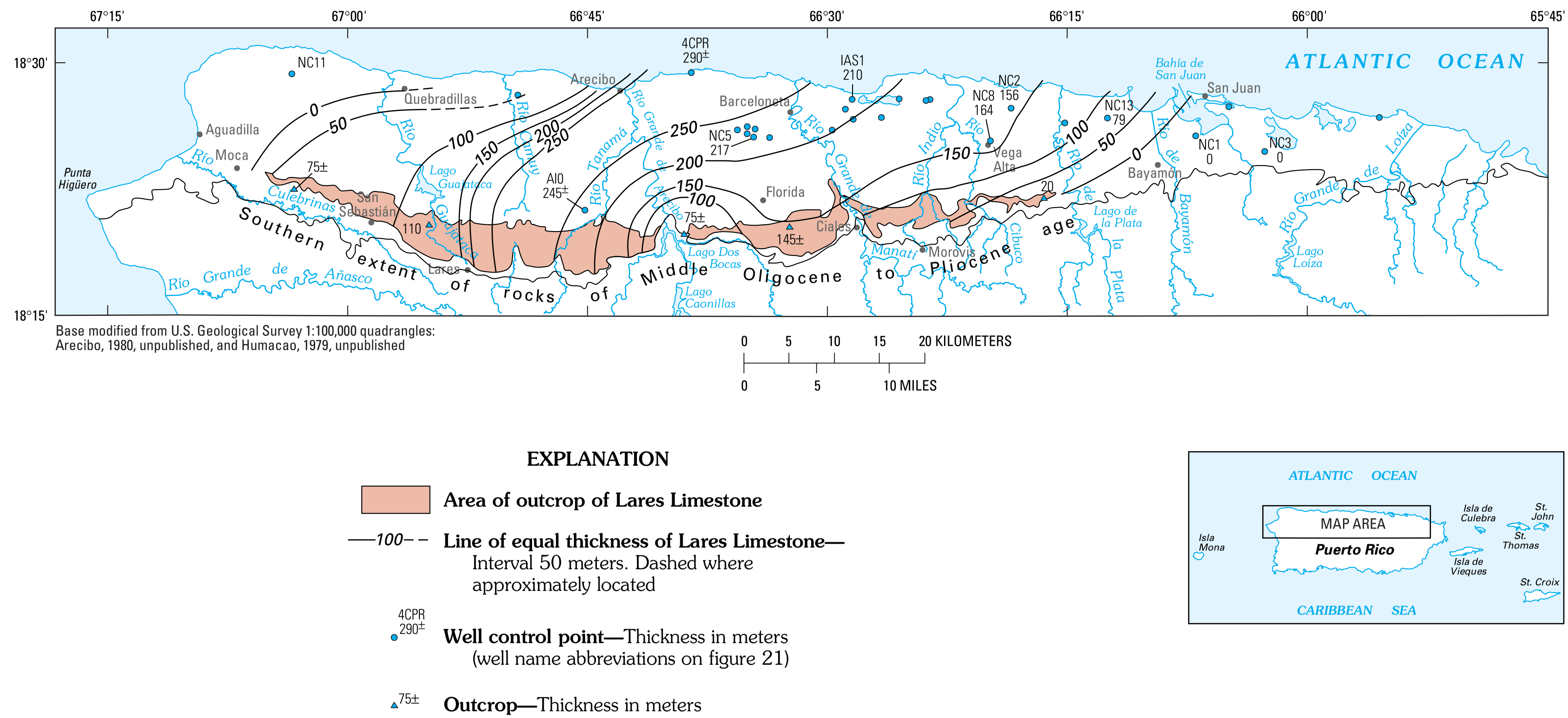

FIGURE 23.—Thickness of Lares Limestone, northern Puerto Rico (outcrop extent modified from Monroe, 1980).

and Río Grande de Manatí, upper Lares is dolomitic wackestone and clayey wackestone with coral, red algae, rhodolites, and benthic foraminifers *Heterostegina* sp., *Amphistegina* sp., and *Miogypsina* sp. Soritid and miliolid foraminifers are common near the top of the formation.

An eastern tongue of the Lares Limestone was cored in well NC 13 (pl. 3; fig. 21). The dominant rock type is clayey soritid wackestone (Scharlach, 1990), similar to carbonate rocks of the overlying Cibao Formation. In this eastern area, the lower Lares is marly wackestone and lesser packstone containing bryozoans, *Lepidocyclina* sp., *Heterostegina* sp., mollusks, and red algae with clay and marly sandstone layers. Middle Lares is predominantly clayey wackestone with soritids, *Heterostegina* sp., oysters, pecten, branching and crustose red algae, and lesser miliolids, ostracodes, and bryozoans (Scharlach, 1990). The upper part of the Lares in well NC 13 is composed of mixed carbonate and terrigenous lithology. Much of the upper interval is glauconitic sandy skeletal grainstone with marly fossiliferous sandstone. The common fossils in these beds are *Heterostegina* sp., soritid foraminifers, red algae, echinoids, and mollusks.

In the western part of the basin, the upper Lares equivalent penetrated by test well NC 6 is similar to the carbonate rocks of the Cibao Formation. Here, the stratigraphic equivalent of the upper Lares consists of clayey wackestone and dolomitized wackestone with bivalves, echinoids, miliolids, some red algae, and *Miogypsina* sp. This section also contains thin carbonaceous claystone. No Lares Limestone was identified in NC 11. In this area, the lithology of rocks that apparently are time-equivalent to the Lares is more typical of the upper San Sebastián Formation.

Seiglie and Moussa (1984) describe the Lares Limestone as a depositional cycle in their study of the drill cuttings from two wells located in the north-central part of the basin (Dupont 5 (D5) and Union Carbide 1 (UC); fig. 21). In the Dupont 5 well, the lower, regressive part of the Lares exhibits a progressive upward increase in the percentage of planktonic foraminifers through the middle of the formation. The upper, transgressive section exhibits an upward decrease in planktonic foraminifers toward the top of the formation. *Lepidocyclina* sp. and *Heterostegina* sp. also are common throughout the Lares section in this well, but are slightly more abundant in the lower part of the formation. In the Union Carbide 1, the transgressive phase of the depositional cycle is represented by an upward increase in the percentage of *Amphistegina* sp. From the middle Lares upward, the decrease in abundance of this foraminifer records the regressive phase, the close of which is marked by oyster beds at the base of the Montebello Limestone.

In the most downdip well, the 4 CPR (fig. 21), Briggs (1961) describes 504 m of Lares “calcarenite,” the lower 175 m of which are interbedded with calcareous claystone and sandy marl. Gordon (1961b) reported this unit to contain an outer-neritic foraminiferal assemblage, except near the top and bottom where middle-neritic foraminifers are more abundant. These foraminiferal assemblages indicate that the downdip Lares also records a cycle of deposition.

MUCARABONES SAND (UPPER OLIGOCENE TO LOWER MIOCENE)

Outcrop

In the eastern part of the North Coast Tertiary Basin, the Lares Limestone and the lower part of the overlying Cibao Formation interfinger with sandstone, conglomerate, and mudstone, which were shed off the eastern highlands during the late Oligocene and early Miocene. These terrigenous deposits were assigned to the Mucarabones Sand (Nelson, 1966).

Monroe (1980) mapped nearly continuous exposures of Mucarabones Sand between the Río Grande de Manatí and the outskirts of San Juan (fig. 3; pl. 4). In the vicinity of the Río Grande de Manatí, the Mucarabones is a 10-m-thick unit overlying the San Sebastián Formation and underlying and interfingering with the lower Lares Limestone. East of the Río de la Plata, the Mucarabones consists of as much as 120 m of sandstone and conglomerate that grades laterally into the Lares and lower two-thirds of the Cibao Formation. East of the Río de Bayamón, this formation is "indistinguishable" from the underlying San Sebastián Formation and the overlying alluvial deposits (Monroe, 1980).

The basal Mucarabones Sand is composed of coarse sandstone with lenses of conglomerate and greenish-gray clay. The middle and upper parts of this unit are characteristically yellow to grayish-orange crossbedded partly glauconitic fine to medium sandstone with scattered lenses of fossiliferous sandy limestone and fossiliferous sandy claystone (Monroe, 1980). Fossils include echinoids, mollusks, and large benthic foraminifers. *Lepidocyclina undosa* is common in the lower and middle parts of the Mucarabones Sand (Monroe, 1980).

Subsurface

The Mucarabones Sand is the basal Tertiary sedimentary unit penetrated by two wells drilled in the San Juan metropolitan area (NC 1 and NC 3) (Scharlach, 1990). In the NC 3 well (pl. 4), 7.5 m of Mucarabones rests on weathered basaltic basement rock. The NC 1 well was completed in Mucarabones Sand after penetrating 103 m of the unit (pl. 4). In both wells, this formation underlies the Cibao Formation. The upper 24 m of terrigenous rocks that underlie the Lares Limestone in well NC 13 (pl. 4) consists of calcareous claystone and fine- to medium-sandstone that could be equivalent to westernmost outcrops of the Mucarabones Sand. This interval in NC 13, in turn, is underlain by San Sebastián lithology.

The Mucarabones Sand in the subsurface consists of intermixed olive-green and greenish-gray silty claystone, siltstone, sandstone, and conglomerate. Sandstones are immature to submature fine to medium lithic arkose to subarkose (Scharlach, 1990). Monocrystalline and polycrystalline quartz, fresh and weathered plagioclase, and volcanic-rock fragments are the predominant constituents of the sandstones (Scharlach, 1990). Conglomerates consist of rounded volcanic-rock fragments up to 4 cm.

A 14-m-thick fossiliferous interval was encountered in the upper part of the Mucarabones in well NC 1 (pl. 4). This rock is cross-laminated quartz-sandy grainstone that consists of encrusting foraminifers, small benthic foraminifers, red algae, and echinoids with lesser amounts of bryozoans, ostracodes, and planktonic foraminifers (Scharlach, 1990). This grainstone is underlain and overlain by non-fossiliferous siltstone and grainstone.

CIBAO FORMATION (LOWER MIOCENE)

Outcrop

The Cibao Formation is a complex unit of carbonate, mixed carbonate-siliciclastic, and siliciclastic sedimentary rocks, which Monroe (1980) divided into six members on the basis of surface exposures (fig. 24). Typically, the formation consists of clayey skeletal wackestone and fossiliferous calcareous claystone (marl) with thin units of mudstone and sandstone. In the central part of the North Coast Tertiary Basin, however, much of the Cibao section is limestone similar to the underlying Lares.

In the western part of the basin, clayey wackestone and marl (“typical Cibao lithology”) interfinger with volcaniclastic sandstone and conglomerate and shale of the Guajataca Member. This apparent fan-delta deposit is as much as 160 m thick between the towns of San Sebastián and Moca (figs. 3, 21).

Between the Río Camuy and Río Grande de Manatí, the lower member of the Cibao Formation is the Montebello Limestone, formerly included in the Lares Limestone (Zapp and others, 1948). Nelson and Monroe (1966) separated the Montebello from the Lares on the basis of an upward change from “fine-grained calcarenite” of the Lares to “weakly indurated medium to coarse calcarenite” of the Montebello (Monroe, 1980, p. 33). Across most of the Montebello outcrop belt, beds of large oysters mark the base of this limestone member. The Montebello is about 200 m thick in the vicinity of the Río Grande de Arecíbo, where, in some places, this limestone rests directly on a paleohigh of basement rock. In this area, the “typical” Cibao limestone/marl is only a few meters thick. The Montebello packstone and grainstone commonly contain abundant large foraminifers *Lepidocyclina (L. undosa, L. gigas, L. cancellei,* and *L. yurnagunensis), Heterostegina* sp., and *Nummulites dia* (Monroe, 1980; Frost and others, 1983). The Montebello Limestone is overlain by marl and clayey limestone of the upper Cibao Formation, except in the area between the Río Grande de Arecibo and northeast of the town of Florida, where the Montebello is overlain by the Aguada (Los Puertos) Limestone (fig. 3).

About 3 km west of the Río Grande de Manatí, the Montebello Limestone thins abruptly and is replaced eastward by marl and clayey limestone of the Cibao Formation (fig. 3). Eastward of the Río Indio, these “typical deposits of Cibao . . . grade laterally eastward and intertongue with a predominantly limestone sequence” (Monroe, 1980, p. 34). Monroe (1962) divided this limestone sequence into two members: the lower Río Indio Limestone Member and the upper Quebrada Arenas Limestone Member. These units crop out from just west of the Río Indio to 4 to 5 km west of Bayamón (figs. 3). A thin limestone in the upper part of the predominantly clay and marl Cibao Formation between Río Grande de Manatí and Río Indio is mapped as a westward extension of the Quebrada Arenas Limestone (Berryhill, 1965; Monroe, 1980).

The Río Indio Limestone Member is about 66 m thick near the Río Indio, where it consists of three units: at the base (1) 40 m of partly glauconitic intraclastic fossiliferous limestone with layers of large oysters, overlain by (2) 6 m of cross-bedded fossiliferous glauconitic sandstone and pebble conglomerate (Almirante Sur Sand Lentil), overlain, in turn, by (3) limestone containing quartz sand (Monroe, 1980). The Río Indio Limestone Member contains *Lepidocyclina* sp., and other benthic foraminifers, mollusks, and red algae (Monroe, 1980). This member is increasingly sandy and clayey eastward and grades into the Mucarabones Sand about 4 km west of Bayamón.

Monroe (1980) considers the Quebrada Arenas Limestone Member to be an eastward extension of the Montebello Limestone. This fossiliferous limestone member is about 60 m thick south of Vega Alta, where it consists of “alternating beds of very pale orange to grayish-orange indurated limestone in strata about 50 cm thick and grayish-orange chalky limestone in strata about 50 cm thick” (Monroe, 1980, p. 36). The base of this member in this area is coral-rich limestone. The Quebrada Arenas Limestone also grades eastward into the Mucarabones Sand about 5 km west of Bayamón.

In at least three areas (fig. 24*A*), the upper part of the Quebrada Arenas Limestone is incised by channels filled with mottled grayish red and yellow-gray noncalcareous, nonfossiliferous clayey coarse sand and gravel. The gravel consists of pebbles and cobbles of quartz and volcanic-rock fragments. These discontinuous terrigenous deposits are the Miranda Sand Member of Monroe (1980).

Across most of the outcrop belt, the upper Cibao is characterized by clayey limestone and calcareous mudstone, informally termed “upper member” (Monroe, 1962). This widespread unit crops out from the western tip of Puerto Rico near Punta Higüero to the area south of Bahía de San Juan

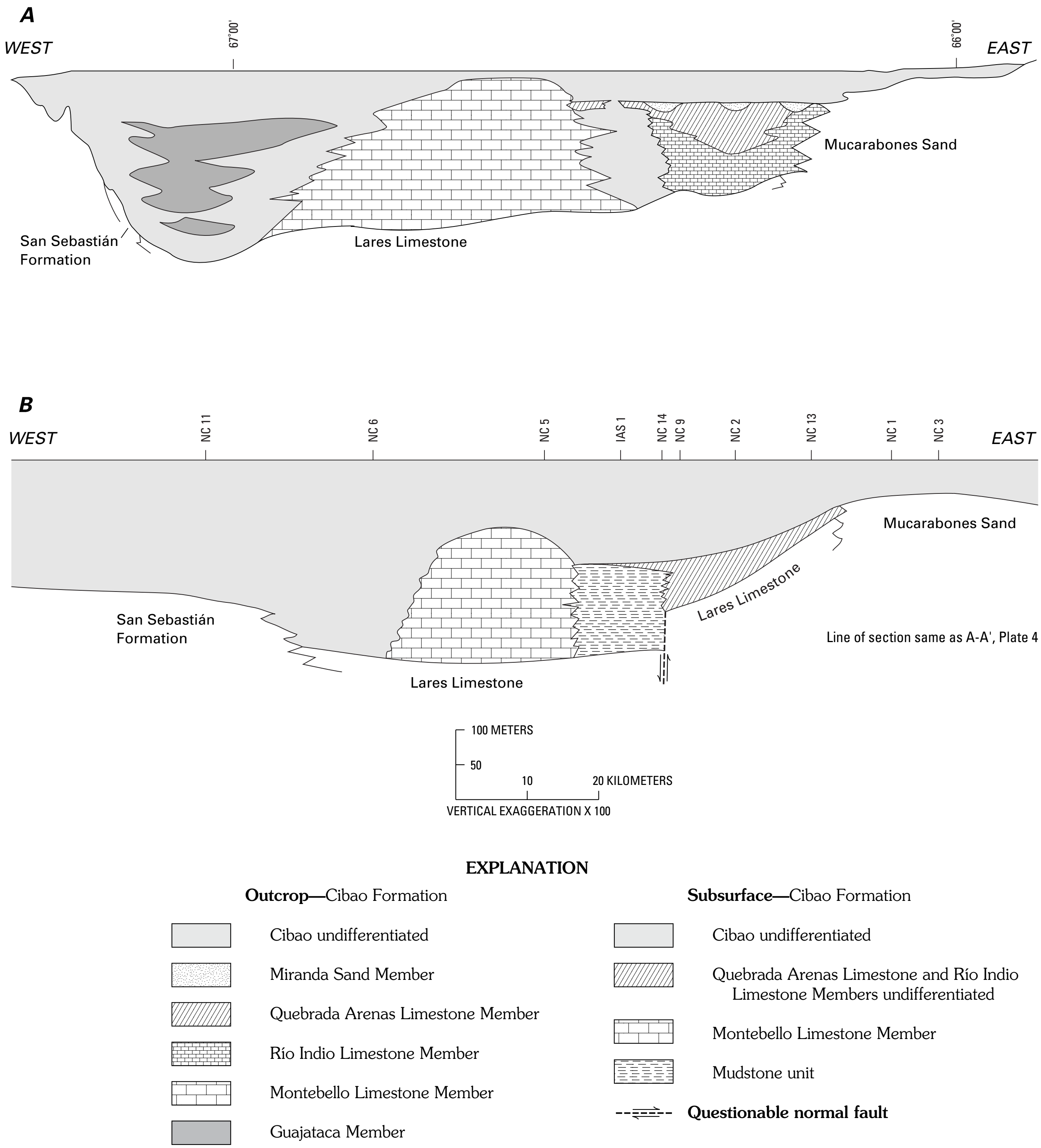

FIGURE 24.—Stratigraphic relations of Cibao Formation and its members at the outcrop (*A*) and in the subsurface (*B*) (section *A* modified from Monroe, 1980, figure 16).

(pl. 4). Thickness of the upper member is about 80 m in the western part of the basin, about 10 m where it overlies the Montebello Limestone in the west-central part of the basin, and about 50 m in much of the eastern basin (Monroe, 1980). Fossils include oysters and other marine mollusks as well as large benthic foraminifers *Lepidocyclina* sp., *Nummulites* sp., *Planorbulinella* sp., and *Marginopora* sp. (Monroe, 1980). From the descriptions of Monroe (1980), the Cibao Formation is sharply overlain by the Aguada (Los Puertos) Limestone.

Subsurface

For this report, the Cibao Formation of subsurface northern Puerto Rico is differentiated into four members: (1) Montebello Limestone, (2) mudstone unit, (3) Río Indio-Quebrada Arenas Limestone, and (4) undifferentiated Cibao (fig. 24*B*).

Montebello Limestone Member

Wells which document the entire Montebello section are NC 5, IAS 4, and Union Carbide 1 (fig. 21). Well NC 10 bottomed in the Montebello about 140 m below the top of the unit (Hartley, 1989), and the Arecibo Ionospheric Observatory (AIO) well was drilled through the basal 8 m of the Montebello (Monroe, 1980). It is questionable that Montebello lithology extends downdip into the area of the 4 CPR well, and only a few thin limestones in the NC 6 core test (Hartley, 1989) could be equivalent to the Montebello.

In the subsurface, the Montebello Limestone Member is separated from the underlying Lares Limestone on the basis that the Montebello represents a separate transgressive-regressive depositional cycle (Seiglie and Moussa, 1984; Hartley, 1989). Seiglie and Moussa (1984) use the abundance of *Miogypsina tani* to define a 60-m-thick Montebello section overlying a basal oyster-rich layer.

Thickness of the Montebello in NC 5 is 197 m (fig. 25). The lower 45 m of the Montebello is characterized by yellow-gray and pale-orange *Heterostegina* sp. and *Lepidocyclina* sp. packstone and wackestone with mollusks, red algae, and corals. Overlying this are 84 m of yellow-gray and pale-orange large-foraminifer packstone with thin packstone-grainstone and coral-rich layers. *Heterostegina* sp., *Miogypsina* sp., and *Amphistegina* sp. are abundant. The upper 87 m of Montebello is light-gray partly dolomitic packstone, wackestone, and grainstone with rhodolites, corals, and large foraminifers *Amphistegina* sp., and *Miogypsina* sp. In wells NC 5 and NC 10 (fig. 25), the Montebello is composed of generally coarsening-upward depositional units a few meters thick. Typically these cycles consist of skeletal wackestone passing upward to large-foraminifer-bearing packstone or packstone-grainstone. Some cycles are capped by coral and red algal boundstone.

Mudstone unit

The term mudstone unit is adapted from an informal designation by Seiglie and Moussa (1984) for a calcareous mudstone overlying the Lares Limestone in the Dupont 5 (D5) well (figs. 21, 22). According to Seiglie and Moussa (1984), this planktonic-foraminifer-bearing unit is age equivalent to the lower part of the subsurface Montebello Limestone to the west and the subsurface Río Indio Limestone to the east.

The mudstone unit is restricted to a narrow area east of the Río Grande de Manatí (Scharlach, 1990). The nature of the apparently abrupt stratigraphic or structural boundaries with lateral equivalents is unknown. This unit was encountered in wells NC 4, NC 14, IAS 1, IAS 2, and Dupont 5 (D5) (fig. 21). Thickness ranges from about 137 m in NC 4 to about 60 m in Abbott 1 (A1) (fig. 26). The mudstone unit overlies the Lares Limestone and underlies either the Río Indio/Quebrada Arenas Limestone or undifferentiated Cibao Forma-tion. In the subsurface, neither the lower nor upper contact is sharp. The lower boundary is placed where terrigenous strata become more abundant and thicker than carbonate strata. The upper boundary is placed where calcareous mudstone and wackestone-packstone bearing planktonic foraminifers pass upward to interbedded mudstone, marl, and clayey-sandy limestone with benthic foraminifers and other shallow-marine fossils.

Scharlach (1990) divided the mudstone unit penetrated by NC 4 into three parts. The lower 30 m of the mudstone unit is composed of grayish-green and light-olive-green marly sandstone, siltstone, wackestone, and rare packstone. The carbonate rocks are locally dolomitic. The diverse fauna includes planktonic and benthic foraminifers, thin-shelled mollusks, echinoids, and, in places, large thin *Lepidocyclina* sp., *Halimeda* sp., red algae, and bryozoans.

The middle part of the mudstone unit in NC 4 is predominantly grayish-green clay, silt, carbonate mudstone-wackestone, and dolomudstone-dolowackestone. This interval is less fossiliferous than the lower part, but bears planktonic foraminifers, thin-shelled bivalves, scaphopods, and echinoid fragments. In the lower half of the middle mudstone unit are thin beds of marly quartz and lithic sandstones and glauconitic sandy-clayey wackestone-packstone. These coarser rocks contain scattered *Lepidocyclina* sp. and other coarse skeletal grains.

The uppermost mudstone unit is composed of pale-olive and grayish-olive marl and claystone with upwardly increasing skeletal wackestone and packstone. Planktonic foraminifers and large benthic foraminifers (mostly *Miogypsina* sp.) are common. Other fossils include echinoids, ostracodes, pychnodontid oysters, other mollusks, and bryozoans.

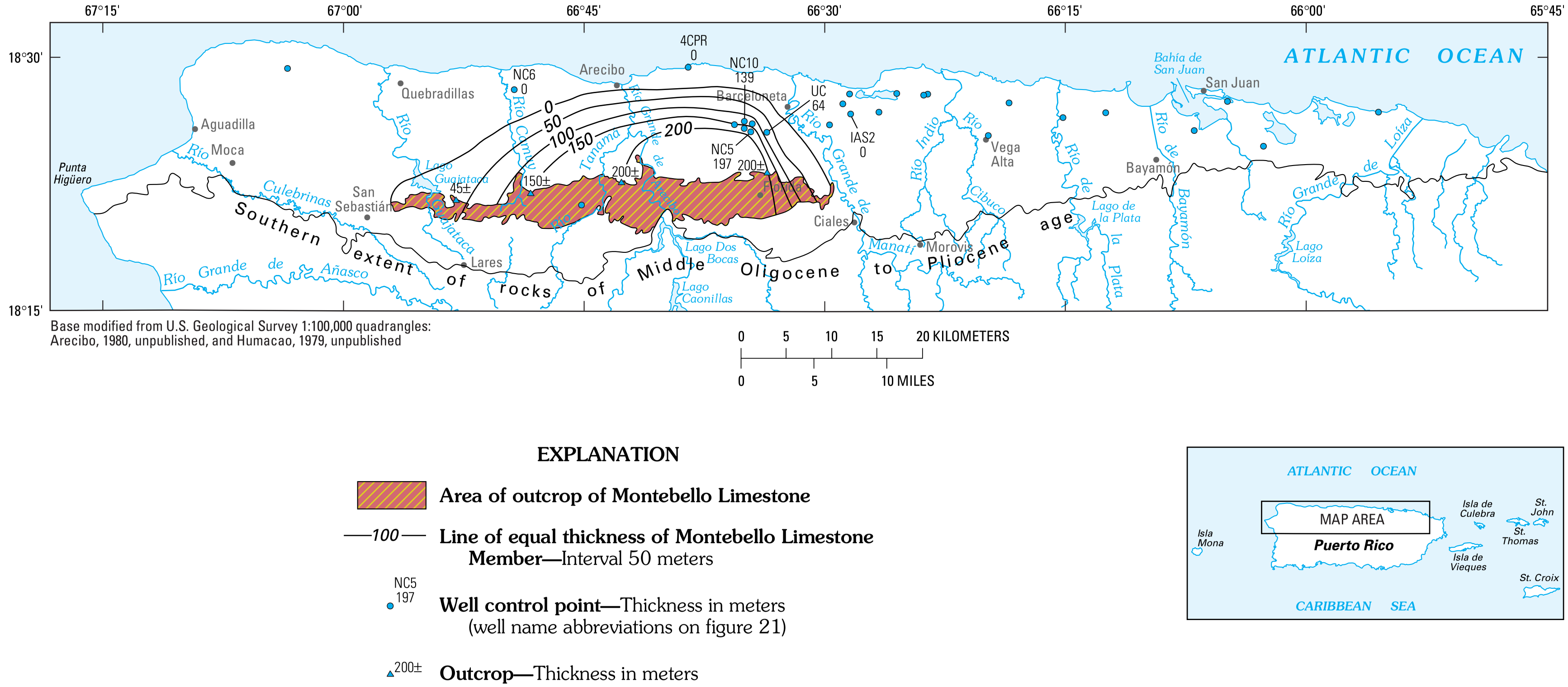

FIGURE 25.—Thickness of Montebello Limestone, northern Puerto Rico (outcrop extent modified from Monroe, 1980).

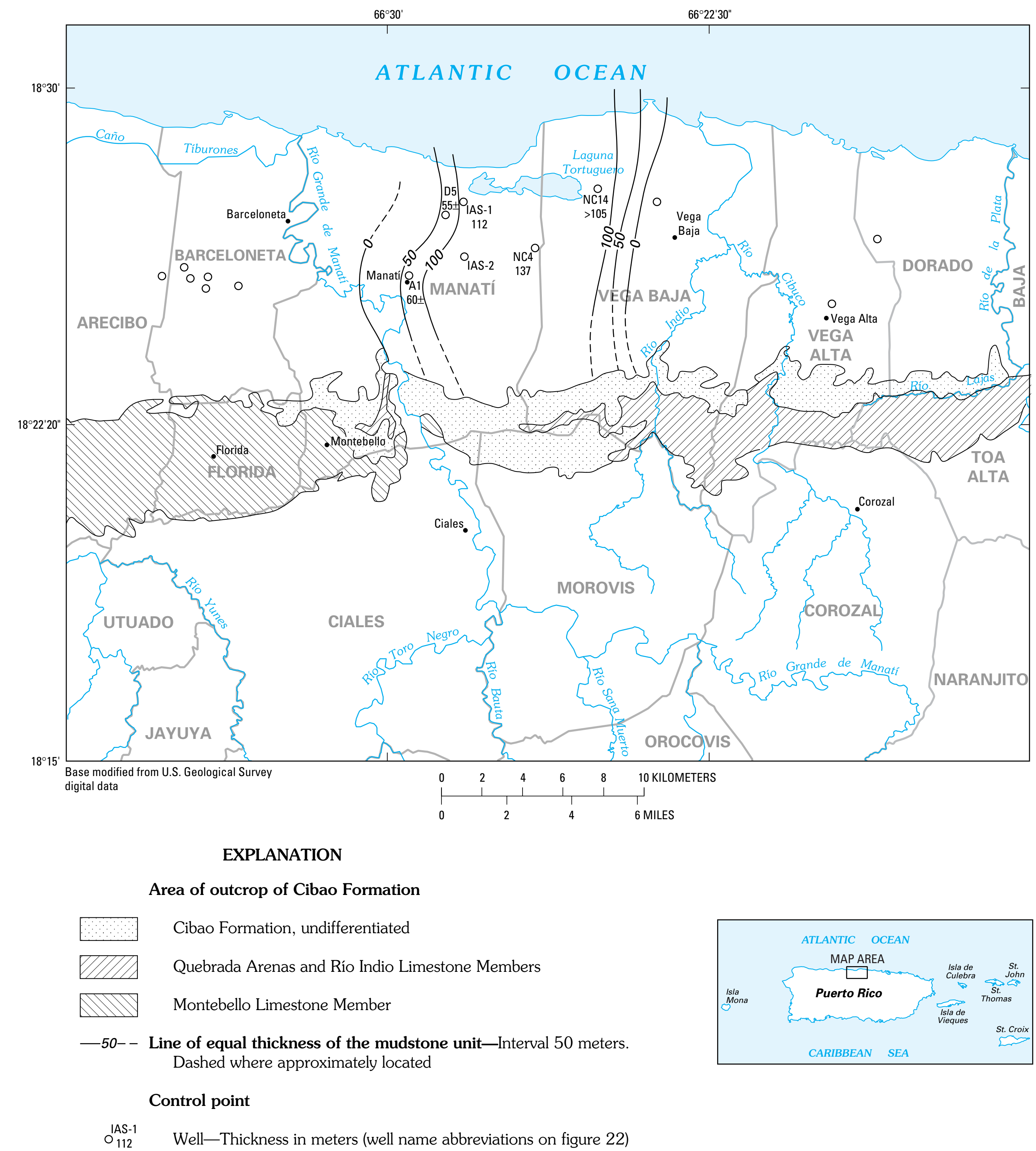

FIGURE 26.—Thickness of the mudstone unit of the Cibao Formation, northern Puerto Rico.

Río Indio/Quebrada Arenas Limestone Members

Between the Lares Limestone and the Cibao Formation in the eastern part of the basin is a transition zone of variable lithology, here termed Río Indio/Quebrada Arenas Limestone Members. No attempt is made to distinguish between these two members in the subsurface.

The Río Indio/Quebrada Arenas Limestone section was encountered in test wells NC 2, NC 4, NC 8, NC 9A, NC 13, and NC 14 (fig. 21; pl. 4). In NC 8, the section of variable lithology is 63 m thick, but it thins downdip to about 27 m in NC 2. The Río Indio/Quebrada Arenas section encountered in NC 8 is light-gray and yellowish-gray sandy skeletal grainstone, packstone, and wackestone interbedded with fossiliferous lithic sandstone with thin layers of claystone and siltstone. The large benthic foraminifers *Miogypsina* sp., *Heterostegina* sp., and *Lepidocyclina* sp. are common. The Río Indio/Quebrada Arenas Limestone section also contains a thin cobble-pebble conglomerate composed of volcanic-rock fragments, corals, and mollusks. In NC 2, the Río Indio/Quebrada Arenas is composed of glauconitic sandy and clayey skeletal packstone and wackestone and glauconitic fossiliferous marl. Skeletal grains include bryozoans, large benthic foraminifers *Heterostegina* sp., *Miogysina* sp., *Amphistegina* sp., and *Lepidocyclina* sp., echinoids, red algae, and mollusks, including oysters and pectens.

The Río Indio/Quebrada Limestone lithology is not recognized in the subsurface west of NC 4 between Río Grande de Manatí and Río Cibuco (fig. 21; pl. 4). In NC 4 in the central part of the basin, there is a 30 m-thick transition zone above the mudstone unit. East of the Río de la Plata, where the Cibao Formation apparently becomes more terrigenous and the Lares Limestone interfingers with the Mucarabones Sand, the Río Indio/Quebrada Arenas Limestone section is difficult to distinguish from the sandy Lares Limestone. For this study, 26 m of glauconitic sandy wackestone-packstone and fossiliferous sandstone cored in the NC 13 well is tentatively assigned to the Río Indio/Quebrada Arenas Limestone section (pl. 4). Fossils in these beds include red algae, small benthic foraminifers, *Heterostegina* sp., mollusks, and echinoids.

Undifferentiated Cibao Formation

For this report, all of the subsurface sequence that is composed predominantly of the “typical” Cibao lithology of marl, calcareous mudstone, and clayey wackestone is referred to as “undifferentiated Cibao Formation.” The thickness of the undifferentiated Cibao ranges from more than 300 m in the western downdip area (between Río Camuy and Río Grande de Manatí) (fig. 27) to tens of meters in the eastern part of the basin (east of Río de la Plata). Over most of the area, this unit is the upper part of the Cibao Formation, but in the western end of the basin the entire Cibao section is composed of this lithology (pl. 4). The lower part of the Cibao Formation in the western part of the basin in the vicinity of the Río Camuy most likely is time equivalent to the uppermost Lares Limestone and the Montebello Limestone Member. Cibao lithology penetrated by NC 11 rests directly on San Sebastián lithology (pl. 4). Well NC 6, downdip from the Lares and Montebello outcrop (pl. 4), encountered only a few thin layers of carbonate rocks which could be attributed to the Lares or Montebello Limestones. For this report, therefore, the entire lower 285 m of section in the NC 6 well is considered to be Cibao lithology, although a thin limestone at 747 m could be equivalent to the top of the updip Lares Limestone. The other downdip well in the west-central part of the basin, the 4 CPR (pl. 4), drilled through more than 300 m of the Cibao Formation above the Lares Limestone (Briggs, 1961). Over a paleohigh in the eastern end of the basin, undifferentiated Cibao overlies the Mucarabones Sand (NC 1 and NC 3; pl. 4).

The predominant lithology of the undifferentiated Cibao Formation in the subsurface of northern Puerto Rico is medium-gray, yellowish-gray, and olive-gray soritid-miliolid wackestone and packstone interbedded with marl and claystone. Much of the limestone is clayey and sandy. Dolomitic zones occur in the upper and lower parts of the formation in several places. Several gray green yellow-gray and red-brown paleosols are preserved in the Cibao of the eastern and central parts of the basin (Scharlach, 1990), and caliche crusts occur in a few zones of the Cibao of the central and western part of the basin (Hartley, 1989; Scharlach, 1990).

In addition to abundant soritid and miliolid foraminifers, typical limestones of the undifferentiated Cibao Formation also contain small rotalid foraminifers, encrusting porcellaneous foraminifers, agglutinated foraminifers, a variety of mollusks, ostracodes, red algae, echinoids, and less commonly, bryozoans and small corals. The large benthic foraminifer *Miogypsina* sp. is restricted to the lower part of the undifferentiated Cibao (Scharlach, 1990), except in the west, where this foraminifer occurs in a few limestones within the lower three-quarters of the undifferentiated Cibao section (Hartley, 1989). Most fine-grained terrigenous layers in the Cibao contain benthic foraminifers and mollusks, but some mudstones, sandstones, and conglomerates are non-fossiliferous. Dark-gray to dark-green carbonaceous claystones occur locally.

AGUADA (LOS PUERTOS) LIMESTONE (LOWER TO MIDDLE MIOCENE)

Outcrop

At outcrop as well as in the subsurface, a 100- to more than 500-m thick section of carbonate rock overlies the Cibao Formation across the whole North Coast Tertiary Basin (fig. 28). The lower part of this lower to middle Miocene sequence is the Aguada (Los Puertos) Limestone.

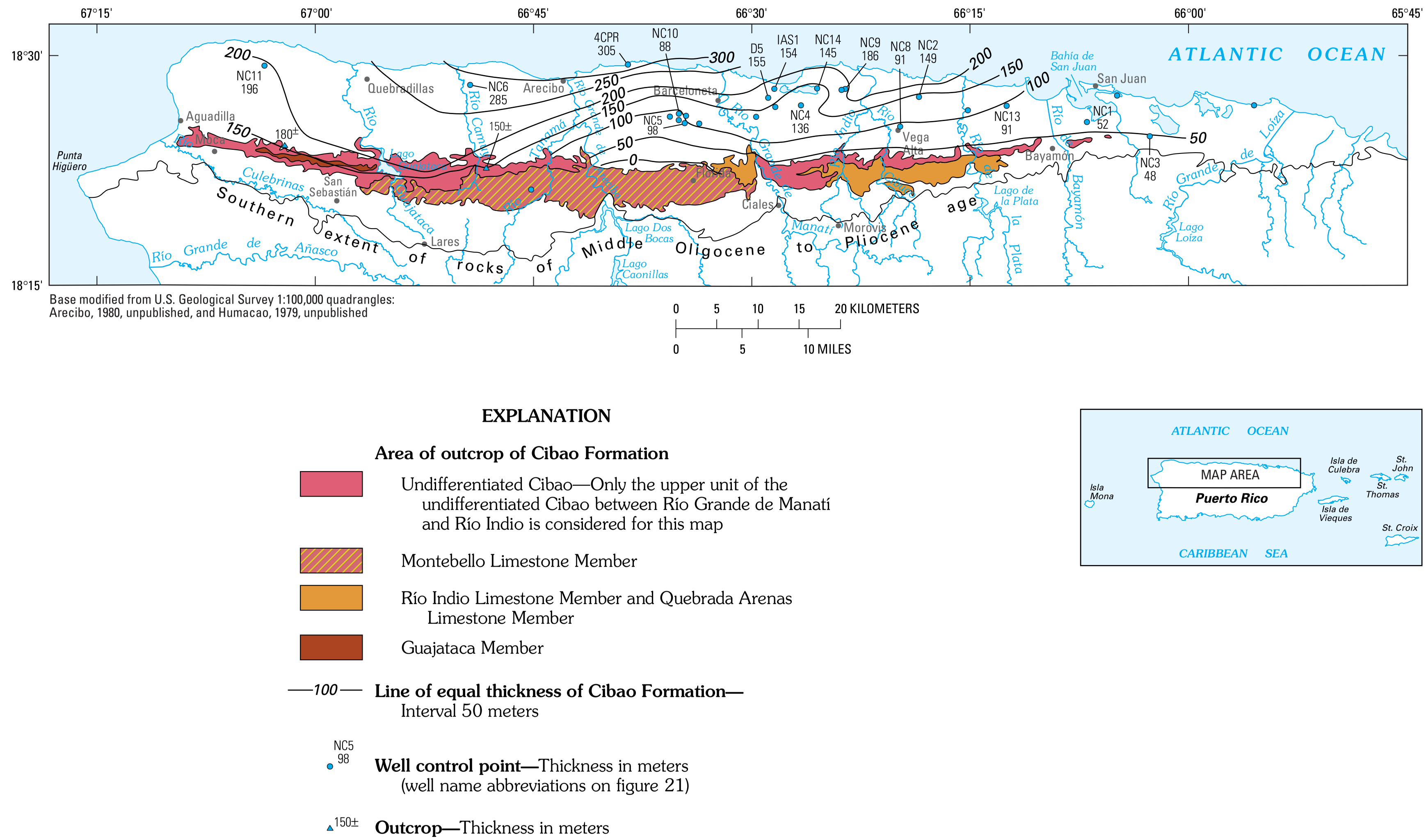

FIGURE 27.—Thickness of undifferentiated Cibao Formation, northern Puerto Rico (outcrop extent modified from Monroe, 1980).

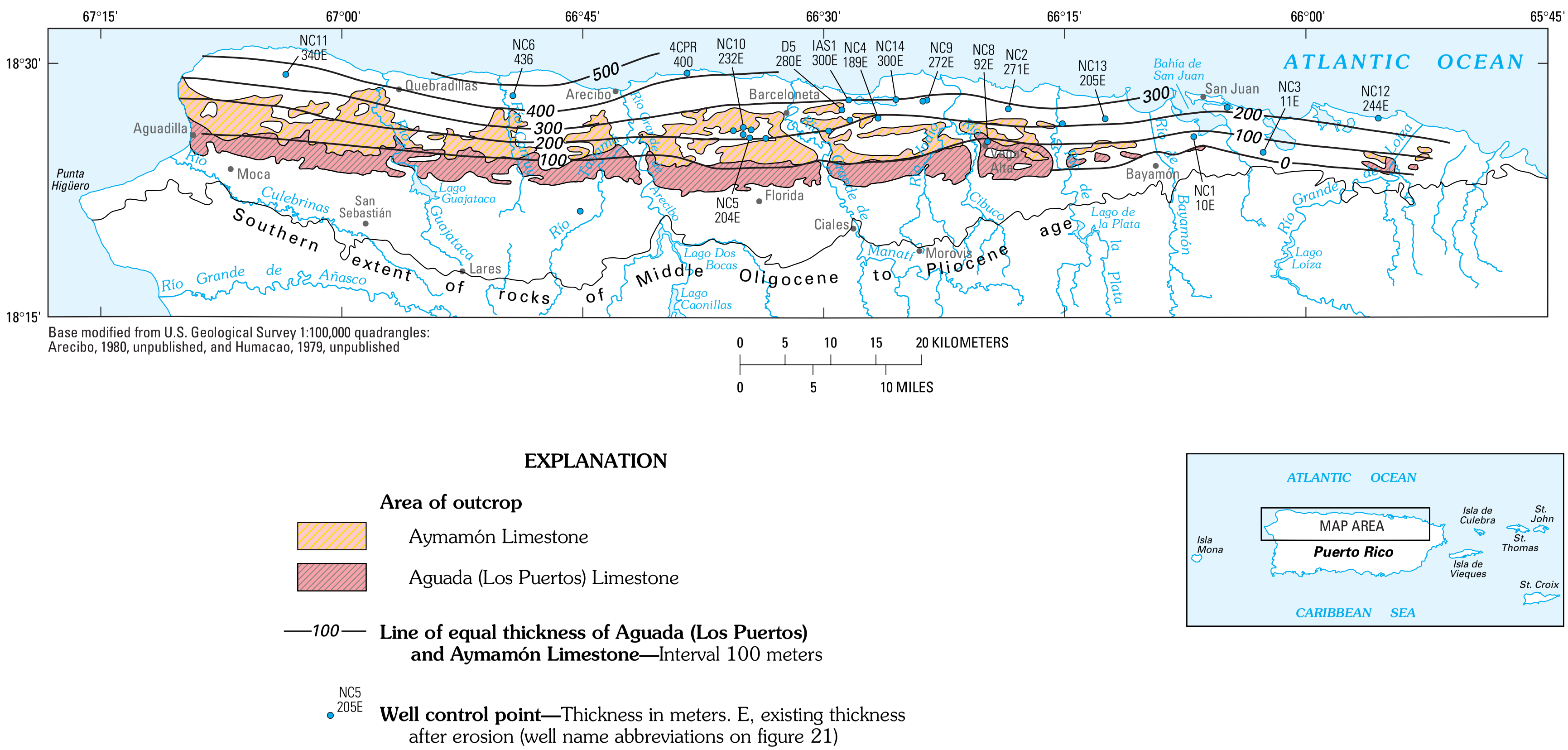

FIGURE 28.—Combined thickness of Aguada (Los Puertos) and Aymamón Limestone, northern Puerto Rico (outcrop extent modified from Monroe, 1980).

The Aguada (Los Puertos) Limestone crops out across the entire northern coastal plain, except east of Río Bayamón where the outcrop is narrow and discontinuous (fig.3; pl. 4). Although the Aguada (Los Puertos) is predominantly carbonate rocks, it has been described as a transitional unit between the underlying Cibao Formation and the overlying Aymamón Limestone (Zapp and others, 1948; Monroe, 1980). At the surface, the lower part of this unit consists of pink to grayish-orange "chalky" fine crystalline limestones and fine- to medium-grained calcarenite, commonly containing scattered quartz sand (Monroe, 1980). Upper parts of the Aguada (Los Puertos) commonly are grayish-pink and pale-orange thinly bedded, partly cross-bedded, fossiliferous to "relatively unfossiliferous" calcarenite (Monroe, 1980). Fossils include *Marginopora* sp., *Archaias angulatus, Gypsina globula* and other benthic foraminifers, mollusks, red algae, and green algae. Meyerhoff and others (1983) describe the Los Puertos Limestone as white, yellow, pink, and light-orange massive limestone, light-brownish-gray to white recrystallized massive limestone, and white dolomitic limestone. East of the Río de la Plata, the lower Aguada (Los Puertos) passes into chalky limestone and calcareous clay indistinguishable from the upper Cibao (Monroe, 1980).

In the western part of the outcrop, the Aguada (Los Puertos) Limestone is about 90 m thick (Monroe, 1980). East of the Río Grande de Manatí thickness varies from about 60 m updip to 110 m downdip, and east of the Río de la Plata the formation thins to approximately 35 m (Monroe, 1980).

The Aguada (Los Puertos) Limestone rests conformably on the Cibao Formation and in many places "it is difficult to distinguish the two formations" (Monroe, 1980, p. 45). In most places, Monroe (1980) marks the base of this unit at the lowest occurrence of "calcarenite." The top of this formation is in sharp contact with the overlying Aymamón Limestone (Monroe, 1980), and Meyerhoff and others (1983) believe this contact to be an island-wide unconformity. In the easternmost outcrops, the Aguada (Los Puertos) intertongues with the uppermost Cibao (Monroe, 1980; Meyerhoff and others, 1983).

Subsurface

All of the NC core holes (figs. 21, 28) penetrated the Aguada (Los Puertos) Limestone, with the possible exceptions of test holes NC 1 and NC 3, which cored sandy carbonate rock of uncertain equivalency (Scharlach, 1990). The lower contact of the Aguada (Los Puertos) Limestone is gradational with the Cibao Formation, and for this report the lower boundary of the Aguada (Los Puertos) is placed where carbonate rock becomes the predominant lithology. The upper boundary is marked by paleokarst in updip wells (NC 2, NC 9, and NC 10), but the subaerial unconformity apparently passes into a conformable contact downdip (Hartley, 1989; Scharlach, 1990), as previously suggested by Meyerhoff and others (1983). The upper contact of the Aguada (Los Puertos), therefore, is poorly defined in downdip wells (NC 14 and IAS 1). In the eastern part of the basin, the Aguada (Los Puertos) Limestone is about 60 to 90 m. In the western half, it is about 90 to 120 m thick and thickens in the downdip well 4 CPR downdip to between 115 and 175 m, according to where the top of the formation is placed (Briggs, 1961).

The Aguada (Los Puertos) Limestone typically consists of shoaling-upward cycles of grayish-orange and yellowish-gray skeletal wackestone to packstone several meters thick. In the lower part of the formation, the predominant fauna are soritid and miliolid benthic foraminifers and mollusks, and in many places the limestone is sandy. *Amphistegina* sp., red algae, corals, *Halimeda* sp., *Kuphus* sp., and echinoids become more abundant up section and downdip (Hartley, 1989; Scharlach, 1990). *Amphistegina* sp. is the most abundant foraminifer in all samples from the Aguada penetrated by 4 CPR (Gordon, 1961b). Calichified zones cap some of the depositional cycles in the lower part of the Aguada (Los Puertos) in the west-central area (NC 5, NC 6, and NC 10). Elsewhere in the basin, cycles consist of skeletal wackestone passing upward to skeletal packstone, skeletal packstone to packstone/grainstone, and packstone to coral/red algae patch-reef limestone. The small branching coral *Stylophora affinis* is common in the coral-bearing layers.

In the updip wells NC 1 and NC 3 (pl. 4), the section overlying the Mucarabones Sand is sandy packstone and grainstone with thinner interbeds of clay and sand (Scharlach, 1990). Most limestones in this sequence have fauna similar to that of the Aguada (Los Puertos) Limestone cored in the other wells. The upper part of this updip sandy limestone sequence, therefore, probably is time equivalent of the Aguada (Los Puertos) Limestone.

In the downdip part of the east-central basin (NC 9 and IAS 1), much of the Aguada (Los Puertos) Limestone is dolomitized. Elsewhere in the basin, the Aguada (Los Puertos) contains scattered yellowish-brown dolomitic zones. Briggs (1961) described the Aguada in the 4 CPR well as "largely calcarenite, possibly largely magnesian," suggesting the most-basinward Aguada (Los Puertos) also is dolomitic.

AYMAMÓN LIMESTONE (MIDDLE MIOCENE)

Outcrop

The Aymamón Limestone is exposed in topographic highs across a wide belt that extends from the northwestern coast to the Río de la Plata, but is covered in broad areas by surface deposits of Quaternary and Tertiary(?) age. East of the Río de la Plata, where much of the Aymamón Limestone is buried under Quaternary alluvial and coastal deposits, the outcrops are narrow and discontinuous (fig. 3). Monroe (1980) considers this limestone to be the most uniform in lithology and thickness of all the Tertiary formations cropping out in northern Puerto Rico. Estimated thickness across the outcrop belt is 190 to 200 m (Monroe, 1980; Meyerhoff and others, 1983).

The Aymamón is "thick-bedded to massive commonly quartz-free, very pure limestone" (Monroe, 1980, p. 53). The lower half of the formation is very pale-orange to white, thick-bedded quartz-free limestone. In some places, there are many layers of limestone breccia, some of which may be organic-reef debris, but much of which is solution breccia (Monroe, 1980). On northwestern coastal plain, the upper part of the Aymamón is pale-grayish-orange unconsolidated chalk that alternates with thick beds of recrystallized porcelain-like pure limestone (Monroe, 1980, p. 53). Near the coast, the formation is dolomitic (Monroe, 1980). Some beds contain abundant fossils, including *"Ostraea" haitensis* in the upper part of the formation, corals *Montastrea limbata, Psammocora gasparillensis*, and *Porites* sp., the echinoid *Clypeaster cubensis*, and benthic foraminifers *Marginopora* sp., *Archais* sp., and *Gypsina* sp. (Monroe, 1980).

In a study of the northwestern part of the outcrop, Seiglie and Moussa (1984) observed the following stratigraphic sequence, in ascending order: (1) branching-red-algae/miliolid/soritid back-reef lagoonal deposits, (2) open-shelf coral-reef debris and gastropod-bivalve deposits, and (3) a forereef containing encrusting coralline algae, an *Amphistegina angulata* assemblage and rare planktonic foraminifers. Meyerhoff and others (1983) described a similar sequence of rock types and included a locally absent basal unit of cross-bedded calcarenite. Osbourne and others (1979) also described an *Amphistegina angulata* microfacies in the upper Aymamón.

The Aymamón Limestone rests sharply on the Aguada (Los Puertos) Limestone (Monroe, 1980; Meyerhoff and others, 1983). Monroe (1980) describes a typical abrupt change from reddish thin-bedded Aguada (Los Puertos) to very-pale-orange and white thicker-bedded Aymamón. Meyerhoff and others (1983) believe the Aymamón overlies a widespread erosional unconformity. Judging from the descriptions of Seiglie and Moussa (1975), Monroe (1980), and Meyerhoff and others (1983), the upper boundary of the Aymamón Limestone is a karsted surface. In the northwestern half of the Tertiary outcrop, the Aymamón is overlain by the Pliocene Quebradillas Limestone (fig. 3; pl. 4).

Subsurface

Most of the deeper water-supply wells and test wells in northern Puerto Rico are located within the outcrop belt of the Aymamón Limestone; therefore, the total thickness of this formation was penetrated only by NC 6 and 4 CPR, which started in the Quebradillas Limestone. The Aymamón Limestone is 330 m in NC 6 and is estimated to be approximately 300 m thick in the 4 CPR (pl. 4; fig. 28).

The Aymamón Limestone is lithologically similar across most of the North Tertiary Basin. Typically, this formation is yellowish-gray and pale-orange skeletal wackestone and packstone with lesser grainstone and common thin coral rudstone and coral-red algae boundstone. For the most part, the Aymamón is composed of shoaling-upward depositional cycles that range from a meter to several meters thick. Cycles commonly consist of skeletal wackestone or wackestone-packstone passing upward to packstone-grainstone. Some cycles are capped by coral rudstone or coral-red algae boundstone.

Red algae and *Amphistegina* sp. are the most abundant grain types. Other common skeletal constituents include miliolids, soritids, homotremids, *Gypsina* sp., echinoids, bivalves including *Kuphus* sp., and *Halimeda* sp. The small branching coral *Stylophora affinis* is scattered throughout the formation. Other corals identified in cores from NC-2 (S. H. Frost, UNOCAL, written commun., 1991) include *Porites waylandi, Porites* sp. cf *P. baracoaensis, Porites* sp. cf *P. portoricoensis, Siderastrea siderea, Montastrea* sp. cf *M. annularis, Montastrea* sp. cf *M. costata, Montastrea* sp. cf *M. bainbridgensis*, and *Goscinaraca coleti.*

Dolomitized zones are common but unevenly distributed in the subsurface Aymamón Formation. Many coral-rich layers in the depositional cycles are selectively dolomitized. Most of the Aymamón in NC 9 is dolomitized. Dolomite and dolomitic limestone also are common in the lower half of the Aymamón in NC 2, NC 4, and NC 11 (Hartley, 1989; Scharlach, 1990). The lower and upper parts of the Aymamón in NC 6 have dolomitic zones, and the upper Aymamón in 4 CPR is dolomite (Briggs, 1961).

QUEBRADILLAS LIMESTONE (UPPERMOST MIOCENE TO PLIOCENE)

Outcrop

The uppermost Tertiary unit exposed in northern Puerto Rico is the Quebradillas Limestone (pl. 4). Most outcrops of this uppermost Miocene-Pliocene limestone are in the northwestern part of the coastal plain west of the Río Grande de Arecibo (fig. 3). From Arecibo to north of Manatí there are only a few small isolated outliers of Quebradillas, and this unit is absent in northeastern Puerto Rico. The Quebradillas Limestone overlies a paleokarst developed on the Aymamón Limestone and underlies, in some places, alluvial and coastal deposits of Quaternary age.

Monroe (1980) divides the Camuy (Quebradillas) Limestone into three parts. The lower unit is about 30 to 40 m of pale-yellowish-orange thin- to medium-bedded "chalky limestone" and pale-orange to pale-reddish-brown thin-bedded and cross-bedded calcarenite. Some layers contain scattered quartz sand, and some basal beds are highly ferruginous. Oyster shells are common near the base of the formation in some localities. Much of this lower unit is rich in planktonic foraminifers. A middle unit consists of about 25 to 30 m of “hard very-pale-orange to light-brown ferruginous calcarenite commonly containing blebs of limonitic clay and scattered grains of quartz and magnetite” (Monroe, 1980, p. 61). These fossiliferous beds contain abundant planktonic foraminifers, benthic foraminifers including *Nummulites* sp., bryozoans, echinoids, and mollusks. An upper unit is recognized only in the central part of the outcrop belt between Río Camuy and Río Grande de Arecibo (fig. 3, 21). It is composed of more than 40 m of fossiliferous “chalk, sandy chalk, sandstone, sandy limestone, and limestone” containing abundant planktonic foraminifers (Monroe, 1980).

Based on a study of outcrops along Highway 2 northwest of the town of Quebradillas (fig. 3), Seiglie and Moussa (1975) also divided the “Quebradillas Limestone” into three units, for which they give no thicknesses. The lower unit, which overlies and infills a dissolution surface on the Aymamón Limestone, is planktonic-foraminifer limestone containing abundant “deep-water” foraminifers such as *Sphaeroidinella* sp. and *Spheroidinellopsis* sp. In some places, the lower unit contains layers of broken oyster shells interbedded with the globigerinid limestone. The middle unit is nummulitid-globigerinid limestone with abundant *Nummulites cojimarensis* as well as other benthic foraminifers *Amphistegina* sp. *Planorbulina* sp., *Carpenteria* sp., and *Sporadotrema* sp. Planktonic foraminifers decrease up section, and the upper part of the Quebradillas Limestone is skeletal limestone rich in the benthic foraminifer *Amphistegina*. Other fossils are red algae, some large miliolids, and bryozoans. Seiglie and Moussa (1975) mention terrigenous material only in their upper unit and at the base of the formation in the fill of solution cavities.

Subsurface

The Quebradillas Limestone was encountered only in test wells NC 6 and 4 CPR (pl. 4). The basal 26 m of this formation in NC 6 is yellow-orange globigerinid packstone, which sharply overlies uppermost Aymamón packstone containing abundant *Amphistegina* sp. and red algae (Hartley, 1989).

Briggs (1961) did not recognize the Quebradillas in the 4 CPR well, but the upper 120 m of his “Aymamón” contain abundant planktonic foraminifers (Gordon, 1961b). Monroe (1980, p. 63-64) estimates that 170 m of Camuy (Quebradillas) Limestone were penetrated in this well. The upper 45 m in the 4 CPR are interbedded dense limestone and limestone rubble and marl with quartz and clay in the uppermost zone (Briggs, 1961). Below this, the “upper Aymamón” is grayish-orange, pale-orange-pink, and yellowish-orange “calcarenite” with scattered quartz grains. Gordon (1961b, p. 33) characterizes the fauna in this interval as an “extremely diverse assemblage of fossils in which globigerinids and amphisteginids are both abundant.”

DEPOSITIONAL HISTORY

INTRODUCTION

Rock types and faunal assemblages were the principal data used to interpret the depositional environments of the major stratigraphic units of the North Coast Tertiary Basin. After deposition of the terrigenous sediments of the San Sebastián Formation, the general depositional setting during the rest of the Tertiary was a gently northward-inclined carbonate platform, i.e., ramp (Ahr, 1973) or distally steepened ramp (Read, 1985). The landward margin of the carbonate platform was fringed by paralic siliciclastic systems. “Inner platform” and “inner neritic” refer to the landward margin of the platform, which generally is characterized by a less diverse fauna than the middle platform. This zone contains subtidal and intertidal settings. The terms “middle platform” and “middle neritic” refer to open, generally subtidal environments from many tens of meters deep to shallow shoals several centimeters deep. “Outer platform” and “outer neritic” refer to parts of the platform from many tens of meters to a few hundreds of meters deep. Although several authors describe northern Puerto Rico depositional environments during the middle and late Tertiary in terms of “backreef” and “forereef,” this usage is avoided here inasmuch as there is no evidence for any shelf-break reef tracts which would have created these environments.

MIDDLE TO LATE OLIGOCENE

At outcrop (Monroe, 1980; Frost and others, 1983) and in the shallow subsurface (Hartley, 1989; Scharlach, 1990), the San Sebastián Formation records a general change from nonmarine to shallow-marine deposition. The basal red- and green-mottled nonfossiliferous mudstone and sandstone represent alluvial-plain or delta-plain sedimentation. The overlying mudstone and marl with restricted-marine fauna and highly carbonaceous layers were deposited in coastal bays, marshes, and swamps. Glauconitic siliciclastic and carbonate rocks with diverse, normal-marine fauna near the top of the San Sebastián Formation were deposited on the shallow open platform as sea level rose and terrigenous influx waned. Repeated depositional cycles within the upper San Sebastián Formation suggest high-order fluctuations of relative sea level during the larger-scale transgression.

The thick lowermost “San Sebastián Formation” that is penetrated only by the 4 CPR well (pl. 4) apparently records one major depositional cycle and is not exposed in outcrop. The ratios of planktonic to benthonic foraminifers reported by Gordon (1961b) indicate that the lowermost San Sebastián was deposited in nonmarine to inner-platform environments, but most of the typical part of the formation was deposited on the middle and outer platform at depths perhaps greater than 100 m (Gordon, 1961b). The fauna of the upper part of the unit, however, suggests a return to a shallower-platform environment.

LATE OLIGOCENE TO EARLY MIOCENE

A major rise of sea level began during the late Oligocene. This is recorded by the gradation of shallow-marine deposits of the upper San Sebastián Formation into the inner- to mid-platform carbonate and terrigenous deposits of the lower Lares Limestone. Small coral patches as well as rhodolite and large-foraminifer packstone and grainstone of the lower Lares represent tidal shoals on a shallow, normal-salinity inner platform. Burrowed large-foraminifer/red algae wackestone accumulated in subtidal parts of the inner to middle platform as sea level continued a general rise.

Over most of the northern Puerto Rico platform, the middle part of the Lares Limestone records the maximum transgression of the late Oligocene sea (fig. 29). The middle unit was deposited in middle to outer-neritic environments, except in the western and eastern extremities of the basin, where predominantly terrigenous inner platform to nonmarine sediment accumulated (fig. 29). Coral reefs developed on the western middle platform (Frost and others, 1983) and in the east-central platform in the vicinity of the NC 9A test well (fig. 21). Rhodolite and large-foraminifer deposits accumulated in somewhat deeper parts of the open platform in the central basin. An increase in planktonic foraminifers in the middle Lares in the west-central part of the basin (NC 5, 4 CPR, and Dupont 5) further attest to the deepening of the northern Puerto Rico platform.

During deposition of the upper Lares Limestone, sea level fell. Soritid- and miliolid-rich limestone of the uppermost Lares indicate that inner- to middle-platform environments spread seaward over much of the early Miocene platform. Packstone and wackestone with corals, red algae, and planktonic foraminifers interbedded with fine terrigenous rocks in the upper Lares of the east-central part of the basin suggest that this area was on a middle to outer platform that was receiving terrigenous influx from the east. At this same time in the west-central basin, the carbonate platform shoaled to shallow water, as recorded by the soritid-miliolid carbonate rocks at the top of the Lares. On the western flank of the basin, paralic and inner-platform terrigenous sediments continued to accumulate. Strata equivalent to upper Lares in the NC 11 well are predominantly claystone and marl with only thin limestone, mostly with shallow-marine fossils. On the flanks of paleohighs in the eastern part of the basin (the vicinity of wells NC 1 and NC 3; pl. 4), the mudstone, sandstone, and conglomerate of Mucarabones Sand were deposited in nonmarine to shallow-marine environments.

EARLY MIOCENE

Following the regression of sea level which marked the end of Lares deposition, sea level began to rise again across the gently inclined insular shelf of northern Puerto Rico. The patterns of deposition during this transgression were the most complicated of any time during the Neogene (fig. 30). Apparently, the complex facies patterns of the Cibao Formation reflect differential uplift or subsidence, or both, in the highlands and under the marine platform. The western part of the basin received an influx of terrigenous material associated with the Guajataca delta system. The inner-platform clayey wackestone and marl of the lower Cibao Formation in the subsurface, as well as the terrigenous Guajataca Member at the outcrop (fig. 24*A*), attest to a large input of siliciclastic sediment in northwestern Puerto Rico. Deposition of the Montebello carbonate sediments at this same time indicates that the west-central part of the basin remained an inner- to middle-platform environment with little terrigenous influx from the land. Contemporaneous with Montebello deposition, a narrow area in the east-central part of the basin was receiving the abundant influx of fine siliciclastic sediment that makes up the mudstone unit. This predominantly terrigenous member has the deepest-water fauna of any Cibao unit indicating that the east-central basin was undergoing preferential subsidence during the early Miocene. The abrupt eastern and western boundaries of both the mudstone unit and its outcrop equivalent may reflect fault-controlled downdropping of a narrow trough that trended north-northwest. Farther east in the east-central basin, the carbonate and terrigenous sedimentary rocks of the Río Indio/Quebrada Arenas Limestone accumulated in inner- to middle-platform environments. At the eastern edge of the basin, fluvial deltaic deposition of the Mucarabones terrigenous sediments continued.

The lower Cibao Formation, except perhaps in the westernmost basin, contains a faunal succession which records a general deepening of the sea, followed by a general fall in sea level. In the east-central part of the basin, inner-platform sediments of undifferentiated Cibao were deposited over mid-platform sediments of the uppermost mudstone unit and Río Indio/Quebrada Arenas Limestone. In the western part of the basin, the area of accumulation of carbonate sediments (Montebello Limestone Member) became progressively restricted as clayey carbonate sediments (undifferentiated Cibao) became increasingly predominant.

The maximum fall of sea level in this major fluctuation of sea level is recorded by several lithologic changes across the basin. In the east, channels subsequently filled with Miranda Sand (fig. 24*A*) were incised into the upper Quebrada Arenas Limestone (Monroe, 1980), and *Miogypsina*-bearing lime-

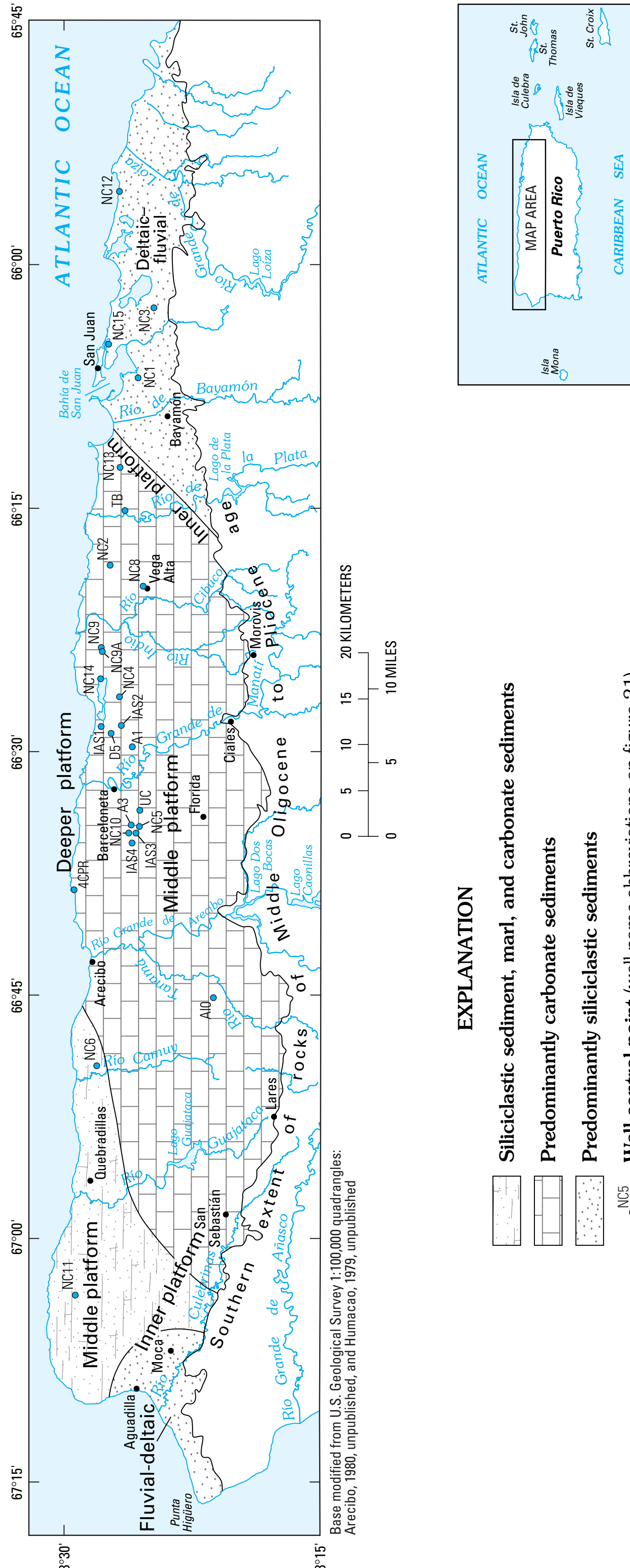

FIGURE 29.—Major depositional environments and facies patterns during deposition of the upper Lares Limestone, northern Puerto Rico.

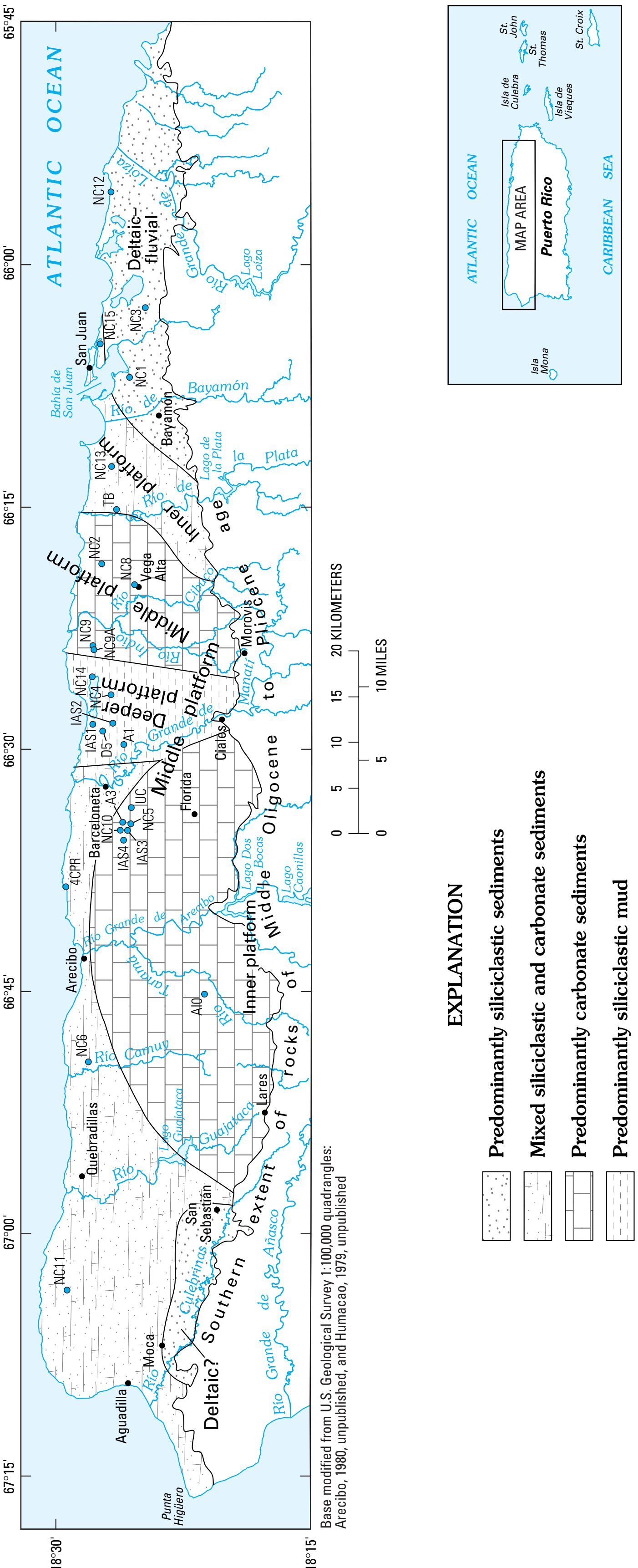

FIGURE 30.—Major depositional environments and facies patterns during deposition of the lower Cibao Formation, northern Puerto Rico.

stone and marl of the lower Cibao are overlain by poorly to non-fossiliferous clay and silt (Scharlach, 1990). In the updip part of the west-central part of the basin, the maximum fall may be recorded by the apparently sharp (partly karsted) top of the thickest Montebello Limestone and, farther west, by the top of the Guajataca fanglomerate.

Another rise in sea level brought deposition of the widespread blanket of inner- to mid-platform clayey limestone, marl, and claystone of the upper undifferentiated Cibao (fig. 31). Soritid- and miliolid-rich carbonate and terrigenous sediments were deposited across most of the basin. Less common were inner-platform foraminifer-sand shoals and *Stylophora affinis* patches. Prograding fluvial systems deposited sand and conglomerate onto the inner parts of the platform and introduced finer terrigenous sediment onto more basinward areas. Several zones of caliche and paleosol horizons within the upper Cibao record repeated subaerial exposure that result from high-frequency sea-level fluctuations and perhaps shifting delta lobes. At the eastern edge of the basin, fluvial-deltaic sedimentation (Mucarabones Sand) continued.

LATE EARLY MIOCENE TO EARLY MIDDLE MIOCENE

As the major sea-level rise continued, terrigenous sedimentation waned, and the predominantly carbonate sediments of the Aguada (Los Puertos) Limestone were deposited basinwide (fig. 32). Aguada limestones are predominantly middle platform packstone and grainstone rich in foraminifers and red algae with patches of coral. An abundance of soritid and miliolid foraminifers in the lower part of the formation passing upward to more abundant *Amphistegina* sp. records a general rise in sea level during deposition of the Aguada (Los Puertos) Limestone. Caliche zones within this formation in the west-central part of the basin indicated that parts of the carbonate platform were periodically exposed because of high-frequency fluctuations of sea level. The karst zone at the top of updip parts of the Aguada (Los Puertos) also is evidence of a regional fall in relative sea level.

MIDDLE MIOCENE

After the end of Aguada (Los Puertos) deposition, the North Tertiary Basin was flooded by another rise in sea level. The shoreline moved farther inland than during previous Oligocene-Miocene sea-level rises, and middle-platform carbonate sediments of the Aymamón Limestone were deposited across the entire area of the platform that is preserved in outcrop and the subsurface. The Aymamón Limestone, rich in *Amphistegina* sp., red algae, and coral is typical of middle-platform carbonates.

Sometime after deposition of the Aymamón Limestone, uplift or a major fall in sea level, or both, exposed much of the northern Puerto Rico carbonate platform to subaerial weathering. The extensive karst zone at the top of the Aymamón began to develop at this time.

LATEST MIOCENE-PLIOCENE

A rise in sea level deeply flooded northern Puerto Rico during the late Miocene (Seiglie and Moussa, 1984). The globigerinid limestone of the lower Quebradillas Limestone records the outer-platform environments that existed during the latest Miocene and early Pliocene. An upward decrease in planktonic foraminifer and increase in *Nummulites* sp. in the Quebradillas at the outcrop (Monroe, 1980) suggests that sea level began to fall during deposition of the upper part of this formation.

EFFECTS OF STRUCTURAL MOVEMENTS ON DEPOSITION OF UPPER OLIGOCENE TO LOWER MIOCENE ROCKS

The thickness of the San Sebastián Formation is variable, apparently reflecting paleotopography. On the outcrop, this formation is thin or absent from just west of the Río Grande de Arecibo to just east of the Río Grande de Manatí (pl. 4; fig. 33), which suggests basement rocks in this area were elevated during deposition of the San Sebastián. Indeed, the Lares Limestone also thins and locally is absent over the western part of this same area, indicating that paleohighs persisted into the early Miocene (fig. 33). Another area where the San Sebastián Formation is relatively thin over an apparent paleohigh is from the Río Grande de Arecibo westward to about 2 km east of the town of San Sebastián. West of that point, the San Sebastián Formation thickens, apparently reflecting subsidence in the western end of the basin and influx of terrigenous sediment from an uplifted region to the south.

Lares Limestone accumulated across the central basin on the flanks of basement highs. Carbonate sediments may have been deposited in this area not only because of the terrigenous influx in the eastern and western ends of the basin, but also because basement highs provided platforms for carbonate buildup (fig. 33). Angular discontinuities within the Lares Limestone (Frost and others, 1983) probably reflect slight vertical movements of basement blocks during deposition of the Lares.

The distribution of the Montebello Limestone and the mudstone unit may represent the most striking control of differential structural movement during the early Miocene (figs. 25, 26). The Montebello carbonate buildup is directly above the paleohighs over which the San Sebastián is thin. This implies that this area remained a slowly subsiding and probably relatively high platform during Montebello deposition. The area of the deeper-water mudstone unit, on the contrary, apparently was a downdropped trough bounded on the west and east by shallow carbonate platforms. These facies relations might be explained by reactivated vertical movement

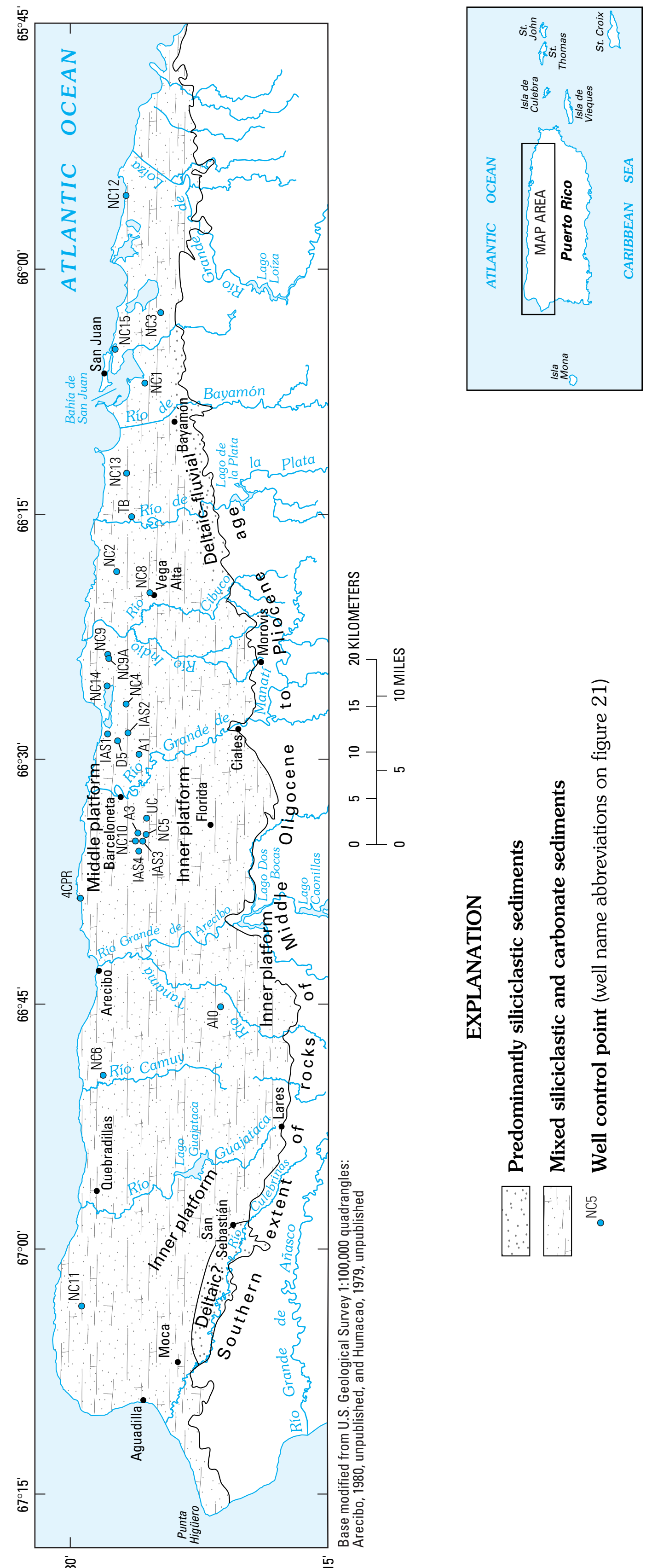

FIGURE 31.—Major depositional environments and facies patterns during deposition of the upper Cibao Formation, northern Puerto Rico.

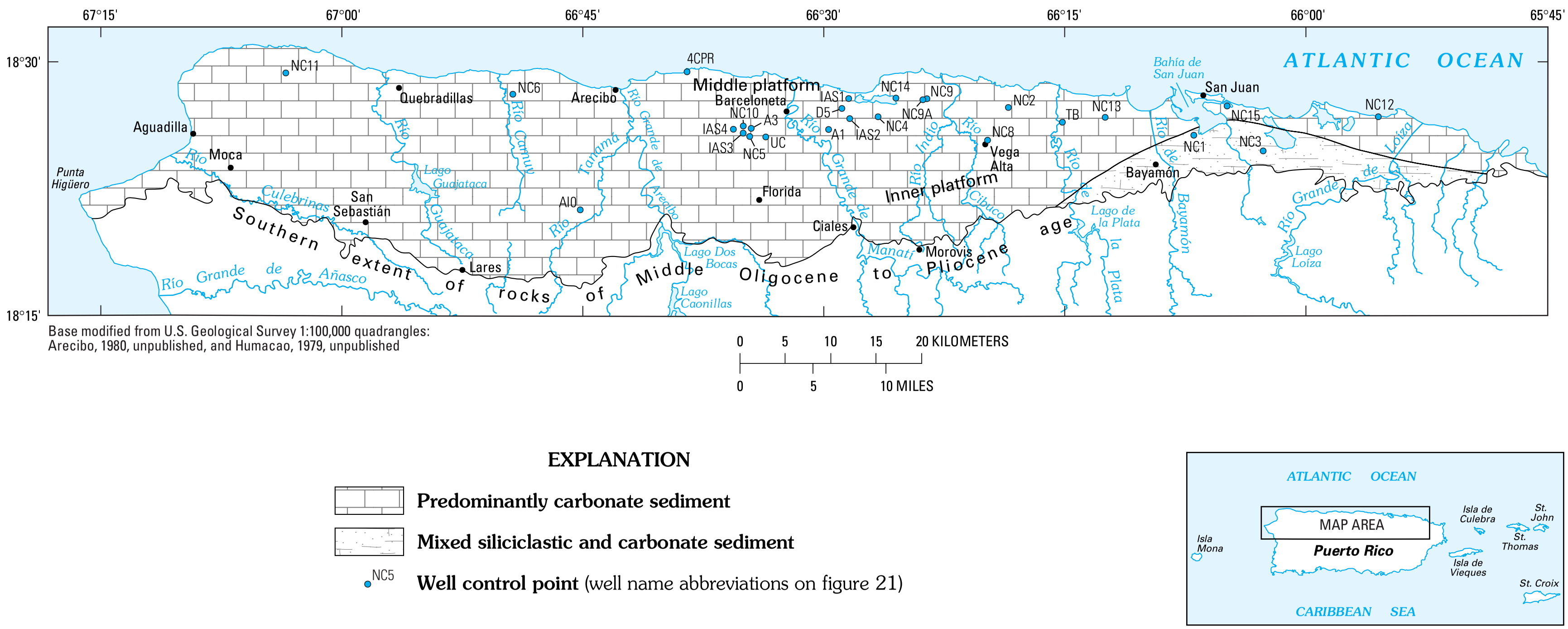

FIGURE 32.—Major depositional environments and facies patterns during deposition of the Aguada (Los Puertos) Limestone, northern Puerto Rico.

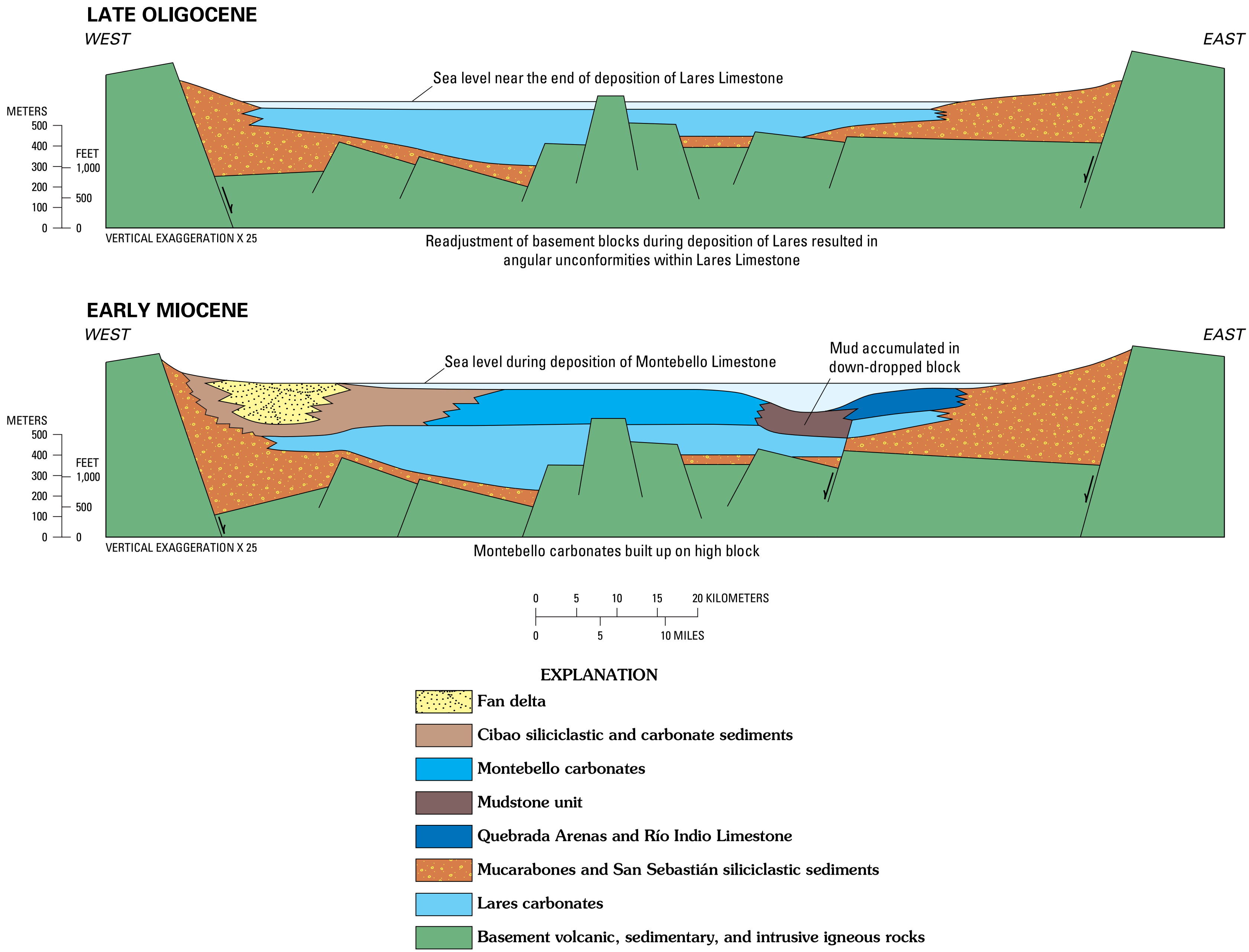

FIGURE 33.—Conceptual model of the southern part of the North Coast Tertiary Basin in Puerto Rico showing influence of structural movement on late Oligocene and early Miocene deposition.

of basement segments during deposition of the lower Cibao Formation (fig. 33).

Beginning with the deposition of the uppermost Cibao, the whole northern Puerto Rico basement underwent more uniform subsidence. This is indicated by the relatively minor variation in thickness of the Aguada (Los Puertos) and Aymamón Limestones along depositional strike (fig. 28).

SEQUENCE STRATIGRAPHY OF OLIGOCENE TO MIDDLE MIOCENE ROCKS

INTRODUCTION

High-resolution biostratigraphy of the northern Puerto Rico limestone province is impractical, because fossils are mostly shallow-water forms with fairly wide stratigraphic ranges. This sedimentary section, however, can be subdivided into major packages of chronostratigraphically related strata using the concepts of sequence stratigraphy, which was developed from seismic stratigraphy (Mitchum and others, 1977; Van Wagoner and others, 1988). "Depositional sequences" are stratigraphic units "composed of a relatively conformable succession of genetically related strata and bounded by unconformities or their correlative conformities" (Mitchum and others, 1977, p. 53). The sequence boundary is meant to be a chronostratigraphic marker.

For the most part, depositional sequences and their boundaries are the products of an interplay between eustatic sea-level fluctuations, regional tectonic movements, and sedimentological processes, all of which affect relative sea level. Ideally, the sequence can be divided into "systems tracts," units deposited during specific intervals of a third-order (0.5 to 5 m.y.) fluctuation of relative sea level. A type 1 sequence is deposited during a third-order rise in relative sea level (or base level) that followed a fall in base level great enough to expose the shelf to subaerial erosion. This type of sequence is made up of lowstand, transgressive, and highstand systems tracts (fig. 34). According to the siliciclastic-based model (Van Wagoner and others, 1988), the lowstand systems tract (LST) commonly can be divided into a lowstand fan (LSF), deposited during the base-level fall, and a lowstand wedge (LSW), deposited at the lowstand and during the early stages of base-level rise. The LST is best developed in basins with a break in slope (shelf break). Where the LST is deposited in a basin without a striking break in slope, such as the North Coast Tertiary Basin of Puerto Rico, it consists of a relatively thin lowstand wedge (Van Wagoner and others, 1988). In a type 2 sequence, which is deposited after a base-level fall not great enough to expose the shelf, the lowermost unit is the shelf-margin wedge systems tract (SMW) (fig. 34). The middle systems tract of type 1 and 2 sequences is the transgressive systems tract (TST) deposited during the subsequent rise of relative sea level. The base of this systems tract is the top of the LST or SMW. Its upper boundary is the maximum flooding surface, which marks the point at which the third-order depositional framework changes from the retrogradational TST to the aggradational/progradational highstand systems tract (HST). This upper unit (HST) is deposited during the late part of a sea-level rise, a stillstand, and the early part of a fall.

Although sequence stratigraphy was derived from seismic stratigraphy of siliciclastic basin fills, the general concepts also can be applied, with some modifications, to analyses of carbonate sections (Sarg, 1988; Handford and Loucks, 1993) (figs. 34 and 35). The response of siliciclastic depositional systems to changes in relative sea level, however, is somewhat different than that of carbonate depositional systems because of the fundamental differences in the source of these sediments. Siliciclastic deposits are derived from outside the basin; carbonate sediments are generated within the basin. Marine carbonate deposits accumulate most rapidly in parts of basins where water depth, temperature, and geochemistry are optimal for carbonate-producing organisms and where siliciclastic influx is slight. The rate of carbonate production, therefore, generally is greatest during times of high sea level when large areas of continental margins are flooded with relatively shallow water and siliciclastic deposition is confined to coastal zones. Lithofacies patterns indicate that the Tertiary limestones of northern Puerto Rico were deposited on a ramp. The coral-algal constituents of these limestones imply they accumulated under a tropical climate. In addition, the associated deltaic deposits and the lack of evaporites suggest the climate was humid (fig. 35). Falls in relative sea level may terminate or retard carbonate production. Commonly, even slight drops in sea level may expose broad areas of a carbonate platform, halting carbonate sedimentation and bringing on karstification or calichification of the inner platform.

SEQUENCE BOUNDARIES IN NORTHERN PUERTO RICO

The distinctive responses of carbonate production and siliciclastic sedimentation to changes in relative sea level were a major consideration in interpreting the sequence stratigraphy of the North Coast ground-water province. This stratigraphic analysis, however, suffers from the sparsity of published detailed descriptions of outcrop sections as well as from the cursory descriptions of cores taken during later stages of the core drilling project and lack of downdip control. Nevertheless, the Oligocene through middle Miocene sedimentary rocks (San Sebastián through Aymamón) can be divided tentatively into five major depositional sequences (fig. 36). Well and outcrop control is insufficient to resolve minor cycles on a basinwide scale.

The oldest sequence was encountered only in the "San Sebastián Formation" penetrated by the 4 CPR well between about 1,430 to 1,690 m (pl. 4; fig. 36). This interval, accord-

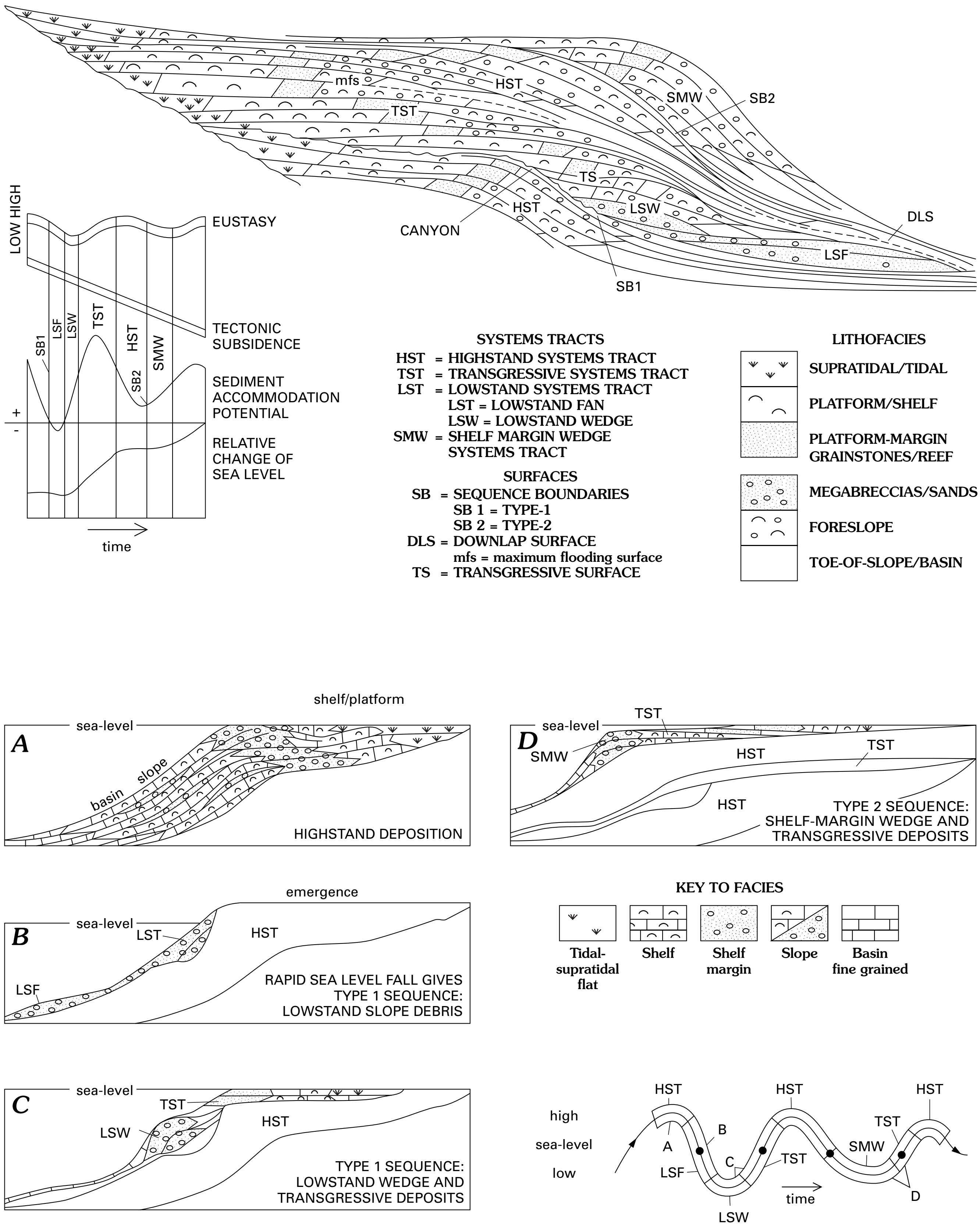

FIGURE 34.—General model for a sequence-stratigraphic framework (reprinted from Tucker and Wright, 1990, and published with permission).

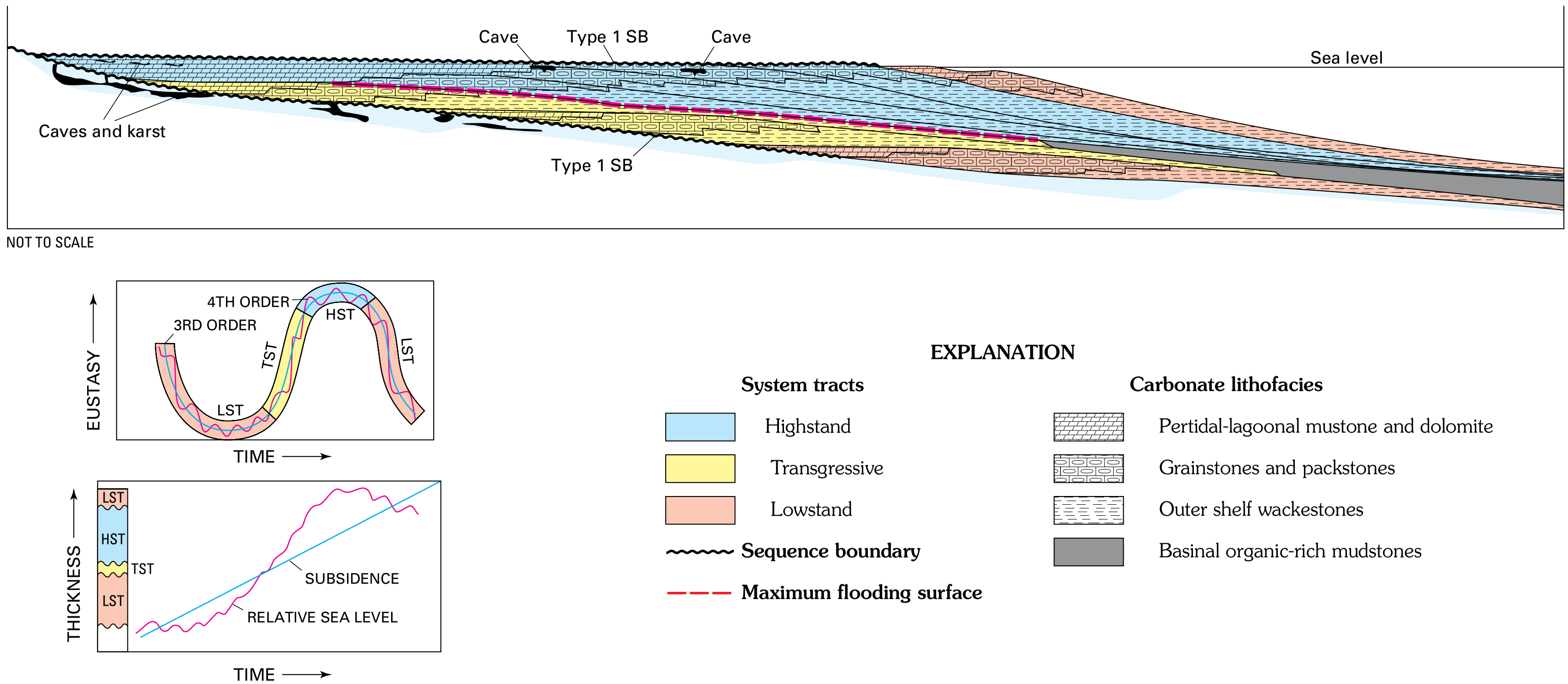

FIGURE 35.—Depositional-sequence model for an inclined carbonate platform or "ramp" located in a humid environment (reprinted from Hanford and Loucks, 1993, and published with permission).

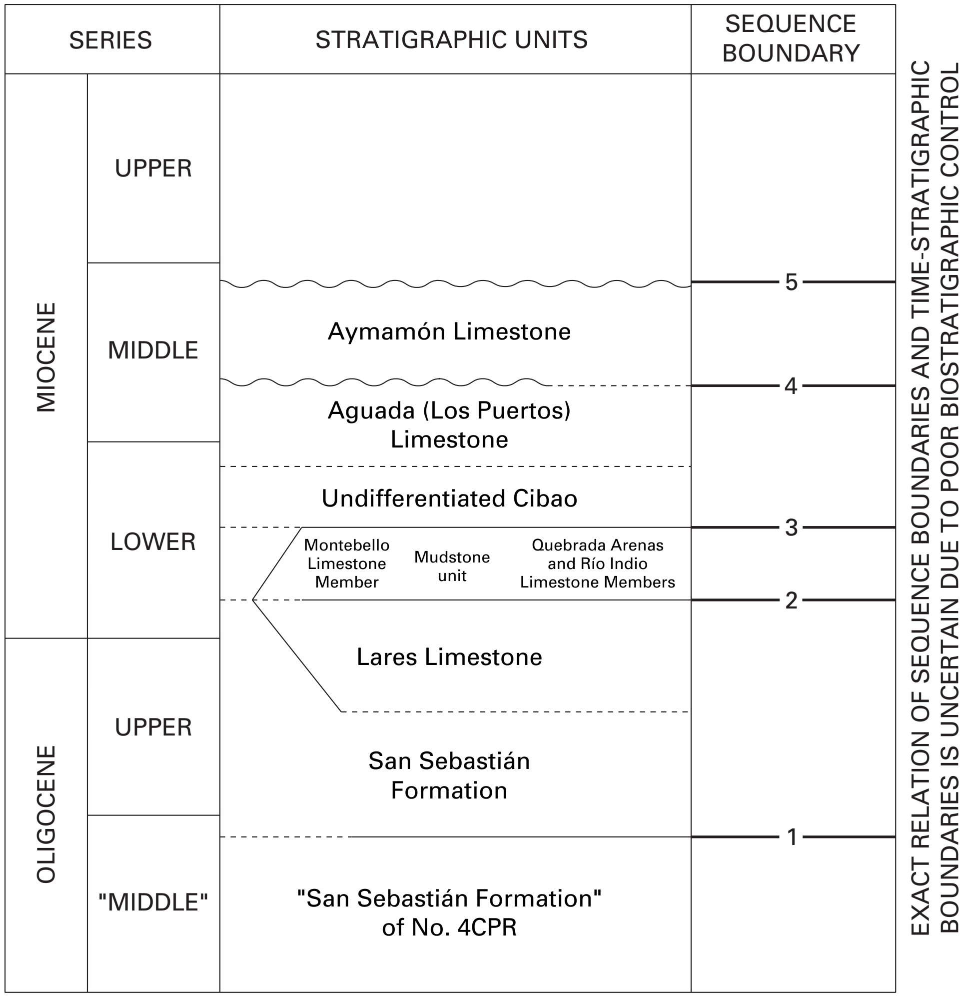

FIGURE 36.—Sequence-stratigraphic framework of the Oligocene to middle Miocene sedimentary rocks of the North Coast Tertiary Basin, Puerto Rico.

ing to sample descriptions and micropaleontology (Gordon, 1961b; Briggs, 1961), represents an onlap of the basement complex during the Oligocene. The maximum transgression is recorded at about 1,525 m, where the foraminiferal assemblage indicates outer neritic to bathyal depositional environments (Briggs, 1961; A. Melillo, Chevron, oral commun., 1993). Briggs (1961, p. 8) speculated that the lower part of the San Sebastián in 4 CPR core is older than any San Sebastián at outcrop. In support of this, it is dubious that most of this San Sebastián section can be correlated with the San Sebastián of updip core tests (pl. 3). Rather, any record of this rise of relative sea level probably was removed by erosion during a subsequent major fall in relative sea level. It is possible that the interval about 1,370 and 1,430 m, which is composed of claystone with common sand layers and some coal layers (Briggs, 1961), represents a lowstand wedge deposited during this fall in base level. Without core data, however, the character of this lithologic unit is speculative.

A second depositional sequence comprises the San Sebastián Formation and the Lares Limestone. The upper San Sebastián-lower Lares interval records progressive onlap onto the subaerially exposed basement rock during a rise in relative sea level. The top of this TST is within the middle Lares, which records the maximum transgression during deposition of this carbonate unit (Seiglie and Moussa, 1984; Hartley, 1989; Scharlach, 1990). Upper parts of the Lares are the HST. The upper boundary of this depositional sequence is the top of the Lares Limestone as mapped by Monroe (1980). In the subsurface, the boundary is less distinct, but it is placed where the generally progradational upper Lares gives way to the various generally retrogressive units of the lower Cibao Formation. A drop in base level after deposition of the Lares Limestone is indicated by the influx of terrigenous sediment of much of the lower Cibao. In the central part of the basin, this drop in relative sea level is suggested by the widespread oyster beds at the base of the Montebello and Río Indio Members of the Cibao Formation (Monroe, 1980).

A third depositional sequence is represented by the lower three-quarters to two-thirds of the Cibao Formation. Interpretation of this unit is complicated by the several facies changes parallel to depositional strike. These probably reflect the influence of tectonic movements on relative sea level and sediment dispersal. Throughout much of the basin, however, there is evidence of general transgression after the lowstand that terminated Lares deposition. The Montebello and the mudstone unit record a cycle of deposition from generally shallower to deeper (TST) and then to shallower environments (HST). The upper boundary of this sequence is marked by the tops of the Montebello and Quebrada Arenas Members (fig. 37). As diagrammed by Monroe (1980, p. 30-31), the distribution of the upper part of the Guajataca suggests basinward progradation of a fan-delta complex, probably during a lowering of sea level. The upper Guajataca and incised-channel deposits of the nonmarine Miranda Sand Member (fig. 37, Section A modified from Monroe, 1980, figure 16) likely were deposited during a low stand of sea level (LST).

The upper part of the Cibao Formation and the Aguada (Los Puertos) Limestone make up another depositional sequence. The TST is represented by the upper Cibao and lower Aguada. Resolution of a HST with present outcrop and subsurface data is tenuous. The upper boundary of this sequence is the widespread karst surface in the outcrop and shallow subsurface. The basinward equivalent of this surface apparently is a conformity, which is difficult to recognize in the deeper cores.

Finally, the widespread Aymamón Limestone is a fifth depositional sequence. In the updip area, this lithologic unit is bounded both at the bottom and top by karst zones. Whether the remaining part of the Aymamón represents more than the TST is undetermined.

GEOLOGY OF CENTRAL ST. CROIX, U.S. VIRGIN ISLANDS

BY I.P. GILL[1], D.K. HUBBARD[2], P.P. MCLAUGHLIN[3], AND C.H. MOORE[4]

INTRODUCTION

The use of water on St. Croix traditionally has depended on the catchment and storage of rainwater and scattered wells. In pre-Columbian times, Native American settlements were apparently located close to the few areas of reliable surface-water supply. Since the 1960's, water from several desalination plants has replaced some dependence on rainwater.

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Today, the Tertiary carbonate rocks of St. Croix are still being utilized as a source of ground water, augmenting rainwater catchment and desalinization. In addition, recent development and population growth is placing increased demand on water supplies; therefore, knowledge of the subsurface geology of central St. Croix is of greater importance now than it has been in the last several decades. The purpose of this discussion is to provide up-to-date information regarding the geology of St. Croix's Tertiary limestone sequence. The following section of the report describes the stratigraphy and setting of the major Tertiary geologic units. A later section examines the pattern of porosity and permeability within this sequence and relates these patterns to the island's structural and sedimentological setting.

Of major concern here are the laterally extensive water-bearing rocks of the Kingshill Basin region (fig. 38). These relatively flat-lying rocks of Tertiary age are bounded to the east by the East End Range and to the northwest by the Northside Range, areas of hills and low mountains with a maximum altitude approaching 335 m. The East End Range and the Northside Range consist of well-lithified Cretaceous rocks of the Mount Eagle Group, a diverse assemblage of deep-water volcaniclastics, tuffaceous sandstones, pelagic sediments, and gabbroic and dioritic intrusives (Whetten, 1966; Speed, 1989; Speed and Joyce, 1989). A number of alluvial-filled valleys abut the coastline of St. Croix. They are limited in extent and are discussed in a later section.

The Cretaceous rocks of the Northside and East End ranges are interpreted to be horst blocks, bounding the graben represented by the Central Limestone Plain (fig. 38; Whetten, 1966). Deposition of Jealousy Formation, Kingshill Limestone, and Blessing Formation limestones in a structural basin, herein named the Kingshill Basin, occurred during the early Miocene to Pliocene (Gill, 1989; McLaughlin and others, 1995). The thickness of sediments in the basin, perhaps as great as 1,800 m as inferred from gravity surveys (Shurbet and others, 1956), indicates that basinal sedimentation may have begun in the Oligocene or earlier. Early Tertiary sedimentation in the Kingshill-Jealousy Basin is supported by the presence of resedimented Eocene foraminifera within the Kingshill limestone (Lidz, 1984). However, the earliest documented age of the Jealousy Formation is early Miocene (Todd and Low, 1976; Gill and others, 1989; McLaughlin and others, 1995), and the deepest drilling of the Kingshill Basin is 460 m below land surface (Cederstrom, 1950) and did not penetrate the basal Jealousy Formation. In ascending order, the principal rock units of St. Croix include the Mount Eagle Group, the Jealousy Formation, Kingshill Limestone, its newly named lower and upper members, the La Reine and

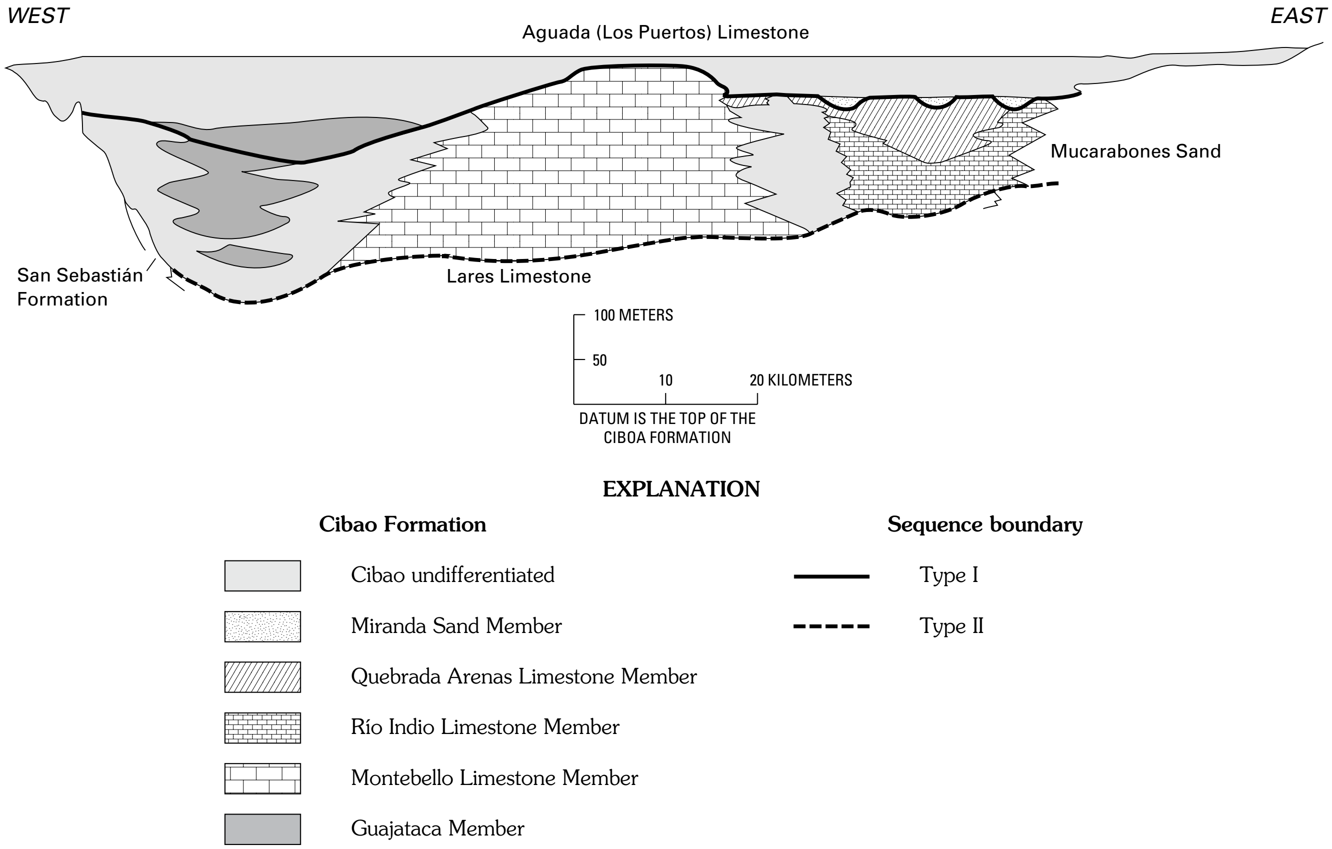


FIGURE 37.—Sequence boundaries related to the updip Cibao Formation, northern Puerto Rico (modified from Monroe, 1980, figure 16).

Mannings Bay Members of Gill (1989) and McLaughlin and others (1995), and newly named Blessing Formation of Gill (1989) (figs. 39, 40).

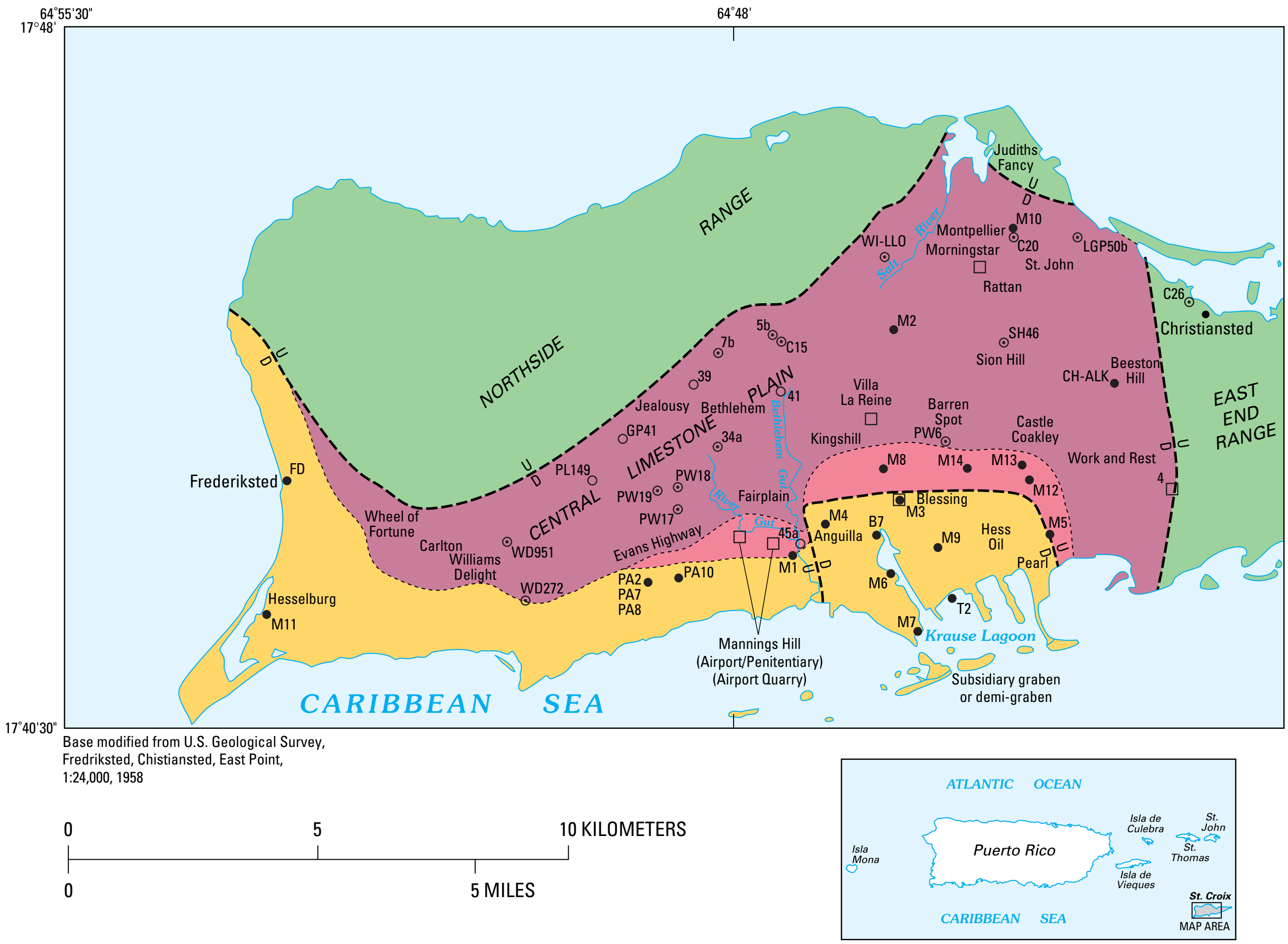
The Mount Eagle Group of Cretaceous age underlies the Northside and East End Ranges and presumably forms the floors of the graben underlying the Kingshill Basin. Additional information on the sedimentologic character and structure of these rocks is provided by Whetten (1966), Speed (1989), and Stanley (1989). The Jealousy Formation of Miocene age consists largely of grey-blue, planktonic foraminifera-rich muds. Locally, the units contains several conglomeratic layers encountered during deep drilling (Cederstrom, 1950). The Kingshill Limestone of Miocene age consists of two members. The basal La Reine Member, named herein, is a lithologically diverse unit dominated by planktonic foraminiferal carbonate mud and marl, and an upper member of shelf and slope facies is named herein the Mannings Bay Member. The Blessing Formation of Pliocene age consists of reef and shelf limestone that unconformably overlies the Kingshill Limestone along St. Croix's southern coast (fig. 5).

STRATIGRAPHY AND SEDIMENTOLOGY OF THE CENTRAL LIMESTONE PLAIN REGION

JEALOUSY FORMATION

Lithology, facies, and depositional environment

The type section of the Jealousy Formation is defined within a 426 m section penetrated by the deep test well no. 41 drilled in 1939 by the Civilian Conservation Corps near the estate of Bethlehem (Cederstrom, 1950) (fig. 38). This well was drilled to a depth of 459 m below land surface, of which the lowest 426 m were identified as Jealousy Formation sediments (Cederstrom, 1950). The Jealousy Formation type section was described by Cederstrom (1950, p. 19) as dark grey, clay-rich strata interrupted by calcareous conglomeratic deposits: " . . . 1,398 feet of dark clayey strata lying below the Kingshill marl were penetrated, the lowest stratum consists of 305 feet of gray clay in which a few streaks of limestone, not more than a few inches in thickness, are present." Two intervals of calcareous conglomerate were noted within the section, containing rounded and subangular boulders identified as Mount Eagle volcanics in a "limy matrix" (Cederstrom, 1950.



EXPLANATION

(yellow)	**Blessing Formation**	FD	**Fredericksted**
	Kingshill Limestone	WD	**Williams Delight**
(pink)	Mannings Bay Member	SH	**Sion Hill**
(mauve)	La Reine Member	WI-LLO	**Windsor**
(green)	**Mt. Eagle Group**	PA	**Paradise**
--U/D--	**Inferred fault**—U, upthrown; D, downthrown	LGP	**La Grande Princesse**
....	**Contact**—Dashed where approximately located	PL	**Plessen**
	Control points	CH-ALK	**Constitution Hill**
●	Test hole—Core and cutting samples	GP	**Grove Place**
○	Well—Cutting samples	C	**Civilian Conservation Corps**
⊙	Well— Driller's log information	M	**Gill-Hubbard drilling project**
□	Outcrop	PW	**Public Works**
		T	**Tibbits, Abbott, McCarthy, and Stratton, (TAMS) Inc.**
		B	**Martin Marietta Alumna—Caribbean Drilling Services**

FIGURE 38.—Generalized geology of St. Croix, U.S. Virgin Islands, and location of control points (modified from Gill, 1989).

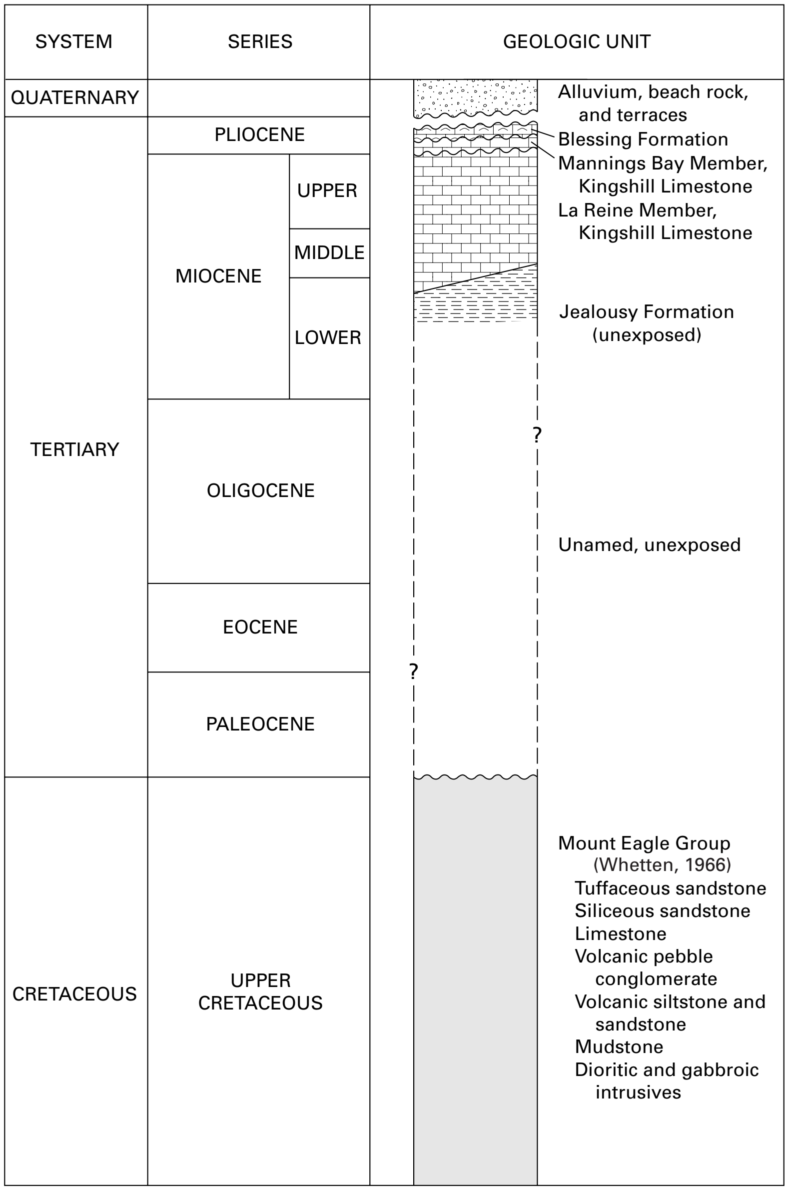


FIGURE 39.—Generalized stratigraphic column of St. Croix, U.S. Virgin Islands (modified from Gill, 1989).

To the west, near Estate Jealousy (test well 39; fig. 38), dark clay of the Jealousy Formation contains more sandy material than do rocks of the type-section. The basal 18.6 m section penetrated in the Estate Jealousy well consists of hard, calcareous conglomerate that directly overlies the basement rock of the Mount Eagle Group. Cederstrom (1950) correlated these rocks with lithologically similar calcareous conglomerate exposed in stream beds west and northeast of well no. 39.

A sharp, distinctive color change marks the boundary between the light buff Kingshill Limestone and the underlying dark, blue-grey to grey Jealousy Formation. Well drillers commonly describe poorly lithified sediments of the Jealousy Formation as "blue clay." However, the Jealousy Formation consists largely of calcareous muds containing a sand fraction composed almost entirely of planktonic foraminifera. The percentage of sand in Jealousy Formation samples ranges from less than 10 percent to almost 25 percent; of the sand fraction, planktonic foraminifera averaged 89 percent ± 5 percent.

X-ray diffraction analyses of samples from the Jealousy Formation indicate a dominant calcite mineralogy, having an insoluble fraction of quartz, feldspar, and clay minerals ranging from 30 to 51 percent (Gill, 1989). On the basis of information available from the five wells drilled into the Jealousy Formation, the mineralogy of the Jealousy Formation does

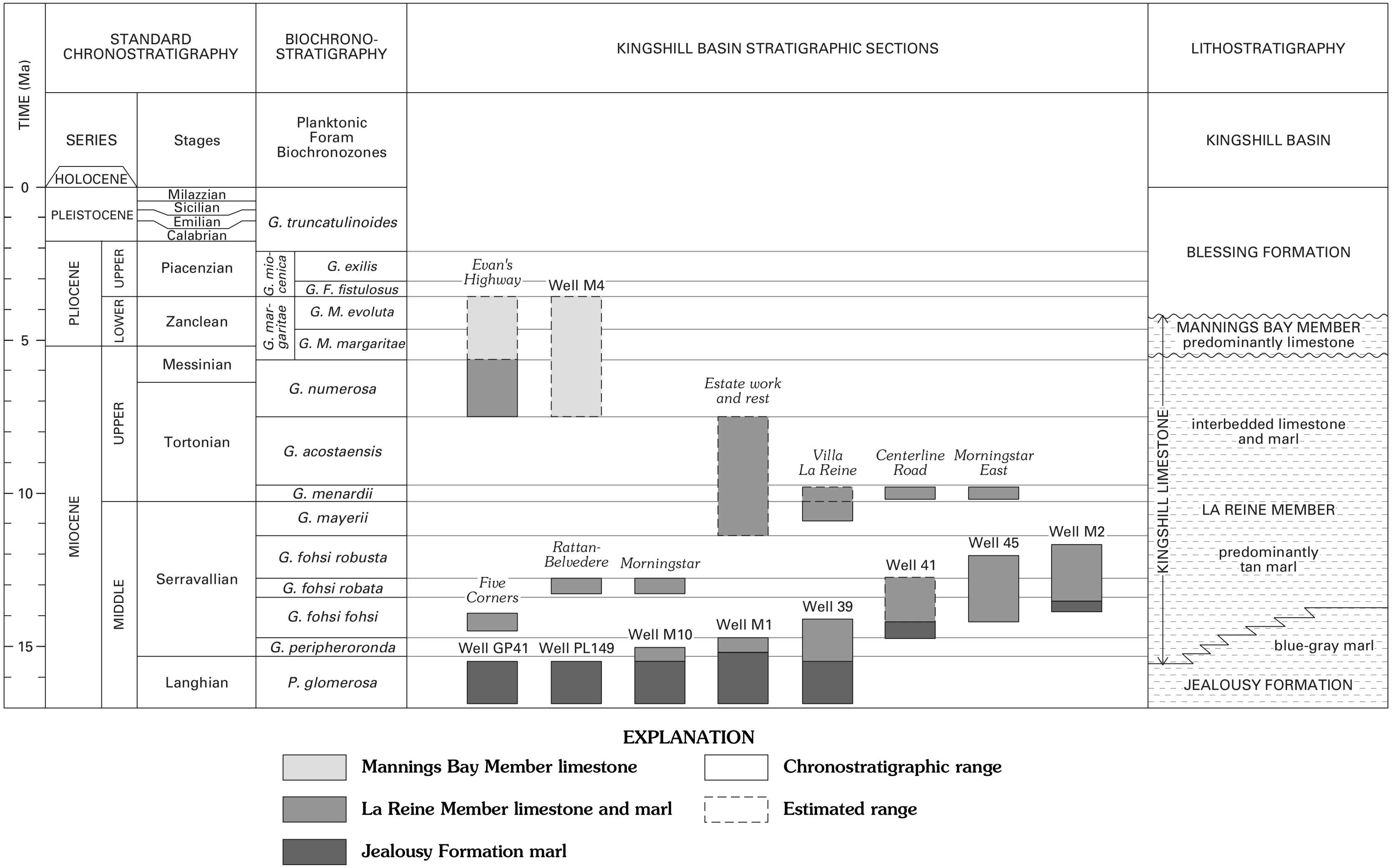


FIGURE 40.—Expanded stratigraphic column showing rocks of late Tertiary age in St. Croix, U.S. Virgin Islands (modified and reprinted from McLaughlin, P.P., Gill, I.P., and Bold, W.A. van den, 1995, and published with permission).

not vary systematically within the Kingshill Basin or within the stratigraphic range sampled. The dominant calcite mineralogy of the Jealousy Formation is not detectably different from Kingshill Limestone samples taken immediately above the contact. However, well cuttings and core samples collected from older wells penetrating the Jealousy Formation are not currently available and thus no direct comparison to lower sections of the Jealousy Formation is possible. However, it is clear that the uppermost Jealousy Formation is best described as a marl or foraminiferal mud, rather than an estuarine clay (Multer and others, 1977), and does not differ significantly from the Kingshill Limestone except for its marked color contrast.

The cause of the color contrast is uncertain, because the calcitic rocks that lie above and below the Kingshill-Jealousy contact are identical in bulk X-ray diffraction analysis. Although the blue-grey color of the Jealousy Formation is striking in fresh, wet split-spoon samples, it often fades upon drying and exposure to air. In many samples, the color does not entirely disappear, but remains as a very faint blue or greyish tinge; in other samples, color differences between Kingshill and Jealousy samples become almost indistinguishable.

The color difference associated with the Kingshill Limestone and upper Jealousy Formation could be caused by a number of factors, including minor mineralogic or elemental differences induced either by depositional or diagenetic effects such as redox state differences. In any case, the Kingshill-Jealousy boundary is not marked by a detectable change in lithology, paleoenvironment or depositional patterns, and the significance and cause of the color change remains unclear. Until the significance of this contact can be clarified, the use of the formation boundary alone for structural interpretation is of questionable value.

Whetten (1966) interpreted the Jealousy Formation to be a marine deposit of altered pyroclastic rock, with its volcanic source located upwind toward the Lesser Antilles. Multer and others (1977) suggested that the Jealousy Formation was an estuarine deposit of Oligocene age with the exposed and eroding horst blocks of the Northside and East End Ranges serving as insular sediment sources (Multer and others, 1977). However, Gerhard and others (1978) noted the possibility that an external sediment source, as opposed to the exposed horst blocks of the structural basin, was required to account for the great thickness of the Jealousy Formation.

It can be shown, however, that Jealousy Formation samples taken from the Kingshill Basin are marine in origin (Gill, 1989), not estuarine, as suggested by Multer and others (1977). The water depth at the time of the deposition of the Jealousy Formation was probably between 600 and 800 m, on the basis of the abundance and type of planktonic and benthic foraminifera (Gill, 1989; Gill and others, 1989; McLaughlin and others, 1995). In addition, the depth of the basin did not vary appreciably from basin center to its outer margins. This could indicate that early Jealousy Formation deposition preceded movement along the Kingshill Basin boundary faults, and thus deposition preceded formation of the basin itself (Gill, 1989).

Structure and distribution

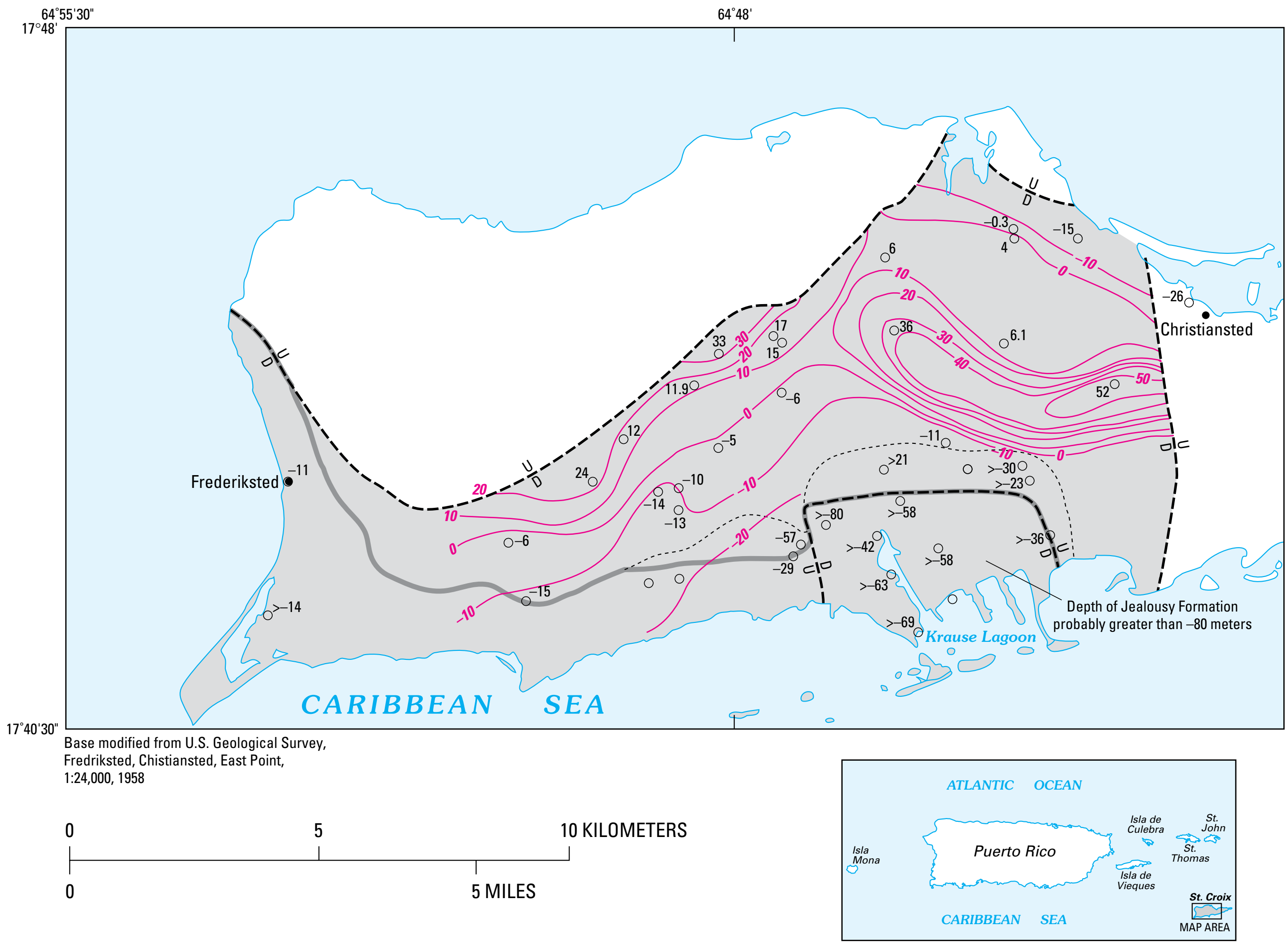
The surface of the Jealousy Formation, as determined from well-log data, is characterized by (1) marked upbowing of its surface beneath the limestone highlands in the northeastern section of the central plain; (2) a gentle dip toward the northern and southern coasts of St. Croix; and (3) a pronounced rise of its surface close to the boundary imposed by the Northside Range (fig. 41; Robison, 1972; Jordan, 1975; Gill and Hubbard, 1987). The altitude of the top of the Jealousy Formation in the southeastern Central Limestone Plain area is poorly known and probably lies at depth greater than 80 m relative to sea level, the maximum depth of well penetration in that area (figs. 41, 42, 43).

The Jealousy Formation underlies the Kingshill Basin throughout the study area. In addition to the subsurface samples, Cederstrom (1950) and Whetten (1966) considered exposures on the northern margin to be part of the Jealousy Formation. These strata should be included as part of the Kingshill Limestone because the exposed strata bear no resemblance to the subsurface Jealousy Formation. They contain a lithologic facies that is similar to other exposures of the Kingshill Limestone, and associated fauna are within the biostratigraphic range of the Kingshill Limestone (Bold, 1970; Gill and Hubbard, 1986; McLaughlin and others, 1995). Including these strata as Kingshill Limestone follows the suggestion of Gerhard and others (1978).

Deposits of the Jealousy Formation are apparently not restricted to the main structural basin. “Blue clays” of the Jealousy Formation are reported in a well that is located northeast of the structural basin (well C 26, Cederstrom, 1950). The occurrence of blue clay outside the limits of the basin suggests that deposition of the Jealousy Formation preceded fault movement. However, samples collected from the C 26 well are no longer available, and their identification is considered to be tentative (Cederstrom, 1950).

Age

The age of the Jealousy Formation ranges from the late early Miocene (N8) to the early middle Miocene (N12) (fig. 40; Gill, 1989; McLaughlin and others, 1995). Biostratigraphic assignments of the Jealousy Formation presented here take into account the revision in the position of the Oligocene/Miocene boundary (Todd and Low, 1976), and utilize planktonic foraminifera abundances (McLaughlin and others, 1995).



EXPLANATION

Area underlain by Jealousy Formation

30 **Structure contour**—Line shows altitude of top of the Jealousy Formation. Contour interval 10 meters. Datum is sea level

U/D **Inferred fault**—U, upthrown; D, downthrown

Inferred northern limit of Blessing Formation

Inferred northern limit of Mannings Bay Member

○ **Well**—Control point. Shows altitude of Jealousy Formation in meters

FIGURE 41.—Structural configuration of the top of the Jealousy Formation (modified from Gill, 1989).

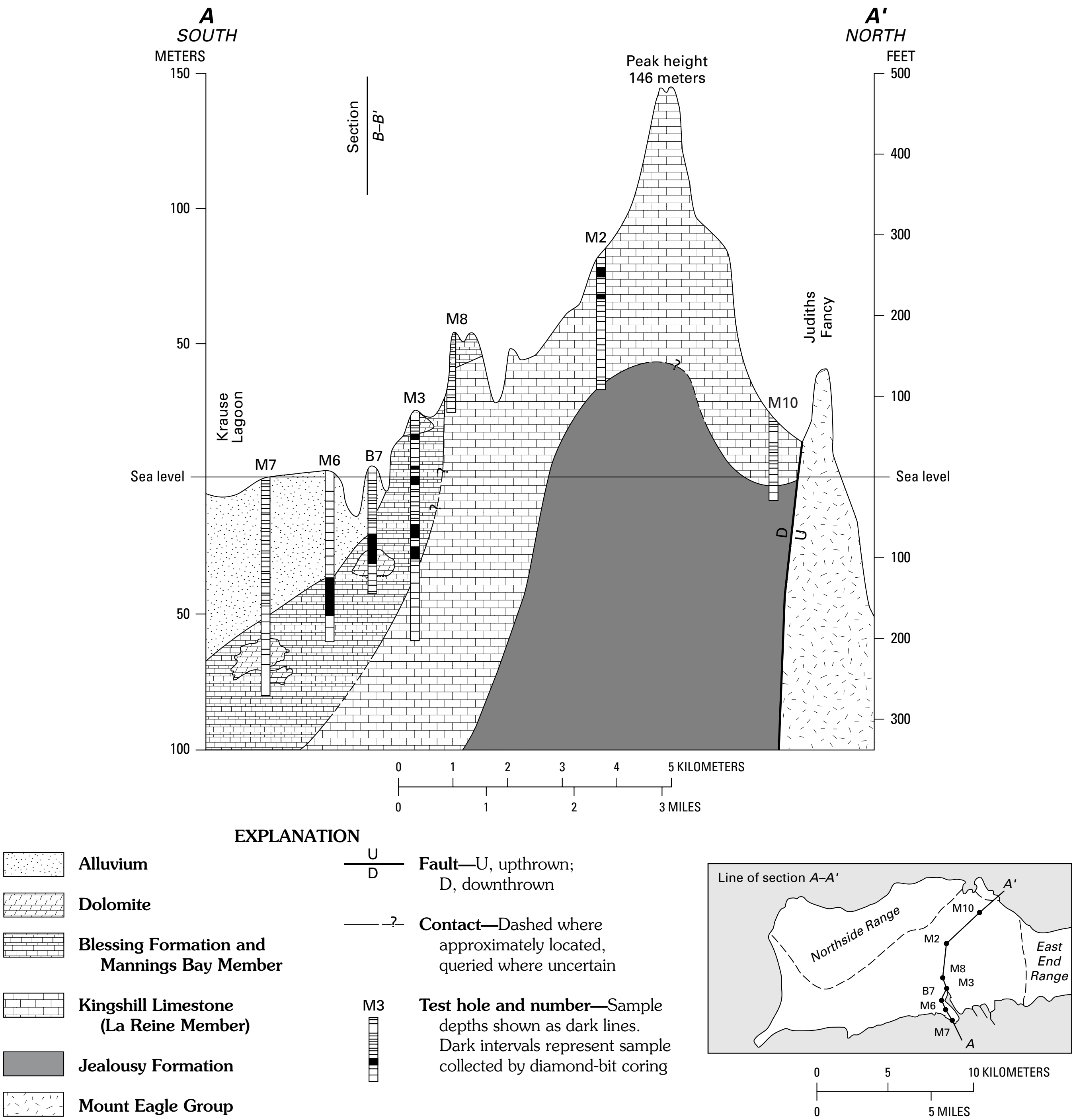


FIGURE 42.—Section *A–A′* from Krause Lagoon to Judiths Fancy (reprinted with permission from Gill and others, 1989).

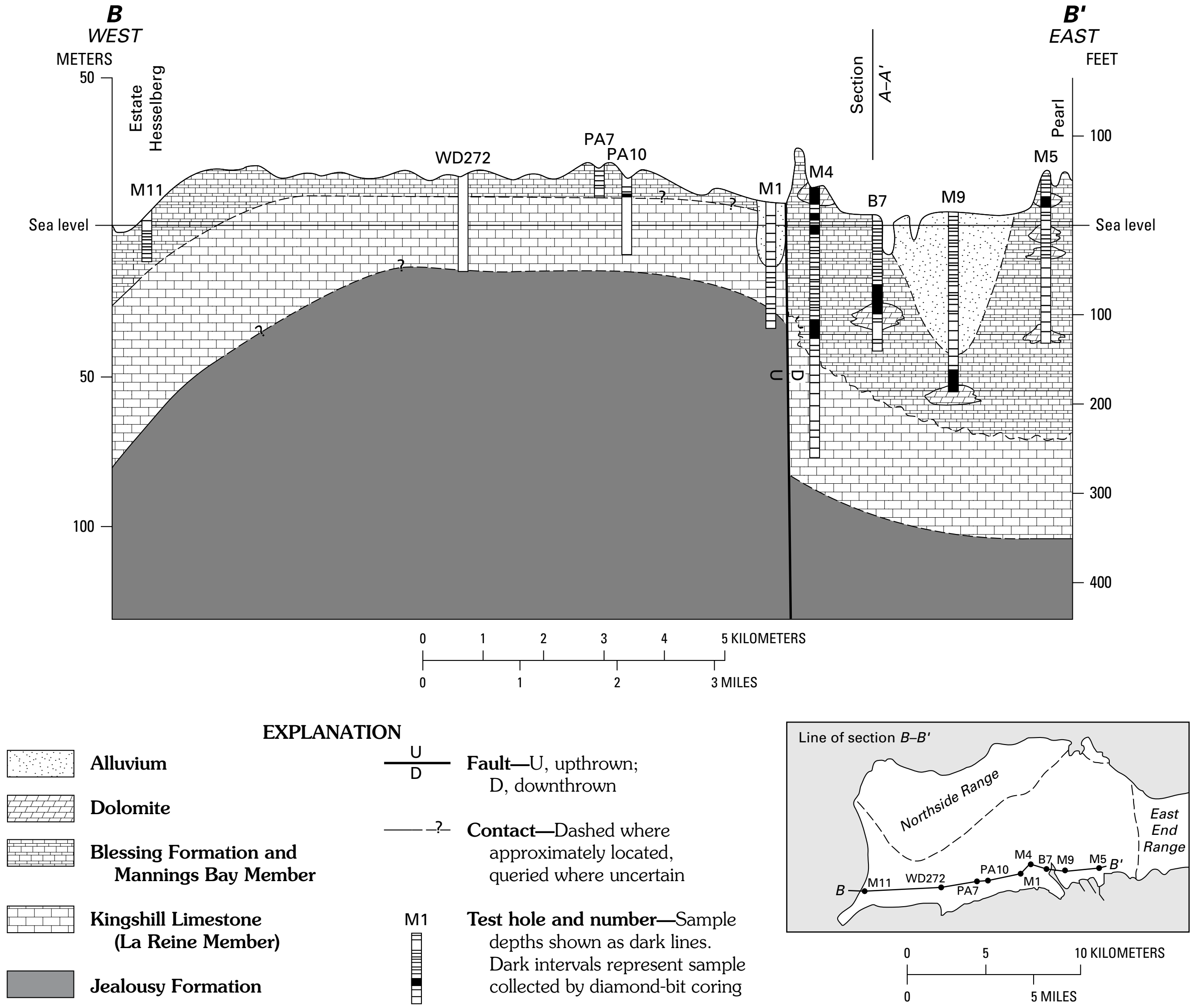


FIGURE 43.—Section *B–B′* from Estate Hesselberg to Pearl (reprinted with permision from Gill and others, 1989).

The Jealousy Formation and Kingshill Limestone contact is diachronous and ranges in age from the late early Miocene to the middle Miocene (Gill, 1989; McLaughlin and others, 1995). These ages are based on planktonic foraminifera in core samples located immediately above and below the contact (figs. 44, 45). Based on gravity data (Shurbet and others, 1956), it is likely that the thickness of the Jealousy Formation and underlying strata is substantial and the Jealousy Formation could, therefore, be Oligocene or older in age. However, it is important to note that no samples confirmed as being of Oligocene age or older have been recovered from the Jealousy Formation, and assignment to the Oligocene or Eocene is speculative.

KINGSHILL LIMESTONE

The nomenclature of the carbonate stratigraphic units on St. Croix has been revised considerably over the years. The name "Kingshill Series" was first used by Kemp (1926) to describe the outcropping Tertiary section of St. Croix. Cederstrom (1950) introduced the name Kingshill Marl differentiating the upper carbonate rocks from the underlying "clay" of the Jealousy Formation. Whetten (1961, 1966) followed the usage of Cederstrom (1950) as did Multer and others (1977), whereas Bold (1970) referred to the unit as the Kingshill Formation. Gerhard and others (1978) formalized the name Kingshill Limestone and designated the section at Villa La Reine to be the type locality. In this report, the Kingshill

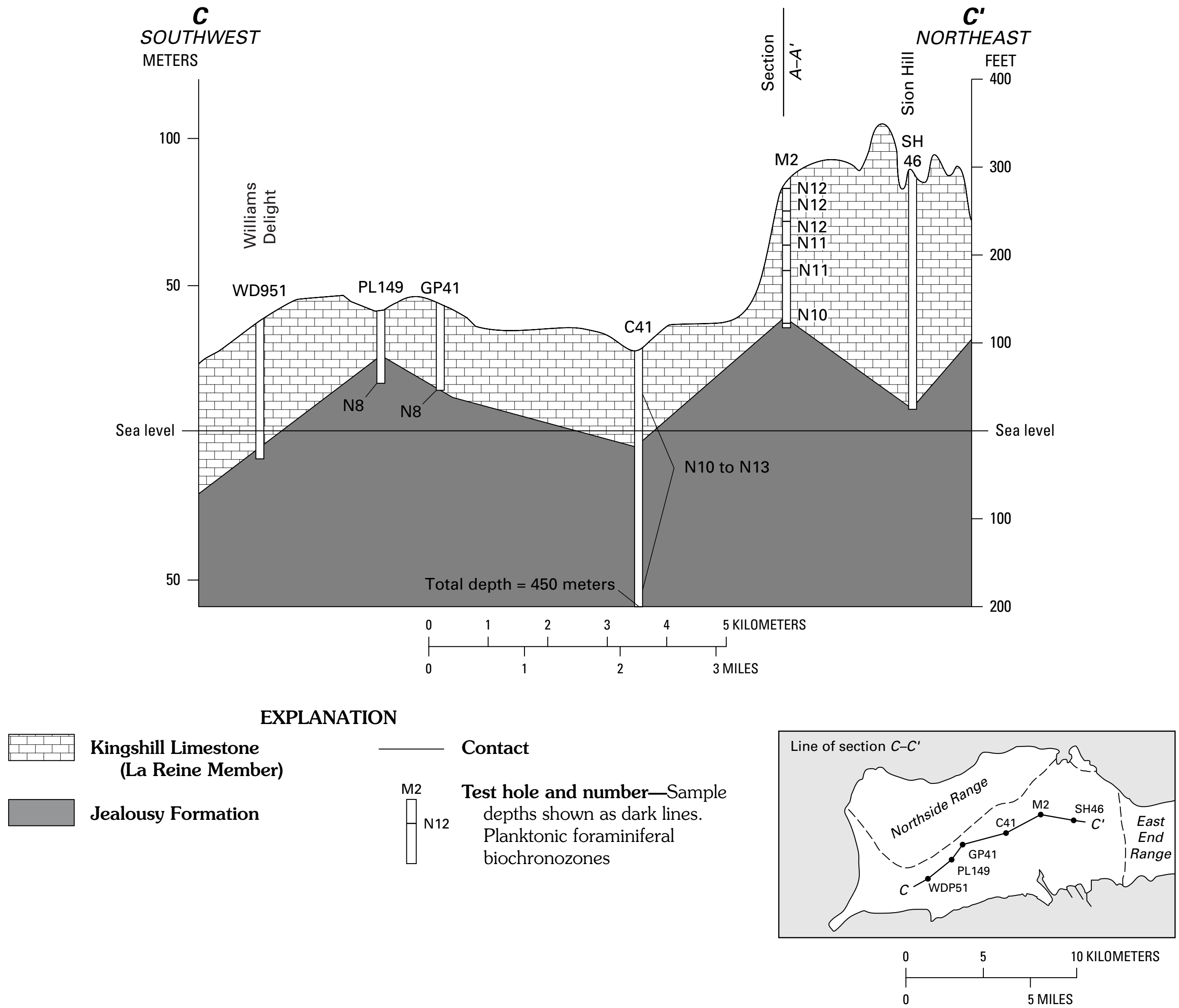


FIGURE 44.—Section *C–C'* from Williams Delight to Sion Hill showing relation between formational units and biostratigraphy.

Limestone is divided into the La Reine (lower) Member and the Mannings Bay (upper) Member.

La Reine (lower) Member of the Kingshill Limestone

The La Reine Member of the Kingshill Limestone is herein defined as the lower member of the Kingshill Limestone described in the type section for the formation by Gerhard and others (1978). The La Reine Member contains the lower three of the five depositional facies of the Kingshill Limestone (Gerhard and others, 1978); the molluscan packstone facies, the clastic grainstone facies and the polymictic packstone facies. The La Reine Member is unconformably overlain by the Mannings Bay (upper) Member. Both members and the unconformity are exposed in the north-facing side of Mannings Hill along the Melvin Evans Highway (Lidz, 1982, 1984; Gill and others, 1989).

Lithology, facies, and depositional environment

Outcropping rocks of the La Reine Member of Kingshill Limestone consist of a variety of sedimentary lithofacies that include packstones, wackestones, and clastic grainstones. In the subsurface, the lower part of the formation is dominated by packstone, predominantly planktonic foraminifera-rich carbonate muds with lithic grains or pebbles occurring at some levels. Less common are lithic-pebble or foraminifera-rich wackestones.

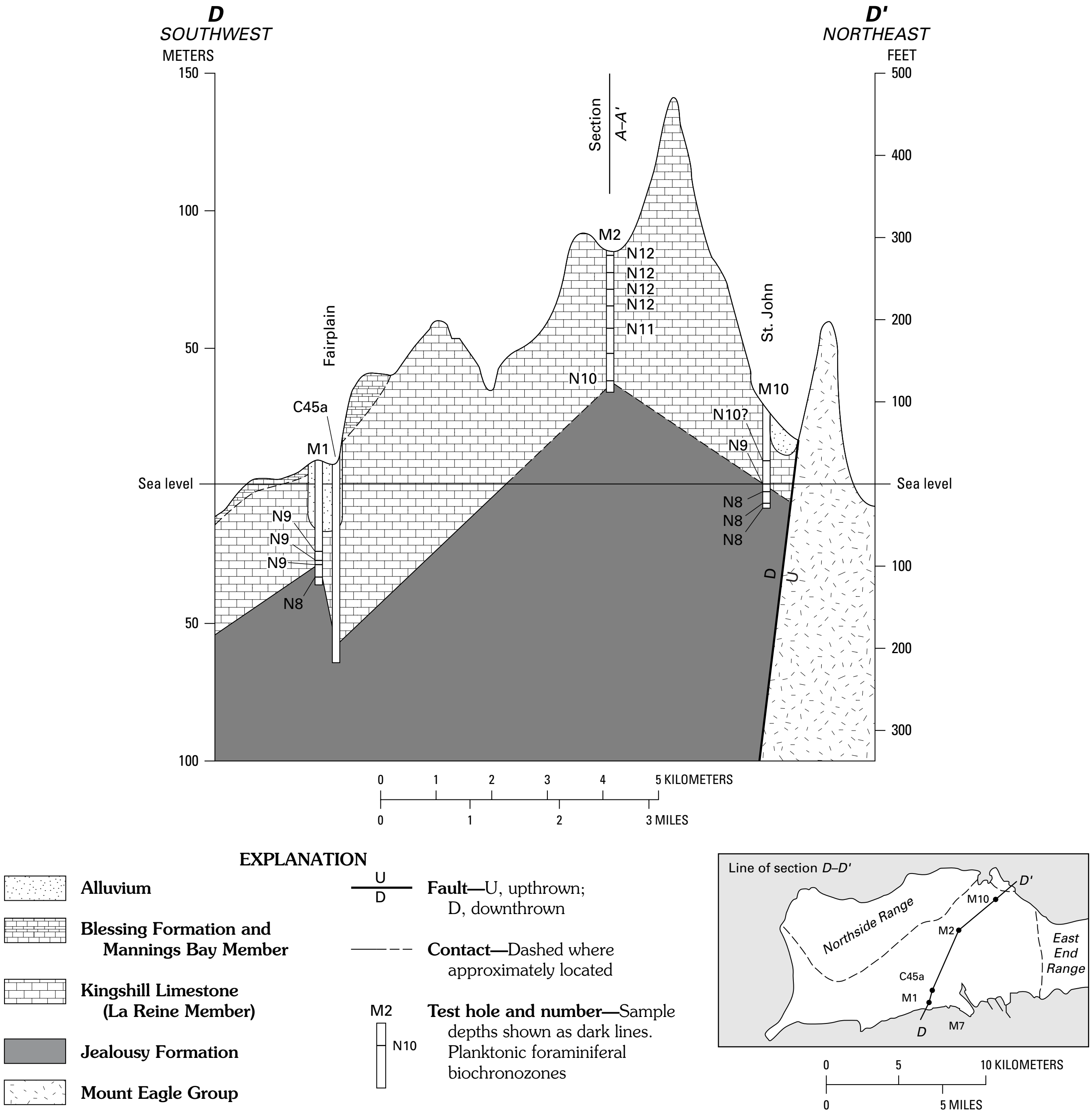


FIGURE 45.—Section D-D' from Fairplain to St. Johns showing relation between formational units and biostratigraphy.

The lowermost Kingshill Limestone strata (La Reine Member) in the Estate St. John and Judith's Fancy areas have been interpreted by Gerhard and others (1978), Lidz (1982), and Andreieff and others (1986) as shelf and lagoon deposits based on the presence of rounded terrigenous gravel, as well as a shallow-water fauna that includes echinoids and benthic forams. However, these deposits lie stratigraphically between the nearby basinal Kingshill Limestone and Jealousy Formation deposits recovered in test well M10 and outcropping in the hills to the south. Interpreting these deposits as in-place would require a major shoaling from bathyal depths, to littoral conditions, and back again. Alternatively, it is possible that the reefs are in-place and positioned on a small step block. If so, they could be the only example of in-place

Miocene reef material in the basin (Gerhard, oral commun., 1994), and could have served as the source of the rounded terrigenous pebbles in Jealousy and Kingshill material in test well M10. A third hypothesis would be that the reef material is allochthonous, deposited in bathyal depths from a source now distant or eroded from the basin. There is certainly abundant allochthonous reef material throughout the rest of the Kingshill Limestone.

Lithofacies exposed at the La Reine Member type section at Villa La Reine are characterized as polymictic packstones (Gerhard and others, 1978), and include foraminiferal chalk, soft marly interbeds and debris flows of coral and terrigenous gravel. The debris flow beds often have erosional bases and include cobble- to boulder-size clasts, primarily coral heads. In most cases, the corals are well-cemented and have been replaced by calcite, but may still be recognized by morphologic type. In some cases, the corals can be identified to the genus and species level.

An exposure located at Estate Work and Rest approximately 5 km to the east, displays foraminifera-rich lithologies similar to those seen at Villa La Reine. Interbedded with the foraminifera-rich beds, however, are beds composed predominantly of terrigenous breccia presumably derived from Cretaceous Mount Eagle Group. Gerhard and others (1978) interpreted this outcrop to be an example of a syntectonic breccia.

The youngest rocks of the Kingshill Limestone (Mannings Bay Member) are exposed along the Melvin Evans Highway (fig. 46) near the southern coastline. The exposure, referred to here as the Airport/Penitentiary outcrop, can be divided into upper and lower parts, separated by a disconformity. Below the disconformity, the exposure is characterized by regularly bedded intercalations of softer, planktonic foraminifera-rich beds and more indurated shelf-derived debris beds similar to that of the other La Reine Member exposures discussed.

Above the disconformity, the lithologic character of beds indicates shoaling of the basin. These strata are included within the Mannings Bay Member of the Kingshill Limestone. The Mannings Bay Member is characterized by channelled beds of shelf-derived carbonate debris, including sediment flows of larger foraminifera interbedded with softer beds containing poorly preserved planktonic foraminifera (foraminiferal wackestone facies of Gerhard and others, 1978). The strata referred herein to as the Mannings Bay Member were formerly included as part of the “post-Kingshill” Limestone by Lidz (1982) and Andreieff and others (1986), whereas Gerhard and others (1978) included them as part of the Kingshill Limestone. The lower contact of the Mannings Bay Member is distinctive where exposed, but is not easily identified in core samples (Gill and Hubbard, 1986, 1987).

The lithologic character and the benthic foraminiferal fauna associated with the La Reine Member of the Kingshill Limestone are indicative of middle bathyal conditions between 600 and 800 m below sea level (Gill, 1989; McLaughlin and others, 1995). This estimate is similar to the depth estimates of Multer and others (1977) or Lidz (1982), and the inferred environmental conditions for the Kingshill Limestone are identical to those inferred for the underlying Jealousy Formation.

The depth of the basin does not appear to have varied throughout the time of lower Kingshill Limestone deposition (exclusive of the Mannings Bay Member), or spatially throughout the basin until late in the Miocene or early in the Pliocene. Basinal shoaling is marked by the deposition of the thinly bedded limestone of the Mannings Bay Member (discussed below), which contains higher concentrations of shelf-derived carbonate clasts and faunal remains.

The large quantity of shelf-derived material in the Kingshill Limestone appears to be allochthonous, and transported to bathyal depths by sediment-gravity flows. The concentrations of sand- to boulder-sized debris indicate the importance of off-shelf transport of coarse material as well as the close proximity of coral reefs and sources of rounded terrigenous clasts. Because there are no known Miocene reefs exposed on modern St. Croix, reefs must either have existed in an area currently separated from the island, or they have been erosionally removed from the uplands during island emergence.

Structure and distribution

Faulting has placed the La Reine Member of the Kingshill Limestone into contact with Cretaceous rocks of the Mount Eagle Group in the Northside and East End Ranges (Whetten, 1966; Multer and others, 1977). Biostratigraphic evidence (McLaughlin and others, 1995) collected from strata thought to be syntectonic breccias (Gerhard and others, 1978) that crop out on the western margin of the East End Range indicates that basin faulting occurred prior to late middle Miocene time (outcrop 4, fig. 38). However, the fault contact along the Northside Range is obscured by alluvium, and structural relationships are difficult to observe directly (figs. 5, 38). Gerhard and others (1978) suggest that there was less displacement along this northern fault boundary than along the eastern basin margin. A north-south cross section through the island (fig. 42) also shows the marked upbowing of the Jealousy Formation and Kingshill Limestone where these strata underlie the carbonate highlands close to the northern coast.

Fault-juxtaposed rocks of the La Reine Member of the Kingshill Limestone and the Cretaceous Mount Eagle Group strata along the eastern boundary fault indicate that the Kingshill Limestone was at least in part deposited prior to basinal faulting (Gill and Hubbard, 1986, 1987). Initiation of the St. Croix normal fault system occurred after the late early Miocene. However, it is not certain whether the Kingshill Basin fault boundaries had formed penecontemporaneously

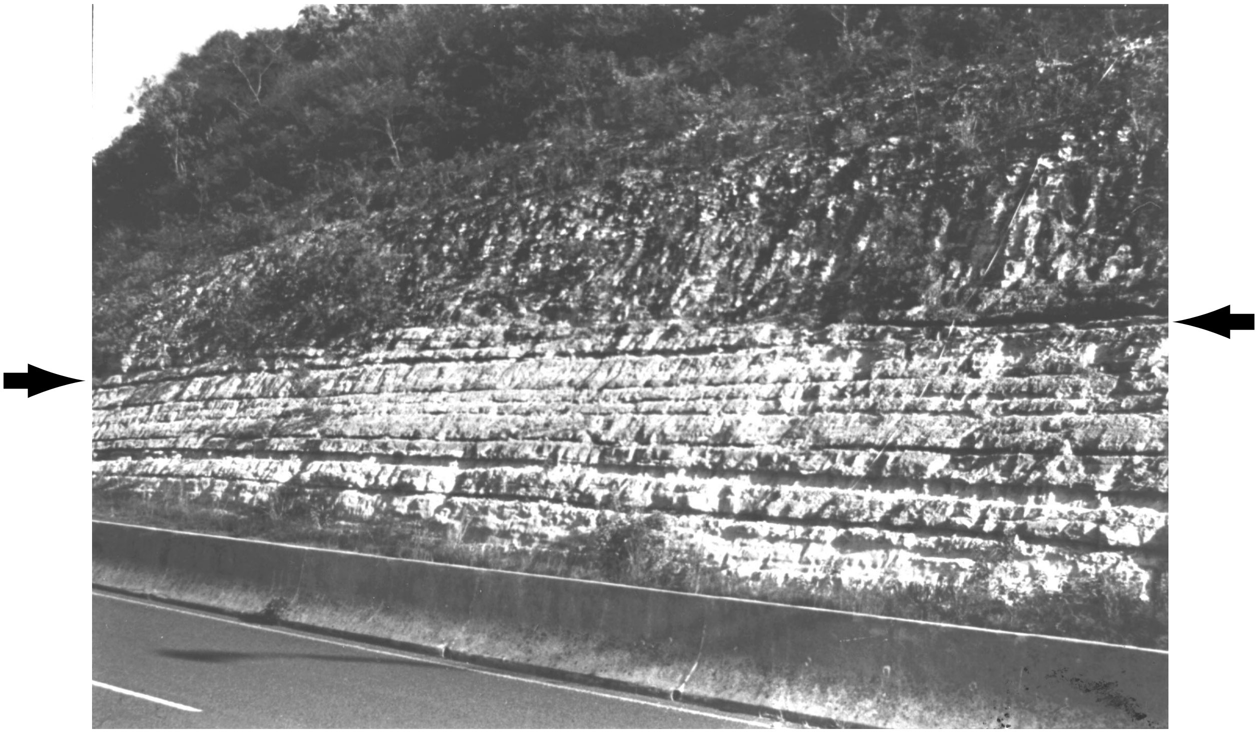


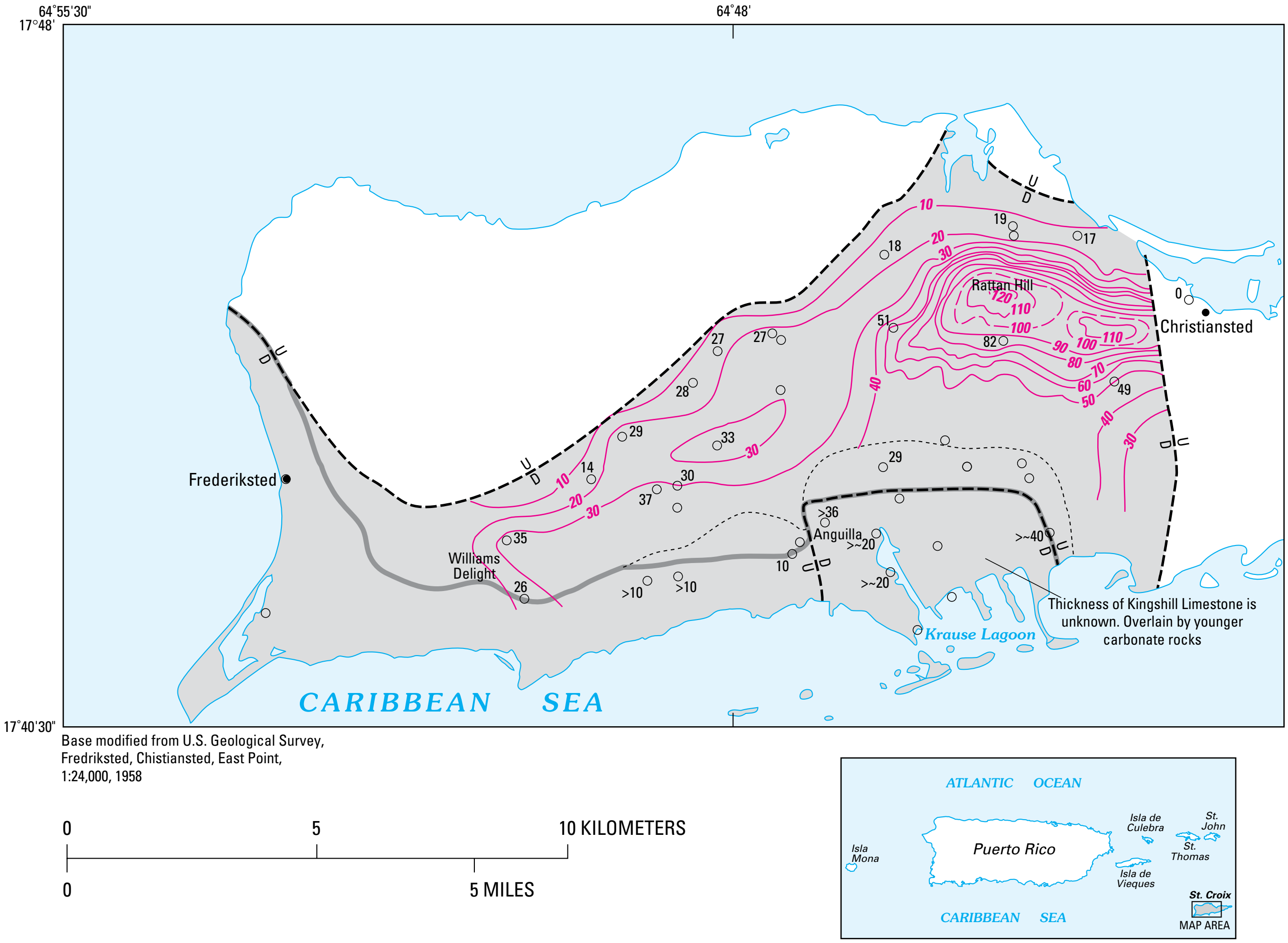
FIGURE 46.—A south-facing view of the disconformity separating the Mannings Bay Member from underlying beds of the La Reine Member lies approximately 7 meters above the Highway 66 road bed, north of Alexander Hamilton Airport. Arrows mark the position of the unconformity (reprinted and published with permission from Gill and others, 1989).

with the deposition of the Kingshill Limestone, or whether the bounding horst blocks were exposed during Kingshill Limestone deposition. Gerhard and others (1978) support an exposed horst model largely on the basis of syntectonic breccias along the eastern fault boundary of the Kingshill Basin. If the terrigenous clasts within the Kingshill are indeed derived from Mount Eagle Group strata, then the graben boundaries must have formed no later than middle Miocene time, because strata in the eastern fault zone can be assigned to zones between N14 and N16 (McLaughlin, written commun., 1978; Gill, 1989).

Strata thickness patterns of the Kingshill Limestone reveal three major trends (fig. 47): (1) the Kingshill Limestone pinches out toward the north and northwest margins of the basin; (2) there is a pronounced thickening of the Kingshill Limestone in the carbonate highlands near the northern coast of St. Croix; and (3) gentle thickening of the Kingshill Limestone toward the south of the basin is interrupted by post-depositional faults located along St. Croix's southern coast (fig. 47). The maximum estimated thickness of the Kingshill Limestone is 180 m in the carbonate highlands areas near Rattan Hill (Cederstrom, 1950), whereas the maximum documented thickness of the Kingshill Limestone, encountered in the same area, is nearly 140 m (fig. 47). Well control for the Kingshill Limestone section is poor in the vicinity of the post-Kingshill carbonate section on the south coast, and to the west of Estate Williams Delight (fig. 38). If faulting and folding are assumed to be minor, Kingshill Limestone thickness patterns imply a basin opening to the south but deepest in the section presently occupied by the carbonate highlands.

The Jealousy Formation underlies the Kingshill Limestone across most of the south coast of St. Croix. The position of the Kingshill Limestone-Jealousy Formation contact is unknown west of Estate Williams Delight due to poor core control, and east of Estate Anguilla due to faulting within the Tertiary section between test holes M1 and M4 (figs. 38, 43). In the latter areas, extensive thicknesses of Mannings Bay Member and the Blessing Formation accumulation put the Kingshill/Jealousy boundary beyond the reach of shallow drilling.

The Kingshill Limestone has a general southerly dip that averages less than 12 degrees, and exposures of the formation therefore are progressively younger to the south (Lidz, 1982). However, Cederstrom (1950) mapped a number of localized structures in the exposed parts of the Kingshill not mentioned in subsequent reports. In particular, Cederstrom (1950) mapped a series of low-angle synclinal structures with axial traces oriented in a crudely radial pattern that ranged from WSW-ENE in the southwestern part of the basin to SW-NE in the north, and back to WSW-ENE in the southeastern part of



EXPLANATION

Area underlain by Kingshill Limestone

30 **Structure contour**—Line shows altitude of top of the Kingshill Limestone. Dashed where uncertain. Contour interval 10 meters. Datum is sea level

U D **Inferred fault**—U, upthrown; D, downthrown

Inferred northern limit of Blessing Formation

Inferred northern limit of Mannings Bay Member

Well—Control point. Thickness in meters

FIGURE 47.—Thickness of the Kingshill Limestone (modified from Gill, 1989).

the basin (Cederstrom, 1950). The synclines mapped by Cederstrom (1950) correspond to topographic highs, with the synclinal axes mapped along ridgelines. A possible, but speculative, interpretation of this pattern is post-Kingshill deformation of the Kingshill Basin, with the long axis of St. Croix being bent northward around a pivot point in the northern part of the Kingshill Basin. Such a pattern might explain the extensional faulting along the south shore, and the gentle folding mapped by Cederstrom (1950) in the northern part of the Kingshill Basin.

A wide variation in dip is evident near the fault contact of the Kingshill Limestone and the Cretaceous Mount Eagle Group in the Northside and East End Ranges. Two steep scarps outline the edge of the limestone highlands, and are suggestive of structural control. These scarps trend NW-SE from Beeston Hill to Morningstar and then NNE to SSW to Fair Plain. However, despite geomorphic evidence and the marked upbowing of the Jealousy Formation beneath the limestone highland area, available biostratigraphic data do not support faulting in this area (Gill, 1989).

Age

The Kingshill Limestone ranges in age from the early Miocene (N8) to close to the Miocene and Pliocene boundary (N17). The La Reine Member can range in age from early Miocene (N8) to as young as late Miocene in age (lower N17). In the subsurface, the Kingshill Limestone spans a narrower range, from early Miocene (N8) to middle Miocene (N12). The age of the Kingshill Limestone (at the Mannings Bay Member-La Reine Member boundary) is placed within the upper N17 zone (*Globorotalia numerosa* Zone). The determination of age (Gill, 1989) was based on the presence of planktonic foraminifera *Globorotalia numerosa, Candeina nitida* (d'Orbigny) and the absence of Pliocene marker species, *Globorotalia margaritae* and *Sphaeroidinella dehiscens* (McLaughlin and others, 1995).

Mannings Bay (upper) Member of the Kingshill Limestone

The Mannings Bay Member is herein named for uppermost well-bedded limestone strata of late Miocene to early Pliocene age (McLaughlin and others, 1995) that are characterized in part by larger benthic foraminifera and shelf-derived debris. Previous workers have included these strata either as part of the Kingshill Limestone (Gerhard and others, 1978) or considered them to be part of the post-Kingshill Limestone sequence (Lidz, 1982; Andreieff and others, 1986; Gill and Hubbard, 1987). They are defined herein as the uppermost member of the Kingshill Limestone and include the foraminiferal wackestone facies and foraminiferal grainstone facies of Gerhard and others (1978). The Mannings Bay Member is exposed along the Evans Highway near the Alexander Hamilton Airport (fig. 46). A quarry located on the southeastern side of Mannings Hill adjacent to the airport is proposed as the type section (fig. 48). More than 20 m of Kingshill Limestone, including the top of the unit, are exposed in this outcrop (Gerhard and others, 1978; Gill and others, 1989). Limestone strata of the Mannings Bay Member were also penetrated in several test wells described in this report, but the strata are difficult to differentiate from the lower Kingshill Limestone without the detail of an exposed section.

Lithology, facies, and depositional environment

The Mannings Bay Member is bracketed by unconformable surfaces that separate it from the lower part of the Kingshill Limestone and from the overlying Blessing Formation, a lagoonal and reefal limestone. The lower unconformable surface is erosional, and characterized by coarse benthic foraminiferal and other skeletal debris of the Mannings Bay Member cutting into the underlying alternating hemipelagic and pelagic beds of the La Reine Member of the Kingshill Limestone. There are numerous pinchouts of the coarser-grained beds of the Mannings Bay Member, probably indicating channelization (Lidz, 1984), but no caliche, karstification, or paleosols have been observed (Gill, 1989).

The unconformity separating the Mannings Bay Member of the Kingshill Limestone from the overlying Blessing Formation sharply separates the two units, but there is no clear evidence of subaerial exposure at the Airport Quarry exposure. To the east, the unconformity separating the Mannings Bay Member from the Blessing Formation was observed to have the red oxidized coloration and the clay content of terra rosa (Behrens, 1976; Gerhard and others, 1978; S.H. Frost, UNOCAL, oral commun., 1986; L.C. Gerhard, Kansas Geological Survey, oral commun., 1994), but this exposure has since been lost to industrial development.

The Mannings Bay Member of the Kingshill Limestone has at its base, channelized beds containing shelf-derived skeletal material including larger benthic foraminifera. The Mannings Bay Member tends to be more thinly bedded and contain a significantly larger component of shelf-derived skeletal clasts than the La Reine Member, and is dominated by bioclastic wackestones and packstones. Within the Blessing fault block to the east of the Fairplain fault, the Mannings Bay Member has been patchily dolomitized and heavily leached by meteoric weathering.

The occurrence of larger foraminifera within the Mannings Bay Member signals the establishment of a shallowing Kingshill Limestone environment that does not have a modern St. Croix analog. The fossil assemblage includes and is dominated in places by the operculinoid foraminifera *Operculinoides cojimarensis* and *Paraspiroclypeus chawneri* (Behrens, 1976; Gerhard and others, 1978; S.H. Frost, UNOCAL, oral commun., 1986). These foraminifera occasionally show evidence of transport or reworking, such as fracturing, abrasion, and imbrication. The foraminiferal wackestones also contain ubiquitous planktonic foraminifera, including *Orbulina universa* and *Globigerina* spp.

Foraminifera such as *Operculinoides* and *Paraspiroclypeus* were more than likely photic zone forms (S.H. Frost, UNOCAL, oral commun., 1986) and temporarily dominated St. Croix shallow carbonate environments. Other bioclasts that contribute significantly to the facies are coralline algal crusts and rhodoliths, benthic foraminifera such as *Archaeis* and *Amphistigina*, and echinoid spines and plate fragments. Minor coral fragments and molluscan debris are also part of the assemblage, but are primarily represented by external molds and pore space in the cores.

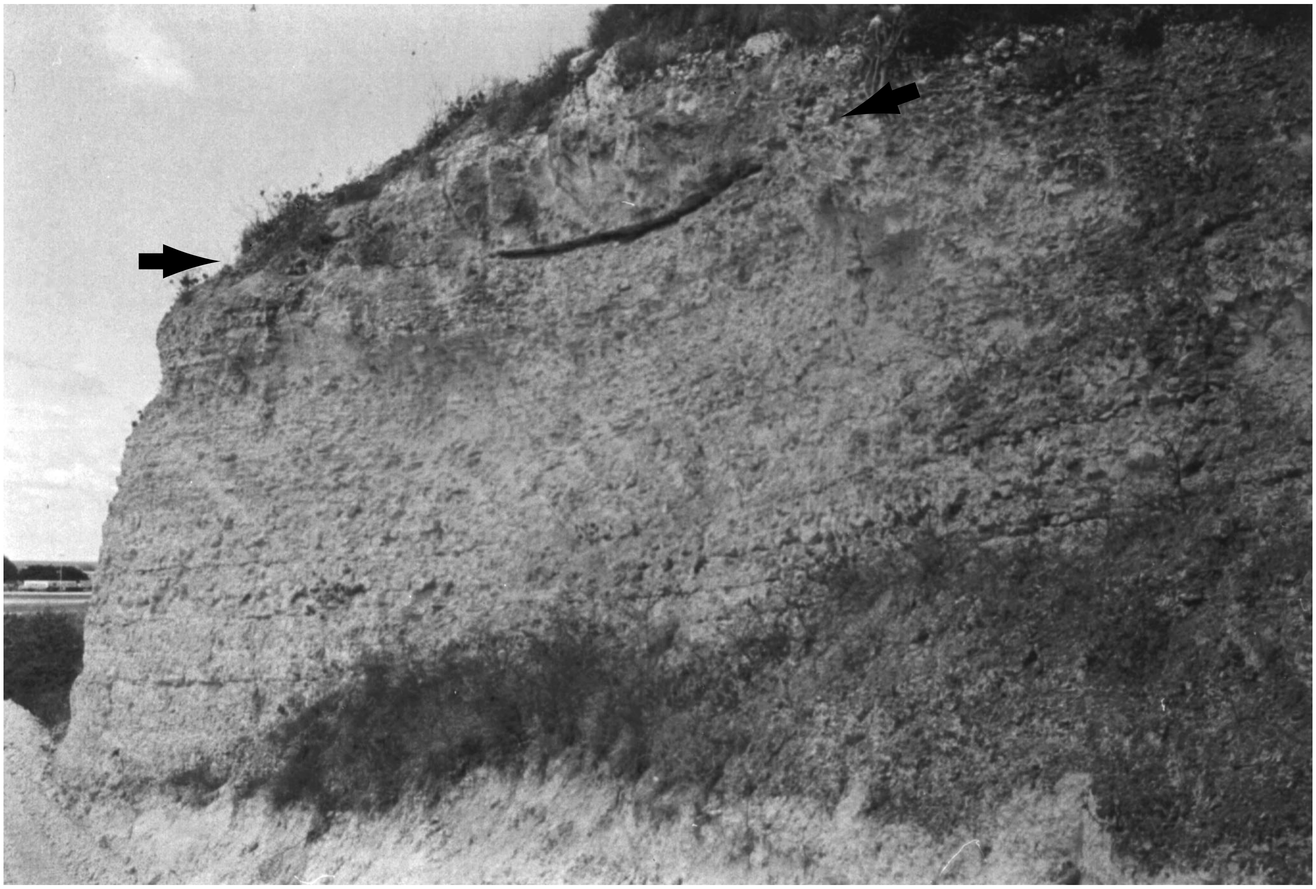


FIGURE 48.—An east-facing view of the unconformity that separates the Mannings Bay Member from the Blessing Formation at the Hamilton Airport Quarry exposure. Arrows mark the position of the unconformity (reprinted and published with permission from Gill and others, 1989).

The bioclast assemblage in the Mannings Bay Member was analyzed primarily from thin sections. Benthic foraminiferal assemblages were not statistically analyzed due to extensive diagenetic alteration. However, the presence of shallow and poorly developed deep-water planktonic foraminifera within the Mannings Bay Member suggests deposition in a marine setting approximately 100 m deep (McLaughlin and others, 1995).

Structure and distribution

On the basis of core material, the lower boundary of the Mannings Bay Member is 44 m below sea level in well M4 (fig. 43). The transition is marked by a change in dominance from the deep-water planktic fauna of the Kingshill Limestone to the mixture of planktonic and shelf-derived benthic fauna of the Mannings Bay Formation. The core material from well M4 indicates that the Mannings Bay Member is at least 56 m thick.

The Mannings Bay Member of the Kingshill Limestone occurs only close to the southern central coastline of St. Croix, and is exposed along Evans Highway from Estates Barren Spot and Castle Coakley in the East to the western end of Manning Hill in the West. Poor exposures make identification outside of this region difficult. The Mannings Bay Member (and the overlying Blessing Formation) is interrupted by a fault near Fairplain (fig. 43). Well M1 at Fairplain was completed in the Jealousy Formation at 29 m below sea level, whereas well M4, located less than 180 m to the east, did not encounter the Jealousy Formation despite penetration to 80 m below sea level. Similarly, a well (45a) drilled 60 m to the east of M1 (fig. 38) penetrated the Jealousy Formation 24 m deeper than at M1 indicating that the intervening fault zone is steeply dipping.

The existence of a fault at Fairplain is also supported by the vertical displacement of the lower contact of the Mannings Bay Member. West of well M1, Kingshill Limestone strata in Mannings Hill dip toward the fault, and the lower Mannings Bay contact is elevated 24 m above sea level. In contrast, the lower Mannings Bay contact is reached at approximately 55 m below sea level in well M4, suggesting a minimum displacement of 79 m. In addition, River and Bethlehem Guts, two ephemeral streams, run along the presumed line of the fault as they extend to the coast (fig. 38).

Vertical displacement of the Mannings Bay Member indicates that tectonic activity occurred after deposition of the Kingshill Limestone. However, the specific orientation and extent of the Fairplain fault is uncertain, although disrupted streamflow occurs between wells M8 and M3, extending from River Gut eastward to hole M5. Streamflow here is oriented parallel to the coastline rather than into the sea and corresponds to the lateral extent of the exposed reef facies. Holocene topography in this area could be partly the result of Tertiary reef development patterns, but may also mark the location of the fault trace of a half-graben or graben block that contains most of the Mannings Bay Member and Blessing Formation strata (fig. 49). A similar location for a fault boundary was published by Cederstrom (1950).

Age

The age of the Mannings Bay Member can range from the late Miocene (upper N17) to as young as early Pliocene in age (upper N19). It is not possible to further refine the biostratigraphic placement due to extensive diagenetic alteration (McLaughlin and others, 1995).

Biostratigraphic assignment of the Mannings Bay Member has been done only on the basis of species presence in core and outcrop samples, because species absences are unreliable due to extensive diagenetic alteration, and the likelihood of unfavorable ecological factors (McLaughlin and others, 1995). Samples from well M4 (21.8 m subsurface) are placed near the Miocene/Pliocene boundary based on the presence of *Globoquadrina altispira, Globigerinoides trilobus* subspp., and *Globigerinoides obliquus extremus*. Tentative identification of a small, menardiform *Globorotalia tumida* would indicate placement in the Pliocene portion of this interval. In outcrop, the Mannings Bay Member appears to lie in the lower Pliocene, due to the tentative identification of *Globorotalia crassaformis* and *Globorotalia crassaformis ronda* in a sample taken from immediately above the basal unconformity of the member. A more detailed discussion of the biostratigraphy is given by McLaughlin and others (1995).

BLESSING FORMATION

The name Blessing Formation is herein used to describe reef and lagoonal carbonate rocks of Pliocene age that extend across the central southern and western coasts of St. Croix (fig. 38). The greatest exposure of the Blessing Formation is in the Hess Refinery outcrop which is suggested here as the type-section (figs. 38, 50). The name Blessing Formation, as used here, combines the strata separated into the Annaberg and Blessing Formations by Behrens (1976) because the two units would be difficult to map individually, and the outcrops used to differentiate the two have deteriorated to the point that much of the original lithologic detail has been lost. Like the Mannings Bay Member, the greatest thickness of Blessing Formation strata is contained within a subsidiary graben located in the southeastern coastal section of the central plain region.

Lithology, facies, and depositional environment

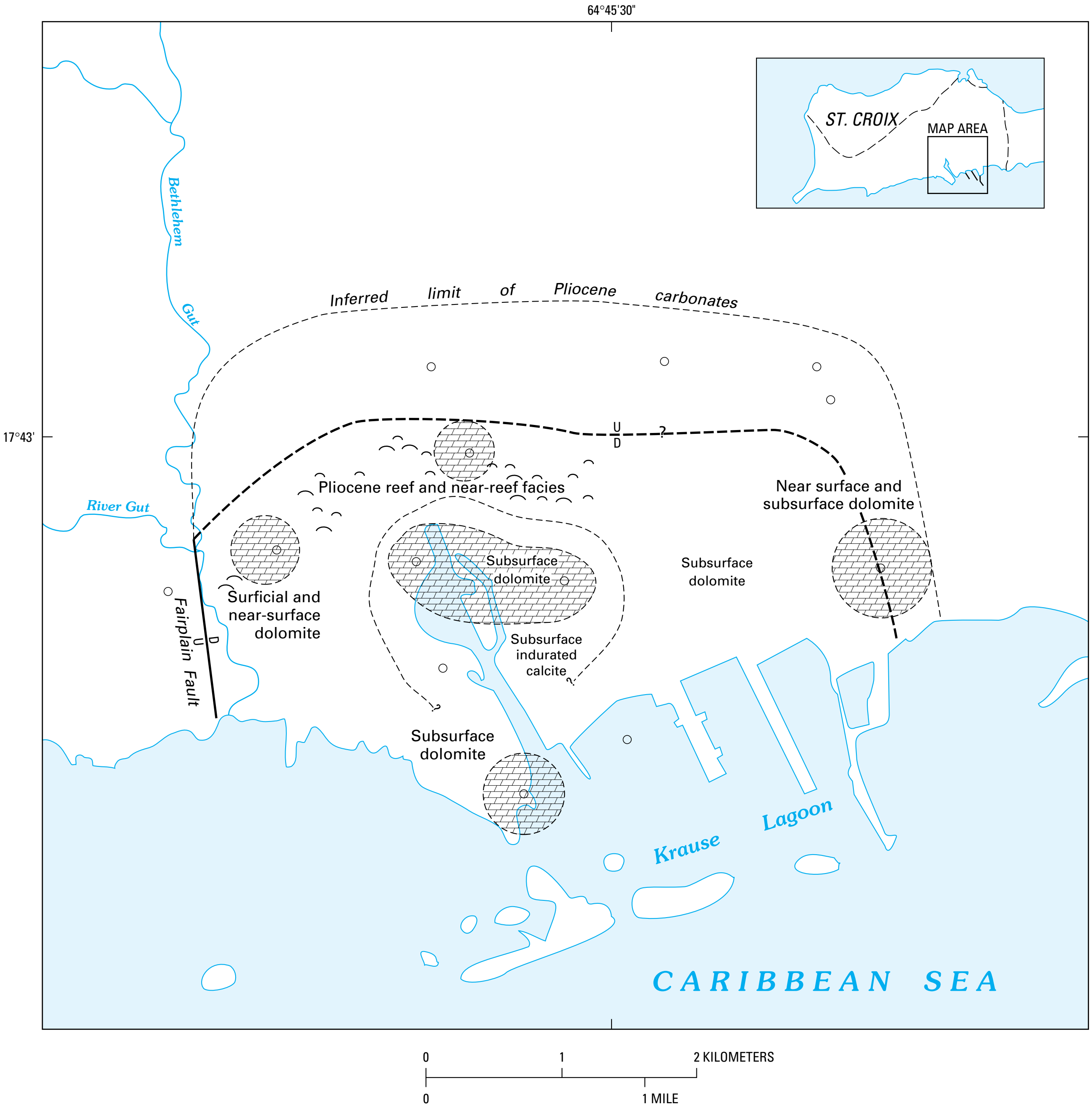
The Blessing Formation unconformably overlies the Mannings Bay Member of the Kingshill Limestone in the quarry face on the eastern side of Mannings Hill adjacent to Alexander Hamilton airport. In this exposure, there is an erosional truncation of the soft, poorly indurated, well-bedded Kingshill Limestone strata, and an abrupt transition to a massively bedded, well-indurated molluscan bioclastic wackestone. There is no strong evidence of subaerial exposure at this unconformity, although Behrens (1976) and Frost (oral commun., 1984) observed a reddish, oxidized zone interpreted as a paleosol between the upper Kingshill Limestone and the Blessing Formation in an outcrop within the Hess Refinery. This latter exposure has since been obliterated by continued construction in the Hess Refinery.

Throughout the Blessing Formation, mollusks and corals are preserved as moldic porosity, and the unit is generally classified as coral- and molluscan-dominated bioclastic wackestones and occasionally packstones. Diagenetic alteration of the Blessing Formation is extensive, with evidence of subaerial exposure and meteoric leaching commonplace. Locally, the unit has been patchily dolomitized within the Blessing graben block. The unit is generally quite porous and friable.

Exposures and core samples from several wells show the Blessing Formation to contain a macrofaunal assemblage represented by external molds of scleractinian corals, gastropods and pelecypods, as well as skeletal debris from foraminifera, coralline algae and a wide variety of shallow-water invertebrates. Scleractinian corals include several extant genera (*Agaricia, Diploria, Montastrea, Siderastrea*, among others) as well as extinct corals such as *Stylophora* sp., *Teliophyllia* sp., and *Thysanus* sp. In general, different faunal assemblages within the Blessing Formation represent coexisting reef, forereef, and lagoon environments that extended along the southern and western coastlines of St. Croix during Pliocene time.

Structure and distribution

The Blessing Formation occurs only along the southern and western coasts of St. Croix, and its distribution suggests that reef and lagoon systems in the Pliocene followed a coastline similar to that of modern St. Croix. The thickest remnant of Blessing Formation strata lies in the subsurface east of the Fairplain fault described above. The thickness of the Blessing Formation could reach 30 m and its extent suggests that sub-



EXPLANATION

Dolomite

Fault—Dashed and queried where infered. U, upthrown; D, downthrown

Inferred facies boundary—Queried where uncertain

Well control point

FIGURE 49.—Major facies within the Blessing Formation in the industrial area north of Krause Lagoon (reprinted from Gill and others, 1989, and published with permission).

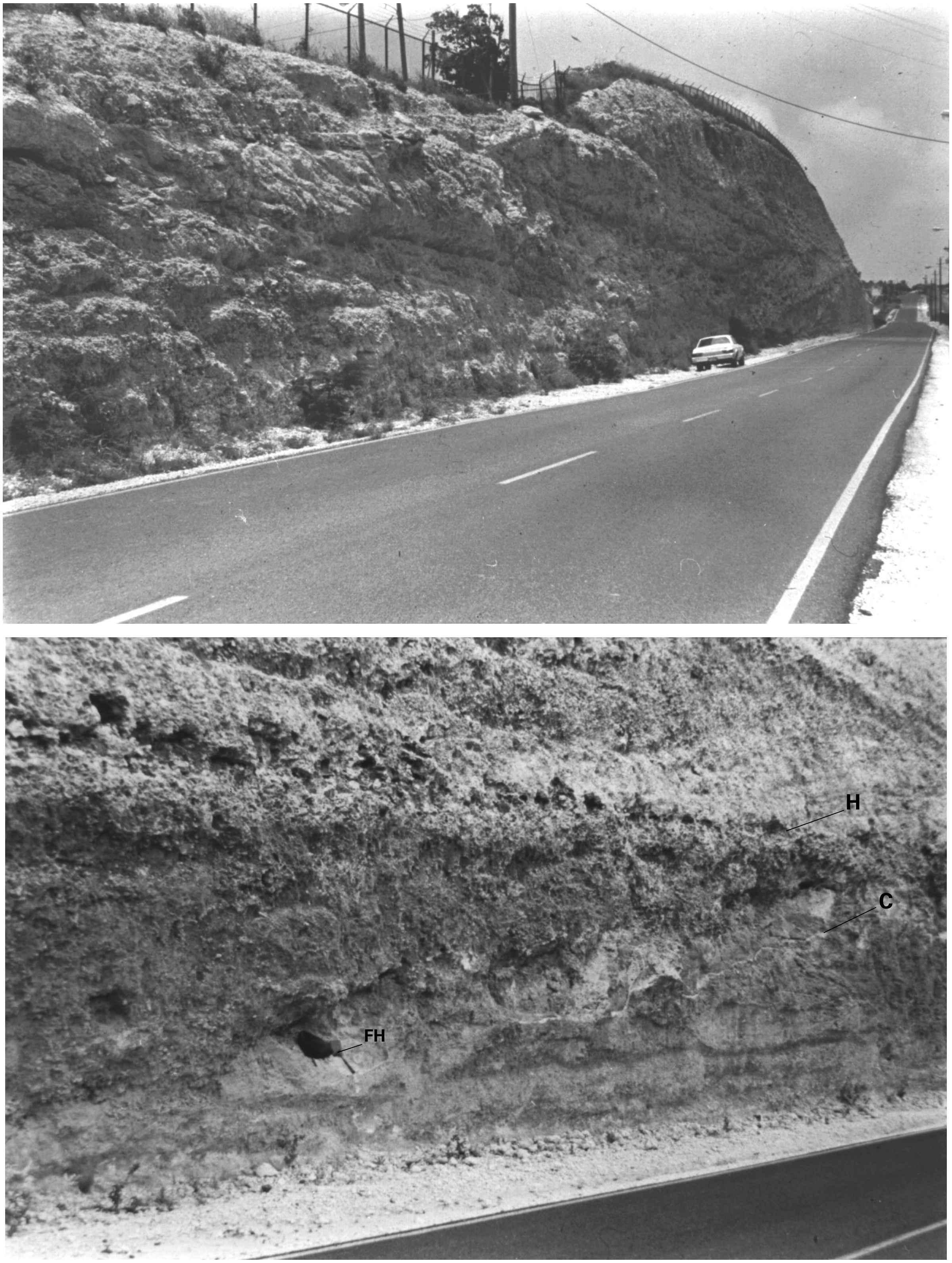


FIGURE 50.—Hardground and exposure surfaces in the Blessing Formation at the Hess Oil exposure. Upper photo shows an oblique view to the north-northwest. Apparent "bedding" dipping upper left to lower right is caused by bulldozer scarring. Lower photo shows hardground (H) and caliche/exposure surfaces (C) in the Blessing Formation reef tract. Rock hammer and field book (FH) for scale (reprinted and published with permission from Gill and others, 1989).

sidence controlled both the accumulation and preservation of the Blessing reef facies. In western St. Croix, well control is poor and exposures sparse; west of the Airport/Evans Highway outcrop, exposures are limited to scattered outcrops along the highway, around Fredericksted, and an exposure of reefal limestone in Estate Carlton described by Gerhard and others (1978). For this reason, the age, nature, and extent of the Blessing Formation reef facies in this area are speculative. The maximum thickness of the Blessing Formation west of the fault at Fairplain is estimated to be between 10 and 20 m.

The structure of the Mannings Hill Member and Blessing Formation is discussed in detail in the previous section. The Fairplain fault displaces Blessing Formation strata as well as that of the Kingshill Limestone. Vertical displacement of the Blessing Formation by faulting indicates tensional fault activity occurred as recently as the early Pliocene, and perhaps later.

Age

The Blessing Formation was deposited during the early Pliocene. This age assignment is based on the tentative identification of *Globorotalia margaritae* in subjacent beds (Lidz, 1982), the co-occurrence of *Operculinoides cojimarenis* and *Paraspiroclypeus chawneri* (Andreieff and others, 1986) in underlying Mannings Bay strata, and the common presence of scleractinians *Stylophora, Teliophyllia,* and *Thysanus* within the Blessing Formation (Behrens, 1976; Frost, oral commun., 1984; Gill, 1989; Gill and others, 1989).

Dolomitization and diagenesis

The Blessing Formation displays patchy areas of dolomitization where exposed as well as in the subsurface (figs. 42, 43). Dolomite has not been detected elsewhere on St. Croix. On the basis of stratigraphic position, the dolomitization occurred during or after Pliocene time, and is discussed in more detail in subsequent sections. Subsurface dissolution has resulted in voids in the Blessing Formation that were encountered during drilling. In contrast, karst has not been observed in rocks of the Kingshill Limestone.

Well-cemented, undulating layers within the Hess outcrop (fig. 50) correspond to karst surfaces with marked light stable-isotopic excursions, and indicate subaerial exposure of the Blessing Formation several times during the Pliocene. The exact timing of the exposure episodes remains uncertain.

ALLUVIAL DEPOSITS

Dark, terrigenous material makes up most of the alluvium in the stream valleys, and is derived from the weathering of the Cretaceous siliciclastics of the highland areas. However, alluvium in areas immediately overlying the Kingshill Limestone tends to be light-colored, and contains carbonate material difficult to distinguish from the unweathered parts of the Kingshill Limestone. For this reason, identifying the uppermost contact of the Kingshill Limestone in well cuttings or cores can be difficult. Red, clay-rich alluvium fills karst cavities in Blessing Formation and Mannings Bay Member strata at the Barren Spot well field, and terrigenous alluvium is penetrated in many of the active well fields on St. Croix.

SEDIMENTARY AND STRUCTURAL SETTING OF THE KINGSHILL BASIN

The Jealousy Formation was deposited in 600 to 800 m of water, and represents deep-marine depositional conditions. On the basis of the evidence discussed above, the graben block which now forms the Kingshill Basin might not have been active before the early Miocene (fig. 51*A*) and the horst blocks were probably not exposed. If the Kingshill Basin did not form before the middle Miocene, then shelf-derived sediments in the Jealousy Formation must be derived from outside of the present island of St. Croix.

The lowermost strata of the Kingshill Limestone were deposited in the same bathyal conditions as the immediately underlying strata of the Jealousy Formation (fig. 51*B*). There are no changes in sediment character, and no changes in basin depth. Tectonic or eustatic changes, if they occurred during this period, either were not substantial enough to be detectable, or cancelled each other out. The origin of the sharp color change between the two formations remains undetermined, but could reflect differences in clay mineralogy or diagenetic effects.

Basinal shallowing only becomes apparent in upsection parts of the Kingshill Limestone along the southern edge of the central plain. Here, the Kingshill Limestone contains greater quantities of shelf-derived sand, is burrowed, and contains an intraformational disconformity separating the La Reine Member of the Kingshill Limestone from the overlying Mannings Bay Member. The presence of a planktonic foraminiferal assemblage of both shallow and deep water forms implies that the deposition of the upper La Reine Member occurred in approximately 200 m of water (Gill, 1989; McLaughlin and others, 1995) (fig. 41).

The structural relation between the Kingshill Limestone and adjacent Cretaceous strata along the eastern margin of the Kingshill Basin indicates that the Kingshill Limestone was, at least in part, deposited prior to basin faulting (Gill and Hubbard, 1986; Gill and others, 1989). Initiation of the St. Croix normal fault system occurred after early Miocene time. It is not entirely clear, however, whether the basin fault boundaries formed during the deposition of the Kingshill Limestone, or if the bounding horst blocks of the Northside and East End Ranges were exposed during this time. Gerhard and others (1978) supported a model with subaerially exposed horst

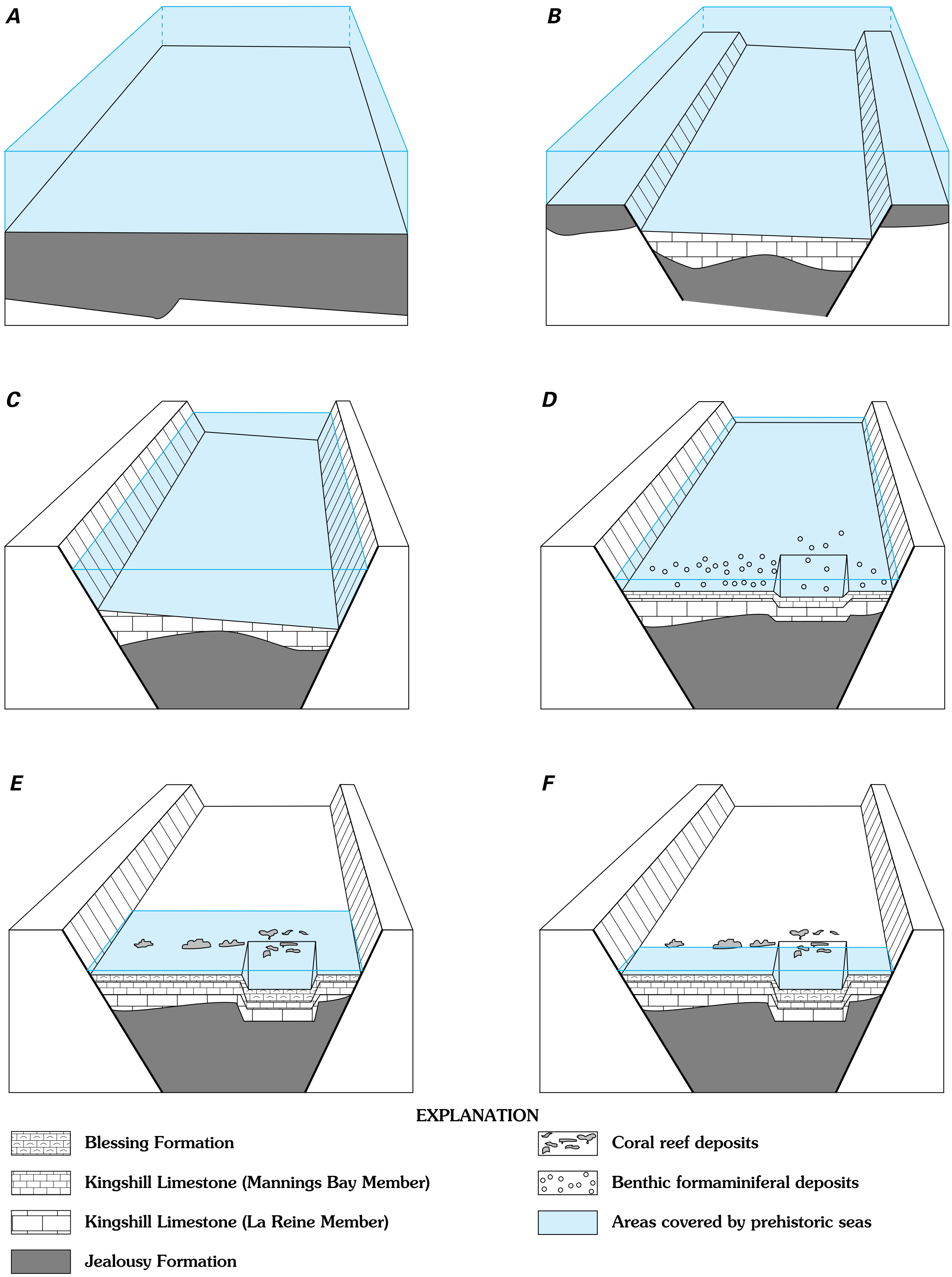


FIGURE 51.—Block models of St. Croix during the early Miocene to Pliocene (reprinted and published with permission from Gill and others, 1989).

blocks (fig. 51*C*), interpreting exposures of the Kingshill Limestone along the eastern fault boundary as syntectonic breccias. If the terrigenous clasts in the Kingshill are indeed derived from Mount Eagle Group strata, then the graben boundaries must have formed no later than the middle Miocene (N14 and N16; Gill, 1989; McLaughlin and others, 1995).

The unconformable contact between the Kingshill Limestone and its upper Mannings Bay Member signals basin shallowing and the development of a source of shallow-water benthic foraminifera, in particular *Operculinoides cojimarensis* and *Paraspiroclypeus chawneri*. An alternative interpretation is that the disconformity represents submarine erosion caused by the transport of coarse, shelf-derived gravity deposits.

The foraminiferal-algal facies of this member marks a period of deposition when shallow-water carbonate production was dominated by benthic foraminifera and coralline algae perhaps at the expense of scleractinian communities. These deposits indicate basin shallowing from bathyal depths to outer platform or upper slope environments of about 100 m water depth (fig. 51*D*).

The amount of shallowing suggested by the character of the Mannings Bay Member is too great to be explained by either basinal fill or eustatic change alone, and must have been caused by tectonic uplift. Neglecting eustatic variation, the Kingshill Basin shallowed from approximately 750 m of water depth in the middle Miocene to approximately 100 m water depth in the lower Pliocene (N17). The average rate of uplift suggested by these estimates of 650 m of vertical movement over a period of roughly 9 million years translates to a minimum average uplift of 72 m.y., or slightly less than 0.1 mm/yr.

These calculations assume continuous uplift from bathyal depths between the middle Miocene and the early Pliocene, and that the foraminiferal biozones on St. Croix are equivalent to the biozones established elsewhere in the Caribbean. This tectonic uplift culminated in the shoaling of the Kingshill Basin and deposition of the Blessing Formation reef tract that extended around St. Croix's southern and western coastlines (fig. 51*E*). The reef tract consisted of interspersed reefs and shelf lagoon systems similar to the arrangement of reefs around the southern coastlines of St. Croix today. The reefs apparently formed planar deposits with little topographic relief. This planar geometry was common in Caribbean Tertiary reef deposits (Frost, oral commun., 1984).

The greatest thickness of Pliocene reef growth is found within the Blessing graben, a small, subsidiary graben in what is now the industrial area on the south-central coastline. The geographical distribution of reefs suggests that faulting in the subsidiary graben affected sedimentation of the Blessing Formation and the Mannings Bay Member. The arcuate distribution of reef and lagoonal lithologies indicates that the Blessing graben area was an embayment during the Pliocene (fig. 49), with the embayment's size and shape controlled by faulting in the Krause Lagoon area.

From a tectonic standpoint, the Fairplain fault that cuts through the Mannings Bay Member and Blessing Formation units demonstrates that normal faulting, and therefore a tensional tectonic regime, extends at least into the Pliocene if not later. The orientation of this fault is poorly controlled, but suggests that the mechanism for the faulting was the same for the basin boundary faults and the subsidiary south coast graben.

Deposition of Mannings Bay Member and Blessing Formation sediments was concentrated in the basin formed by this subsidiary graben, and the strata were preserved by additional subsidence during island uplift. The incorporation of reworked, cemented planktonic forams from the Kingshill Limestone into the Blessing Formation rocks demonstrates that erosion of the uplands area has removed a significant section of the Kingshill Limestone and, by inference, the post-Kingshill rocks as well.

Normal faulting of Blessing Formation strata indicates that tectonic activity continued on St. Croix through the latest periods of Tertiary deposition, and therefore extended into Pliocene time or later. Uplift continued during the Pliocene, and eustatic variation along with tectonic uplift account for the repeated exposure of Blessing Formation strata (fig. 51*F*). Preferential uplift of the northern part of the island accounts for the more extensive erosion in the northern central plain, and the general southerly dip of Tertiary strata in the Kingshill Basin.

HYDROGEOLOGIC FRAMEWORK OF THE U.S. CARIBBEAN ISLANDS

By Robert A. Renken[1], Fernando Gómez-Gómez[1], and Jesús Rodríguez-Martínez[1]

The two most important aquifer systems of the U.S. Caribbean Islands, in terms of areal extent and productivity are the North Coast limestone aquifer system and the South Coast aquifer; they are located on the windward-Atlantic (North Coast ground-water province) and leeward-Caribbean (South Coast ground-water province) sides of the Puerto Rico, respectively. In 1985, withdrawals from Puerto Rico's North Coast limestone aquifer system and South Coast aquifer accounted for approximately 80 per cent of the total amount of ground water withdrawn in the U.S. Caribbean Island study area (U.S. Geological Survey, 1990).

Poorly lithified carbonate rocks combine with a thin overlying alluvial veneer in St. Croix's central plain and compose the only areally extensive sedimentary-rock aquifer in the

[1] U.S. Geological Survey

U.S. Virgin Islands. The importance of the Kingshill aquifer is related more to its physical extent and lack of alternative ground-water supplies on that island than its productivity, which is relatively poor. In 1985, the Kingshill aquifer supplied less than 1 percent of the total water withdrawn from wells in the U.S. Caribbean region (U.S. Geological Survey, 1990).

Puerto Rico contains a number of alluvial valley aquifers that represent important local sources of ground water. Collectively, alluvial valley aquifers supply nearly 14 percent of the total amount of ground water withdrawn in the U.S. Caribbean region, with all but a very small fraction from Puerto Rico (U.S. Geological Survey, 1990). Alluvial aquifers of Puerto Rico are relatively permeable and comparatively restricted in extent. Alluvial aquifers are reported to yield to wells 3 to 10 L/s, and as much as 125 L/s. Alluvial valley aquifers of the U.S. Virgin Islands are much more limited in extent and importance and function only as a local source of water.

Volcanic and volcaniclastic rocks on the different U.S. Caribbean Islands collectively yield about 482,000 m^3/s or about 6 percent of the total ground water withdrawn from the islands (U.S. Geological Survey, 1990). The bulk of that water is derived from Puerto Rico; volcanic and volcaniclastic rocks on St. Thomas, St. John, and St. Croix collectively supply only about 1,360 m^3/d.

A previous section of this report defined the stratigraphic section in the major ground-water provinces of Puerto Rico and in the U.S. Virgin Islands. The major purpose of this section is to establish equivalency between stratigraphic and hydrogeologic units (fig. 52), illustrate how the different geologic processes previously described affect permeability and porosity within water-bearing strata, and compare the pattern of deposition within the various aquifers with the areal distributions of transmissivity and hydraulic conductivity.

THE SOUTH COAST GROUND-WATER PROVINCE

The South Coast ground-water province of Puerto Rico can be separated into three distinct hydrogeologic entities. The South Coast aquifer is comprised of fan-delta and alluvial deposits of Quaternary age that underlie and form a continuous 70 km-long low-lying plain located between Ponce and Patillas. West of Ponce, fan-delta and alluvial deposits do not form a continuous alluvial plain. These deposits are restricted to narrow valleys incised into the underlying strata of the Ponce Limestone and the Juana Díaz Formation or lithified bedrock units of Cretaceous and early Tertiary age that form the mountainous core of the island. These restricted alluvial deposits are considered to be the second major hydrogeologic entity of the South Coast ground-water province.

Rocks of Oligocene and Miocene age (Juana Díaz Formation and Ponce Limestone) represent the third major hydrogeologic unit of the South Coast. For reasons described below, bedded carbonate and clastic strata are poorly permeable or contain ground water of poor quality, or both.

THE SOUTH COAST AQUIFER

Previously referred as the Southern aquifer (Renken, Díaz, and others, 1990; Renken, Gómez-Gómez, and others, 1990), the South Coast aquifer is the most important and widespread clastic aquifer of the U.S. Caribbean Islands and one of Puerto Rico's two largest sources of ground water. Consumptive ground-water withdrawals from this aquifer in 1987 were estimated to be 274,000 cubic meters per day (m^3/d), 67 percent of which was used for irrigation with remaining amounts mostly used for municipal supply (Gómez-Gómez, 1990).

The South Coast aquifer consists of unlithified deposits of boulder- to silt- and some clay-size detritus, mostly of volcaniclastic origin. Boulder- to sand-size detritus composes the major water-bearing units. Beds of coarse-grained sediments are intercalated with thick beds of silt and some clayey material that impede vertical ground-water movement in the downfan areas. The South Coast aquifer contains ground water under both confined and unconfined conditions. Unconfined conditions dominate the coarser-grained proximal and midfan areas, whereas confined conditions appear to be more prevalent within the deep subsurface, or in interfan, and distal fan areas. Interfan and distal fan deposits are important hydrologically because they tend to restrict seaward discharge of fresh ground water and retard the landward, as well as upward, encroachment of saltwater. Quiñones-Aponte (1990) reported a coastal 3-m thick confining unit that lies approximately 10 m below land surface and extends 3 km landward in the Salinas-Jobos area. Given the intercalated, laterally-discontinuous nature of fine- and coarse-grained beds that make up the fan-delta plain, it is unlikely that there are any confining units that can be mapped over a wide area, let alone the entire plain. In places, coastal confinement of the aquifer can be attributed to fine-grained sediment deposited within coastal marsh and mangrove areas. Elsewhere, confinement is due, in part, to the numerous but discontinuous fine-grained beds that collectively retard the vertical movement of water. In any case, the aquifer contains water under confined conditions at depths below 10 m near the coast.

Under predevelopment conditions, the South Coast aquifer was principally recharged by infrequent rainfall and by streambed seepage near the fan apex. Aquifer discharge occurred primarily as (1) seabed seepage, (2) base flow discharge along the lower coastal reach of stream channels, (3) seepage into coastal wetlands, or (4) evapotranspiration in areas underlain by a shallow, coastal water table. In addition to those sources of recharge cited above, recharge to the aquifer also comes from irrigation canal seepage and area irrigation practices. On a regional basis, 30 percent of the surface water used for irrigation recharges the aquifer (Bennett, 1976) and enters the flow system largely within proximal and mid-fan areas of the fan-delta plain.

The development of surface water resources within the fan-delta plain has modified the hydrologic system considerably. Diverted streamflow by a channel-pond irrigation system served as the principal source of water for irrigation between 1900 and 1930. Irrigation deliveries between 1914 to the 1930's increased recharge to the aquifer which, in turn, increased discharge to the coastal reach of streams and coastal wetlands (Quiñones-Aponte, 1990). Coastal drainage canals were constructed as a consequence of irrigation practices; canals were used to control the water-logging of coastal soils, to recover land for sugar cane cultivation, and to control formation of coastal swamps and spread of water-borne diseases (malaria) (Quiñones-Aponte and others, 1996). The development of surface water for irrigation between 1910 and 1960 increased ground water flow within the aquifer by a factor of three when compared to the predevelopment water budget (Quiñones-Aponte and others, 1996).

During the 1960's and 1970's, the net increase in groundwater withdrawals for public supply contributed to a decrease in discharge to coastal drains. By February 1968, there were large cones of depression south of Ponce, near Santa Isabel, and in the Salinas area (pl. 1*F*). Water levels were as much as 6 m below sea level in places. The intrusion of salt water into the aquifer was also of concern. The chloride concentration of water near the Coamo fan-delta coastline was reported to have increased from 50 mg/L in 1960 to 250 mg/L in 1967 (Guisti, 1971). Concern about water-level declines led to a gradual shift from furrow irrigation to drip irrigation and sugar cane was replaced by vegetable crops (Ramos-Ginés, 1994).

Under present day conditions (1986), the reduction in ground-water withdrawals has resulted in a recovery of water levels and has mitigated the problem of coastal salt-water intrusion. Regional ground-water movement within the South Coast aquifer is coastward away from the fan apex or adjoining foothills with local movement of ground water toward streams and coastal drainage canals (pl. 1*G*). In general, ground-water flow closely parallels topography. Although most movement is to the coast or streams, development has locally altered the direction of flow toward several well fields. For example, a small cone of depression was formed at a well field north of Central Aguirre in 1986; withdrawals were reported to be nearly 19,000m^3/d (Torres-González and Gómez-Gómez, 1987). Although there has been a reduction in surface water irrigation and well withdrawals since 1968, present-day (1986) ground-water flow within the aquifer exceeded predevelopment conditions by a factor of two (Quiñones-Aponte and others, 1996).

The thickness of the South Coast aquifer's fresh-water lens (pl. 1*H*) was estimated by applying Ghyben-Herzberg relations to 1986-1987 potentiometric surface maps (Dacosta and Gómez-Gómez, 1987; Quiñones-Aponte and Gómez-Gómez, 1987; Román-Mas and Ramos-Ginés, 1987; Torres-González and Gómez-Gómez, 1987; Rodríguez-del-Río and Quiñones-Aponte, 1990; and Rodríguez-del-Río and Gómez-Gómez, 1990). The authors assumed that the interface between fresh and saline water was relatively sharp and the depth to the interface, z_s, in meters below sea level, could be estimated by the relation:

$$z_s = 40\, z_f \qquad (1)$$

where z_f = height of freshwater, in meters above sea level.

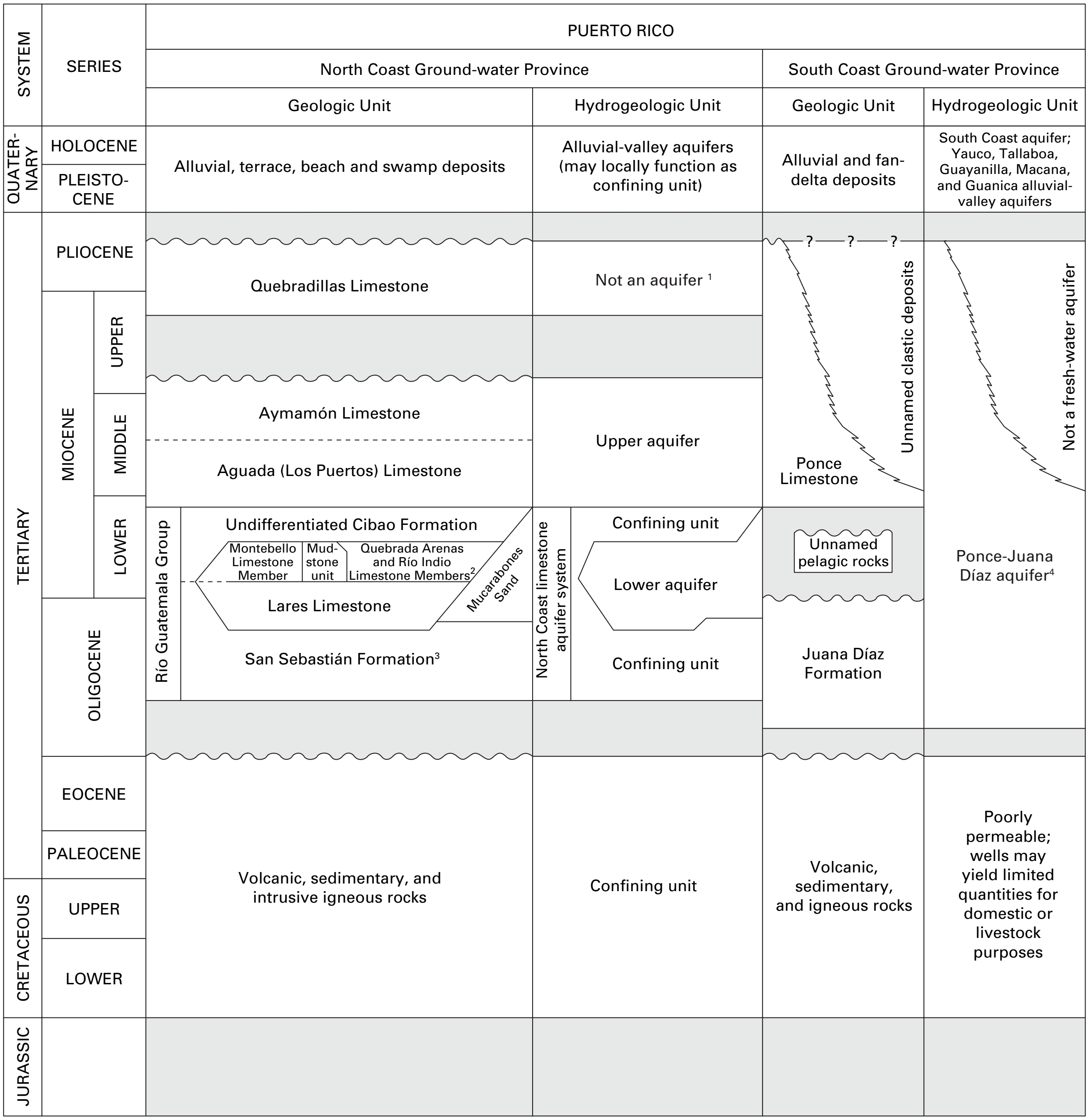
Specific conductivity data collected during the dual-tube drilling operations also served as a source of additional information to estimate the depth of the interface.

The freshwater lens within the South Coast aquifer varies considerably in thickness across the fan-delta plain and, for the most part, is limited to the Quaternary units of the system. In easternmost areas, where the aquifer is relatively thin, the lens is less than 20 m thick; in westernmost areas, the lens ranges from 20 to 40 m thick. The thickest part of the freshwater lens underlies the Coamo fan delta in the central part of the fan-delta plain. Here, the freshwater lens locally exceeds 150 to 200 m in thickness with some freshwater contained within Miocene and Pliocene (?) alluvial sediments (fig. 9).

The Vertical Sequence—Major Water-Bearing Units

Given the inherent non-continuous nature of bedded layers within alluvial fan and fan-delta deposits, it is difficult to separate coarse- and fine-grained layers into widespread mappable zones of permeability with any degree of accuracy. In southern Puerto Rico, these correlation problems are compounded by sparse borehole geophysical data and limited lithologic log control, reported mostly from well driller's completion reports. Therefore, an understanding of the pattern of deposition within an alluvial-fan and fan-delta system is extremely important. Recognition of such spatial depositional patterns, however, can provide a degree of hydrostratigraphic congruity within what otherwise might appear, at first glance, to be a random distribution of permeable and poorly permeable water-bearing units.

Detailed study of the continuously-cored wells that were described earlier in this report (pl. 3) reveals the occurrence of layering of coarser- and finer-grained beds, but also provides an understanding of the cyclic nature of deposition within the vertical sequence as well as eustatic, climatic, and tectonic controls. In a broad sense, distal Portugúez-Bucana,



[1] Mostly or entirely unsaturated.

[2] Quebrada Arenas and Río Indio Limestone Members of the Cibao Formation may function as confining unit in downdip areas.

[3] San Sebastián Formation contains some conglomeratic and sandy deposits in updip areas that may function as part of the lower aquifer.

[4] Juana Díaz Formation clastic beds are poorly permeable. Juana Díaz Formation and Ponce Limestone yield fresh water locally, mostly where they are adjacent to or underlie stream-valley alluvial aquifers. Clastic beds equivalent to the Ponce Limestone are deeply buried and contain saline water.

[5] There are no data available to evaluate water-bearing characteristics.

FIGURE 52.—Relation of major stratigraphic and hydrogeologic units of the U.S. Caribbean Islands.

System	Series		Puerto Rico: East and West Coasts and Interior Ground-water Provinces — Geologic Unit	Puerto Rico: East and West Coasts and Interior Ground-water Provinces — Hydrogeologic Unit	Isla de Vieques — Geologic Unit	Isla de Vieques — Hydrogeologic Unit	U.S. Virgin Islands: St. Croix — Geologic Unit	U.S. Virgin Islands: St. Croix — Hydrogeologic Unit	U.S. Virgin Islands: St. Thomas and St. John — Geologic Unit	U.S. Virgin Islands: St. Thomas and St. John — Hydrogeologic Unit
QUATERNARY	HOLOCENE		Alluvial, alluvial fan, terrace, beach, and swamp deposits	Lajas, Guanajibo, Añasco, Humacao-Naguabo, Maunabo, Yabucoa, and Caguas-Juncos alluvial-valley aquifers	Alluvium, beach, and swamp deposits	Resolución and Esperanza alluvial-valley aquifers	Alluvial fan, alluvium, debris flow, and beach deposits	Alluvial aquifer and coastal embayment aquifers	Alluvium and beach deposits	Alluvial aquifer and coastal embayment aquifers
QUATERNARY	PLEISTOCENE									
TERTIARY	PLIOCENE				Limestone and dolomite[5]	Not an aquifer	Blessing Formation	Kingshill aquifer		
TERTIARY	MIOCENE	UPPER					Kingshill Limestone: Mannings Bay Member			
TERTIARY	MIOCENE	MIDDLE					Kingshill Limestone: La Reine Member			
TERTIARY	MIOCENE	LOWER					Jealousy Formation	Not an aquifer		
TERTIARY	OLIGOCENE						? ?	? ?		
TERTIARY	EOCENE		Volcanic, sedimentary, and igneous rocks	Aquifer is poorly permeable; wells may yield limited quantities for domestic and livestock purposes	Igneous rocks	Aquifer is poorly permeable; wells may yield limited quantities for domestic and livestock purposes				
TERTIARY	PALEOCENE						Igneous intrusive rocks	Weathered mantle-bedrock aquifer		
CRETACEOUS	UPPER				Volcanic and minor limestone rocks		Volcanic, sedimentary, and igneous rocks			
CRETACEOUS	LOWER		Metamorphic, volcanic, and sedimentary rocks	Not an aquifer					Volcanic, sedimentary, and igneous rocks	Weathered mantle-bedrock aquifer
JURASSIC										

Figure 52.—Continued. Relation of major stratigraphic and hydrogeologic units of the U.S. Caribbean Islands.

Capitanejo, and Coamo fan-delta areas (fig. 13) can be separated into regionally-extensive water-bearing zones, distinguished by their intermediate-scale cyclic, coarsening-upward, sand- to boulder-sized detrital nature (mostly 30 to 40 m thick). In the Salinas fan, intermediate-scale layers fine-upward, but can also be viewed as cyclic, 30 to 40 m-thick hydrogeologic layers. The recognition of such stratigraphic layering clarifies the physical characteristics of the hydrogeologic system in general and improves our understanding of the depth and frequency of occurrence of small-scale (less than 1 m to 20 m thick) coarse- and fine-grained bedded layers that could be encountered during drilling operations. This type of stratigraphic evaluation proved to be useful to a limited degree in Puerto Rico's south coast. However, additional deep well information is needed before detailed correlation of regional water-bearing units can be considered.

Hydraulic conductivity and the lateral continuity of water-bearing units

Sand and gravel percentage facies described earlier (pl. 1*D*) show the proximal-to-distal fan spatial variability in grain size. Coarse-grained deposits are concentrated in lobes with the highest concentrations of sand and gravel within proximal and midfan areas or within the paleochannels that extend inland. Coarse-grained sediment is also concentrated within paleochannels that were infilled with conglomeratic deposits during channel aggradation. The highest percentage of fine-grained material occurs within the interfan areas that separate fan lobes and within the distal fan areas.

Maps showing lithofacies variations of the fan-delta plain were compared with maps showing the areas distribution of hydraulic conductivity (pl. 1*I*). Hydraulic conductivity and transmissivity maps are important to an understanding of the hydrogeologic system, in constructing ground-water flow models, and in simulating dissolved-mineral transport. Few aquifer tests have been conducted within the fan-delta plain because of the high cost and lack of opportunity. Within a 474 km^2 area, aquifer test data are available from only three separate sites; these are considered representative of local conditions only (V. Quiñones-Aponte, USGS, written commun., 1989). Accordingly, it would be imprudent to characterize regional hydraulic conductivity of the South Coast aquifer given the inherent limitations of extending aquifer test data to even nearby areas, and the aquifer's depositional heterogeneity.

Hydraulic conductivity estimates based on specific capacity data are available for most wells in the study area. Specific-capacity is defined as the yield per unit of water level drawdown in a pumped well for a specific pumping rate. Estimates of apparent transmissivity (T') for the South Coast aquifer were made from specific-capacity data using empirical equations developed by Theis (1963) and Brown (1963) for water-table or artesian conditions, respectively. The distribution of apparent hydraulic conductivity (K') was computed by dividing estimated transmissivity by the thickness of the aquifer penetrated by a particular well. The areal distribution of hydraulic conductivity shown in plate 1I, is subject to qualification. It is based on specific-capacity methods which assume 100 percent well efficiency, full penetration of the aquifer, a 15 to 45 cm well diameter, a storage coefficient of 1×10^{-4} for wells subject to artesian conditions or 0.15 for wells subject to water-table conditions, and a 24-hour pumping time. An additional qualification is that the distribution of hydraulic conductivity shown in plate 1I is based on wells that penetrate, at the minimum, the upper 50 m of the saturated zone.

Lithofacies maps (pl. 1*D*) were used to indirectly corroborate the distribution of hydraulic conductivity shown for the South Coast aquifer. The estimated hydraulic conductivity for fan-delta deposits of the South Coast aquifer ranges from less than 1 to greater than 100 meters per day (m/d). A comparison of sand and gravel percentage maps with hydraulic conductivity maps indicates that the highest conductivities are generally associated with the proximal and midfan parts of each fan delta. Within the Coamo and Salinas fan-delta areas, the areas of high hydraulic conductivity lie near the present position of the Río Coamo and the Río Nigua at Salinas. The high hydraulic conductivity areas are underlain by deposits that have a large percentage of sand and gravel. An area of moderate hydraulic conductivity (7.5 to 15 m/d) parallels a paleostream channel and the buried fault trace of the Esmeralda Fault that lies north of the bedrock hill at Central Aguirre. The Arroyo, Capitanejo, and Portugúes-Bucana fan deltas, underlain by large concentrations of sand and gravel, also exhibit relatively high hydraulic conductivities exceeding 7.5 to 30 m/d in proximal and midfan areas. Conductivity values of greater than 30 m/d are associated with the fluvial "string" of the Ríos Patillas and Chico.

Maps of sand-gravel percentage and hydraulic conductivity exhibit a poorer correspondence in the Guayama fan area. The highest conductivity values seem to correlate better with the present position of the Río Guamani rather than a depositional lobe. The more restricted occurrence of sand and gravel is indicative of a more channelized sequence, such as along a high-gradient stream.

Specific capacity-derived estimates of conductivity suggest that the Guayama fan-delta deposits are poorly permeable in the Central Machete area. However, favorable conditions for the occurrence of sand and gravel is indicated on the basis of a vertical exposure face visible along the Puerto Arroyo coastline. The exhumed channel seen here (fig. 16) is corroborated further by the percent lithofacies map (pl. 1*D*), and can indicate that permeable water-bearing units are still available for development, but have not yet been used.

ALLUVIAL VALLEY AQUIFERS OF THE SOUTH COAST

Boulder- to sand-size sediments form the principal water-bearing units within alluvial and fan-delta deposits of the Ríos Tallaboa, Guayanilla, Yauco, Macaná and in the Guánica alluvial valley area. Recharge to the aquifer is principally by stream and irrigation ditch seepage (McClymonds, 1967; Crooks and others, 1968) with minor recharge occurring from infiltration of infrequent precipitation that is usually short in duration (Quiñones-Aponte, 1986b). Ground water within the different alluvial valleys occurs mostly under water-table conditions; local artesian conditions also are reported and probably due to stratification of silt and sand-to-boulder sized material. Core data are not currently available within the coastward portions of these alluviated/fan-delta valleys. It is likely, however, that vertical stratification of coarse- and fine-grained bedded units also occurs here, possibly similar to that present within the South Coast aquifer. Ground water is available locally from volcanic and volcaniclastic, fractured or weathered bedrock, or both, or from caverous limestone sequences that underlie the alluvial sequences.

The estimated hydraulic conductivity for alluvial deposits within the Yauco alluvial valley aquifer ranges from 4 m/d near the coast to 60 m/d in upland channel areas (Bennett, 1976). Estimates based on simulation (Quiñones-Aponte, 1986b) indicate that transmissivity within the Yauco alluvial valley ranges between 1,400 to 2,300 square meters per day (m^2/d) in the upland valley and diminishes down valley. Transmissivity in the midfan and distal part of the fan-delta plain range from less than 10 to 900 m^2/d (fig. 53). If a direct correlation between estimates of specific capacity and hydraulic conductivity is assumed, coarse-grained deposits within the Guayanilla and Macaná fan deltas are probably less permeable. Specific-capacity estimates in the Guayanilla and Macaná alluvial valleys range from 1 to 10 liters per second per meter [(L/s)/m] drawdown as compared to the upstream parts of the Yauco which ranged from 1 to more than 21 [(L/s)/m] of drawdown. Higher conductivities within the Yauco alluvial valley as compared to the Guayanilla and Macaná alluvial valleys are attributed to a slightly larger drainage basin size and the narrower upland channel width. Such features may result in higher floodflow velocities and transport of coarser bedload. The transmissivity of alluvium within the Guánica alluvial valley is reported to range from 100 to 7,500 m^2/d; the hydraulic conductivity of the aquifer is reported to range from 20 to 220 m/d (McClymonds, 1967).

THE PONCE-JUANA DÍAZ AQUIFER

The Ponce-Juana Díaz aquifer is most productive where buried beneath the fan-delta plain near Ponce or beneath alluvium in the Tallaboa-Guánica area. In these areas, alluvium is relatively permeable and recharged with ground water, low in dissolved solids and undersaturated with respect to calcite. Monroe (1976, p. 14) reports that the only part of the Juana Díaz Formation that exhibits karstic dissolution and cave development is within the reef tract sediments of the formation that are south and southwest of Peñuelas. Cavernous limestone was reportedly encountered in wells drilled in proximal and midfan areas of the Portugúez-Bucaná and Capitanejo fan deltas; these permeable limestone units are probably associated with fracturing and jointing of beds by nearby faults. Cavernous limestone porosity also was reported in the Guayanilla-Yauco area; wells that penetrate the limestone strata reportedly yield 8 to 63 L/s (42 L/s average) (Crooks and others, 1968).

Although there are limited occurrences of cavernous limestone reported in some localized areas, extensive dissolution within the Ponce-Juana Díaz aquifer has not developed notwithstanding periods of subaerial exposure from the end of the Oligocene to Holocene time. Frost and others (1983, p. 82) suggest three factors that could have effectively reduced the opportunity for solution diagenesis with the reef deposits of the Juana Díaz Formation: (1) meteoric waters were captured by sandy alluvial and nearshore deposits as they moved downgradient; (2) reef deposits were overlain and diagenetically sheltered by poorly permeable forereef and island slope mud; and (3) lime mud, internal sediment, and cementation reduced the original depositional porosity. Arid to semiarid climatic conditions that have prevailed on Puerto Rico's south coast since Pliocene time could have also contributed to the lack of dissolution within the reef tract deposits of the Juana Díaz Formation. Conglomeratic beds in the Juana Díaz Formation, probably deposited as part of an early Oligocene fan-delta sequence, consist of bedded cobble- to sand-size material. Despite their conglomeratic nature, they are not considered a reliable source of ground water. Intergranular voids of the conglomeratic Juana Díaz Formation are infilled with partially-cemented sand and silt, effectively reducing porosity and permeability within the aquifer. For the most part, limestone strata within the Ponce-Juana Díaz aquifer also do not represent important water-bearing units (K<1.5 m/d). Secondary permeability within the aquifer is only locally well-developed due to dissolution along fracture and fault zones that lie buried beneath unconsolidated clastic deposits of Quaternary age.

THE WEST COAST GROUND-WATER PROVINCE

Sandier beds within silt- and clay-dominated alluvium and minor underlying limestone beds represent the principal water-bearing units within Lajas Valley. Igneous and volcaniclastic bedrock units that extend beneath the valley are poorly permeable; wells located on the valley sides and tapping weathered bedrock are reported to yield about 1 L/s. Irregularly-distributed limestone rock of Cretaceous to Tertiary age exposed in the foothill areas is believed to extend beneath the Lajas Valley

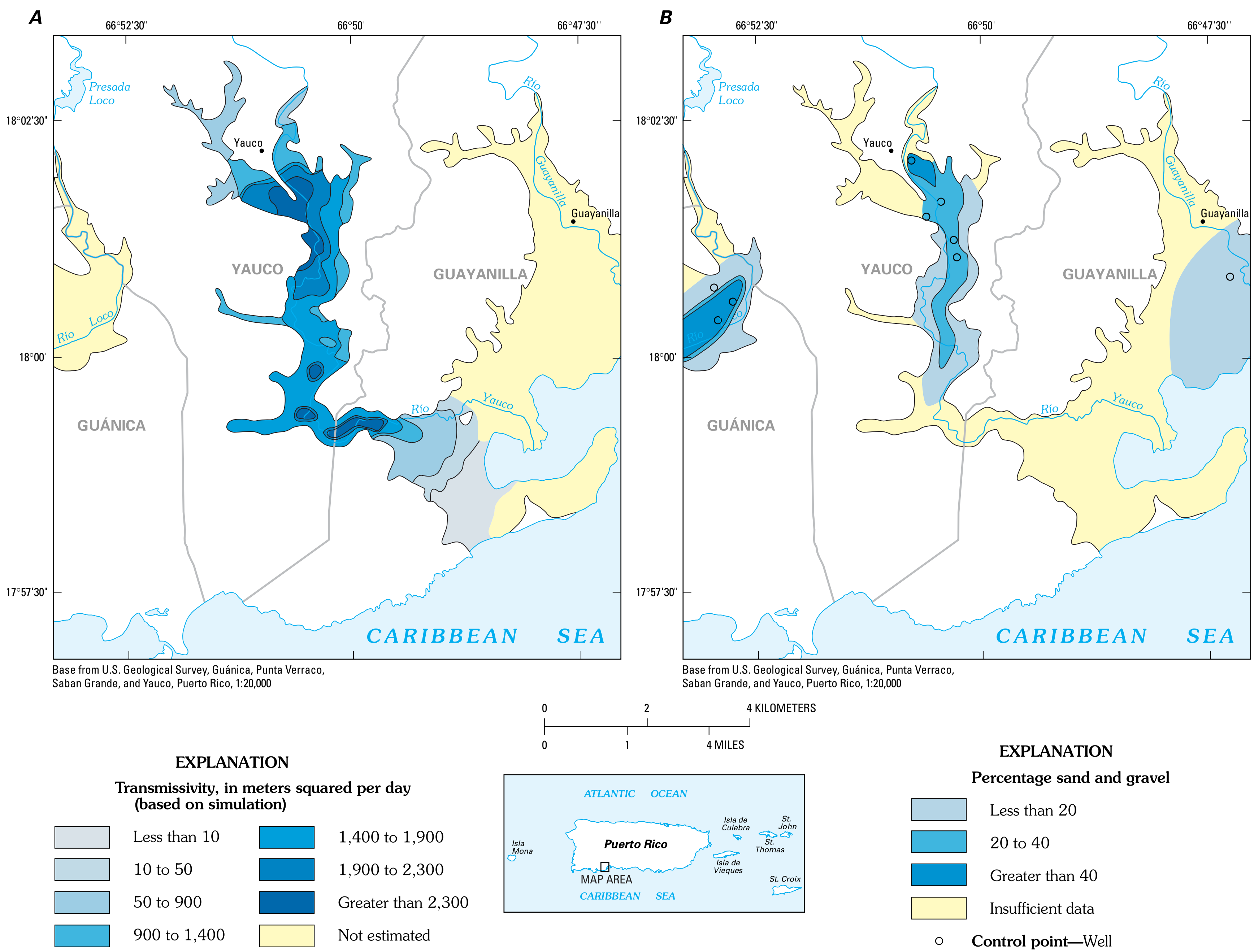


FIGURE 53.—Distribution of transmissivity (*A*) and percentage sand and gravel (*B*) in the Yauco alluvial valley, western south-central Puerto Rico (modified from Quiñones-Aponte, 1986 b).

alluvial cover (Anderson, 1977). This limestone aquifer, which is as much as 12 to 15 m thick, underlies a large area in the central part of Lajas Valley. Eighteen wells tapped the limestone bedrock during the 1920's and 1930's and were reported to yield 30 to 130 L/s; however, these wells were later abandoned due to the toxic effects of mineralized water (greater than 300 mg/L chloride concentration) on crops (Anderson, 1977, p. 32). Ground water within the Lajas Valley aquifer occurs under confined and unconfined conditions. Unconfined conditions generally occur along valley sides where alluvial deposits are most permeable, and the outcropping limestone bedrock has been exposed to dissolution processes. Ground water within the central part of the valley is confined by clayey, poorly permeable, distal fan or lacustrine deposits, or both. Transmissivity is reported to range from 60 to 3,000 m^2/d. Well yields from the alluvial deposits are reported to range from 0.32 to 43 L/s (Graves, 1991), but may yield 10 to 60 L/s where screened in both alluvial and underlying limestone units (Anderson, 1977).

Water-bearing strata within the Añasco alluvial valley aquifer are comprised of sand and minor gravel. However, the Añasco alluvial valley aquifer is poorly permeable and dominated by fine sand- and silt-sized sediment, reportedly yielding less than 9.5 L/s (Díaz and Jordan, 1987). However, an underlying, interlayered limestone-clay sequence also serves as a source of ground water. One well, developed in a 15-m-thick limestone bed having an estimated transmissivity of 200 m^2/d, reportedly yields 32 L/s.

Bedded sand and gravel alluvium and an underlying limestone sequence compose the Guanajibo alluvial valley aquifer. However, fractured andesitic tuff and tuff-breccia along the southwestern edge of the valley also function as important local sources of ground water. The reported transmissivity for wells penetrating both alluvium and limestone ranges from 60 to 560 m^2/d (Colón-Dieppa and Quiñones-Marquez, 1985). Two wells screened in the fractured bedrock aquifer have transmissivities that range from 150 to 1,020 m^2/d. Well performance data indicate that the maximum yield of 7 wells screened in alluvium and limestone ranges from 5 to 70 L/s. Two wells screened in an adjoining fractured bedrock aquifer reportedly yield 12 to 25 L/s.

ALLUVIAL VALLEY AQUIFERS OF THE EAST COAST GROUND-WATER PROVINCE

Coarse-grained (sand- to boulder-size) fanglomerates and alluvial plain deposits function as principal water-bearing units of the East Coast ground-water province. For the most part, East Coast ground-water province alluvial aquifers are unconfined with recharge to the aquifer originating by stream seepage or entering the system through buried, weathered, or fractured bedrock. In coastal areas, discontinuous lenses of coarse sediment are interbedded with less-permeable silt beds. Assuming that areas of greatest hydraulic conductivity reflect highest concentrations of sand and gravel, coarse-grained deposits are probably centered along the axis of the principal streams that drained the valleys.

In the Fajardo area, the most prolific aquifers are located in the upper part of the alluvial valley, where recharge can be induced from flowing streams (Gómez-Gómez, 1987). In the Humacao-Naguabo area, the aquifer is characterized by coarse-grained alluvial valley-fill sediment and an underlying 6-m-thick weathered bedrock zone (Graves, 1989). A weathered bedrock zone underlies alluvial deposits in the Maunabo area, but is relatively thin and not a reliable source of water.

The hydraulic conductivity of Maunabo Valley alluvium reportedly ranges from 30 m/d along the course of the Río Maunabo, to 15 to 23 m/d along its major tributaries (Adolphson and others, 1977). In the Yabucoa Valley, estimated transmissivity of alluvial deposits ranges from 93 to 650 m^2/d with hydraulic conductivity ranging from 3 to 9 m/d. Interstream and colluvial deposits are least permeable (3 m/d). In the Humacao-Naguabo area, aquifer test data collected from two wells screened in the alluvial aquifer indicate that transmissivity of the alluvial aquifer ranges from 56 to 74 m^2/d. The transmissivity of alluvium and underlying fracture weathered bedrock is reported to be 186 m^2/d (Graves, 1989). Transmissivity values were calculated also from specific capacity data for three wells completed in alluvium; on the basis of these data, transmissivity of the aquifer is reported to range from 65 to 140 m^2/d. Specific capacity data were collected from two wells completed in weathered bedrock; transmissivity of the weathered-bedrock aquifer is reported to range from 56 to 84 m^2/d. The hydraulic conductivity of weathered bedrock underlying Maunabo Valley is approximately 1.5 m/d. The clay-and-silt dominated lithology of East Coast ground-water alluvial valley aquifers limits the yield of water to wells. Wells screened in the alluvium of the Humacoa-Naguabo are reported to yield only 2 to 6 L/s with higher yields (as much as 11 L/s) reported in wells completed in alluvium and underlying fractured bedrock. Wells screened in the alluvium of the Maunabo alluvial valley are reported to yield 1.3 to 38 L/s.

ALLUVIAL VALLEY AQUIFERS OF THE INTERIOR GROUND-WATER PROVINCE

Ground water within the Caguas-Juncos alluvial aquifer occurs largely under unconfined conditions and is hydraulically interconnected with streams that cut across the valley (Puig and Rodríguez, 1993). Coarse-grained beds of boulder- to sand-sized deposits function as the principal water-bearing zones in the Caguas-Juncos aquifer. Well yields in the Caguas-Juncos alluvial valley are reported to range from 0.6 to

20 L/s (Puig and Rodríguez, 1993). The transmissivity and hydraulic conductivity of the Juncos valley aquifer is highest along a narrow zone that extends westward from the city of Juncos to the northern edge of the Caguas alluvial basin (fig. 54). The transmissivity of the Caguas aquifer is, in general, less than the Juncos aquifer and is partly be attributed to the aquifer's silt and clay-dominated lithology, but also to its limited thickness. The transmissivity of the Caguas alluvial valley aquifer is reported to average less than 100 m^2/d; the transmissivity of sand- and boulder-size detritus that dominate the Juncos valley aquifer, reportedly ranges from less than 100 to 450 m^2/d.

NORTH COAST GROUND-WATER PROVINCE: THE NORTH COAST LIMESTONE AQUIFER SYSTEM

Platform carbonates and minor clastic rocks that underlie Puerto Rico's northern coastal plain make up the North Coast limestone aquifer system. River alluvium consisting of sand, silt, and clay underlies northward-flowing rivers, forms broad alluvial plains near the coast, and functions as an important local sources of ground water. A minor confining unit comprised of unconsolidated marsh and swamp surficial deposits consisting of clay, silt and fine sand overlies the North Coast limestone aquifer system in some restricted areas near the coast.

The North Coast limestone aquifer system comprises four principal hydrogeologic units that include an upper aquifer, a middle confining unit, a lower aquifer, and a basal confining unit (fig. 55; pl. 5*A*). The highly permeable Aymamón Limestone and the Aguada (Los Puertos) Limestone make up the upper aquifer, whereas the middle confining unit consists largely of the clay and marl contained within the upper part of the Cibao Formation. A lower aquifer, that contains water under confined conditions where buried, consists of carbonate and some clastic rocks of the Montebello Limestone Member, the Lares Formation, Mucarabones Sand, and in updip areas, water-bearing sand and conglomeratic beds of the San Sebastián Formation and the Quebrada Arenas and Río Indio Limestone Members. The lower confining unit consists of mudstone, siltstone, marl, and poorly permeable limestone of the San Sebastián Formation buried in the deep subsurface. In updip areas and to the east, where the lower aquifer grades to more permeable clastic beds of the San Sebastián Formation and Mucarabones Sand, lithified volcaniclastic rocks and minor igneous rocks of Cretaceous and early Tertiary age form the basal confining unit.

The first regional evaluation of ground-water resources in the North Coast limestone aquifer system was conducted by McGuinness (1948) as a part of a reconnaissance study of the island. With the exception of work by Guisti (1978) and Heisel and others (1983), subsequent studies of Puerto Rico's North Coast Limestone aquifer system have focused primarily on hydrologic conditions in localized areas. Region wide pre-development and development (1980-1990) potentiometric maps showing hydrologic conditions within the upper and lower aquifer were only recently published (Renken and Gómez-Gómez, 1994).

Exploratory drilling near Barceloneta in 1968 first confirmed the occurrence of a lower limestone aquifer that contains freshwater under artesian conditions. Discovery well Abbott 1 was drilled principally for the purpose of disposing industrial wastes into underlying limestone strata thought to contain saltwater; however, a fresh water-bearing limestone unit was encountered at 350 m below land surface. Other wells have been completed in the lower aquifer, primarily to provide water for Puerto Rico's pharmaceutical industry. Twelve industrial wells and 3 public supply wells were withdrawing water from the confined system by 1987. In the shallower, updip, unconfined parts of the lower aquifer near the town of Florida and barrio Montebello, 21 public supply wells were withdrawing water in 1987. Twenty-three wells located west of the Río Grande de Arecibo and east of the Río Grande de Manatí areas were also withdrawing water from the lower aquifer.

In 1986, an exploratory drilling program was initiated as part of a cooperative program between the U.S. Geological Survey and the Commonwealth of Puerto Rico (Torres-González and Wolansky, 1984). A major purpose of the drilling project was to evaluate the lithologic and hydraulic character of the limestone sequence, to delineate the geographic extent of confined conditions within the lower aquifer, and to define the water-quality of water-bearing units. As part of this exploration program, seven wells were cored continuously, penetrating the upper and lower aquifer; subsequently, eight additional wells were drilled.

OCCURRENCE AND MOVEMENT OF GROUND WATER

Diffuse fluid flow is the primary mechanism of ground-water movement within the poorly consolidated to unconsolidated clastic deposits that compose the principal aquifers of the southern, eastern, western, and interior ground-water provinces of Puerto Rico. In diffuse fluid flow, the movement of water is contained within, and flows through, the small intergranular pores that exist within the rock. The movement of ground water within carbonate rocks is not, however, restricted to diffuse movement. Flow within carbonate aquifers can range between the two end members, diffuse and conduit (or concentrated) flow. The movement of ground water within conduit-flow aquifers occurs within large openings formed along bedding planes, fractures, joints, and faults.

Bennett and Guisti (1972) and Guisti (1978) inferred that ground-water flow within limestone rocks of northern Puerto Rico largely occurred through a system of closely spaced

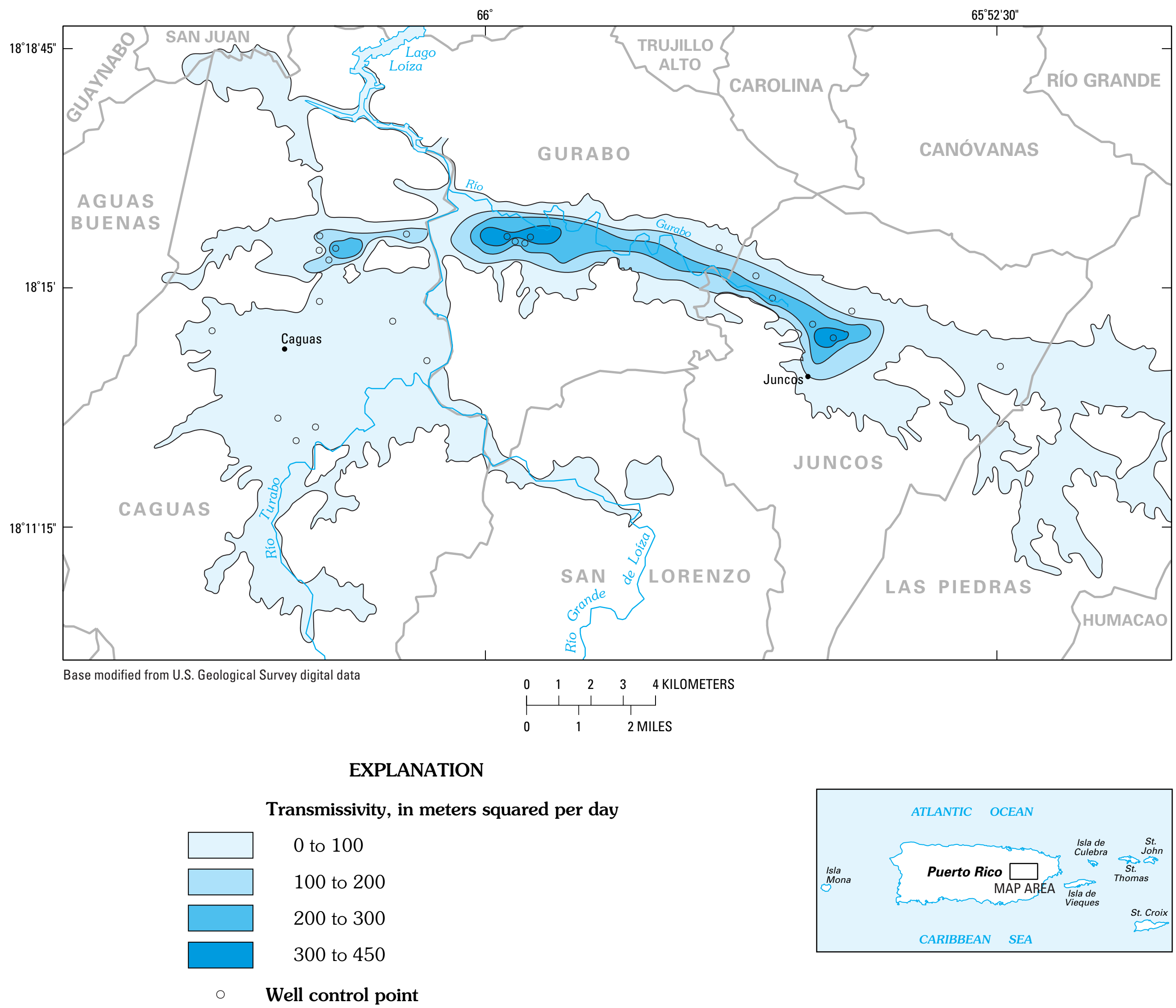


FIGURE 54.—Distribution of transmissivity in the Caguas-Juncos alluvial valley aquifer (modified from Puig and Rodríguez, 1993).

conduits. Their interpretation was based on previously published geologic work, their own study of outcropping limestone rocks that compose principal water-bearing zones, and the observation that numerous springs served as primary points of discharge from the North Coast limestone aquifer system. According to their conceptual model, ground-water movement occurred along preferential flow paths that included bedding planes, vertical fractures, joints, faults (if present), and “pipes”, all of which had expanded in varying degrees by chemical dissolution. Thus, according to their interpretation, the North Coast limestone aquifer system can be viewed as a honey-combed system of solution openings and subterranean caves that combine to form a highly permeable, conduit flow system. Bennett and Guisti (1972) envisioned a hydrologic framework in which solution passageways that served as conduits were of a sufficient density and close spacing so that, for the purpose of simulating ground-water flow, assumptions of diffuse flow were acceptable.

The movement of ground-water within karstic aquifer systems of relatively young rock (in a geologic sense) commonly is not limited to conduit flow. Diffuse and conduit flow occurs within the Floridan aquifer system (U.S.A.) and the Yucatan aquifer (Mexico) that are comprised largely or entirely of Tertiary rocks (Thrailkill, 1976, p. 759). Like the Floridan and Yucatan aquifers, conduit and diffuse-carbonate ground-water flow occurs within the North Coast limestone aquifer system. Diffuse-carbonate flow occurs largely occurs

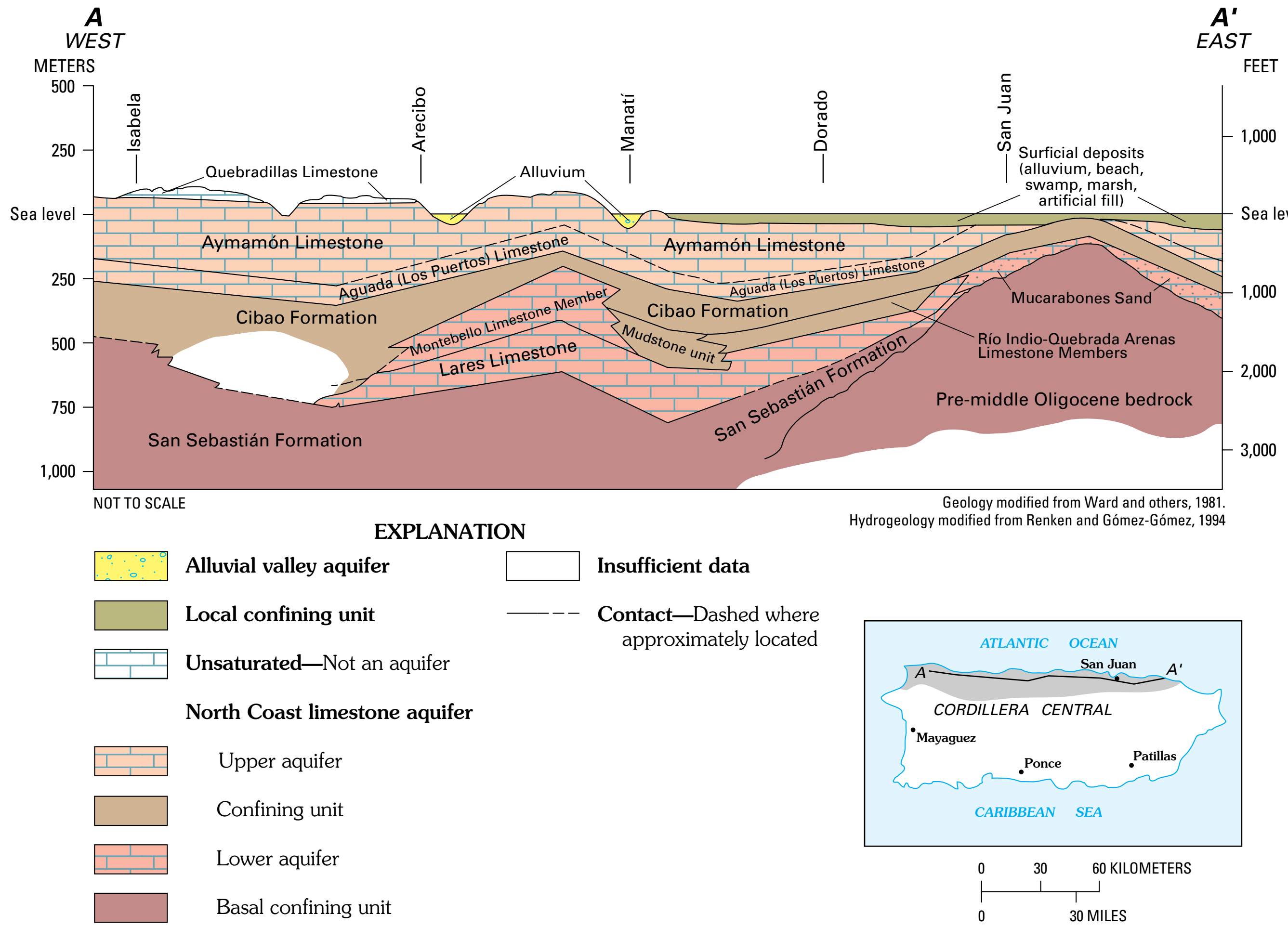


FIGURE 55.—Diagrammatic section A–A' showing principal aquifers and confining units of the North Coast limestone aquifer system (geology modified from Ward and others, 1991; this report).

within intergranular pores contained within bedded grainstone-packstone layers, moldic and intercrystalline pores of thin, dolomitized, coral-rich grainstone-packstone and boundstone layers, and coral-patch reef limestone (Ward and others, 1990, this report). In northern Puerto Rico, conduit flow is generally associated with a poorly defined system of solution-enhanced vugs and fractures within the upper aquifer (Aymamón Limestone and Aguada (Los Puertos) Limestone) and large cave systems contained within the lower aquifer (Lares Limestone). Large cave systems represent major ground-water drains, especially in areas where the lower aquifer crops out.

Topographic relief and incision of carbonate coastal plain rocks by streams are the principal factors that control the direction of ground-water flow in areas of outcrop of the upper and lower aquifer. Areas that have a high potentiometric surface generally correspond to areas of elevated topography and are principal sites for ground-water recharge. Areas that have a low potentiometric surface generally correspond to areas of low topography and commonly are sites of ground-water discharge. Under predevelopment conditions, large rivers, subterranean cave systems, springs, and coastal wetland areas were the principal areas of ground-water discharge. Major rivers of Puerto Rico's North Coast ground-water province that gain flow due to regional ground-water discharge include, from west to east, the Ríos Culebrinas, Guajataca, Camuy, Tanamá, Grande de Arecibo, Grande de Manatí, Indio, Cibuco, and de la Plata. Under present-day conditions (1980-90), well withdrawals and agricultural drainage also represent important mechanisms of ground-water discharge.

Well-completion records and other geologic data indicate that northward-flowing rivers were deeply incised during low-stands of Pleistocene sea level. Mechanical erosion of the coastal plain by fluvial processes may have been extensive enough to have breached middip parts of the middle confining unit. These deeply incised areas are covered by thick alluvial deposits that were deposited by channel aggradation in response to interglacial sea level rise (fig. 56). The large rivers of the North Coast ground-water province are the principal sites of discharge from the lower aquifer. It is postulated that ground water is probably discharged from the lower aquifer upward to large springs within these valleys, or into overlying alluvium that covers the breached part of the middle confining unit, or both (Renken and Gómez-Gómez, 1994) (fig. 57).

Major springs that produce water from the North Coast limestone aquifer system are described by Guzmán-Ríos (1988). These and other North Coast springs are listed in table 1; however, this table is not considered a complete list of all North Coast springs. Other springs could be present, but are difficult to locate as a result of extensive vegetative cover and limited access. No first-order springs (discharge more than 2,800 L/s) are in the North Coast limestone aquifer system, but numerous second- (280 to 2,800 L/s) and third-order (30 to 280 L/s) springs are. One of the two largest springs that produce from the lower aquifer, the Aguas Fría, is the point where discharge from the Río Encantado cave system surfaces. Between December 1982 and January 1984, instantaneous discharge measurements at this spring ranged from 150 to 312 L/s. The other large spring, the San Pedro, is a second- to third-order spring along the Río Grande de Arecibo. Discharge measurements at this spring ranged from 135 to 1,530 L/s between June 1983 and June 1984 (Guzmán-Ríos, 1988). The San Pedro spring probably discharges from the Montebello Limestone Member, which is the most permeable part of the lower aquifer. A dye-trace study in the Río Tanamá Basin area indicates there is loss of the water from that river to the aquifer with subsurface movement of the water to the San Pedro spring located on Río Grande de Arecibo (Jordan, 1970, p. 17). Two large springs (la Cambija and Zanja Fría) that discharge from the upper aquifer are located in the Caño Tiburones area. These two springs are considered to be second- to third-order springs with discharge from la Cambija reported to be as much as 566 L/s (Zack and Class-Cacho, 1984). However, most springs that discharge water from the upper aquifer are third- (30 to 280 L/s) or fourth-order (6 to 30 L/s) springs. Similarly, most freshwater and saltwater springs and seeps located in the Caño Tiburones, which is an area of upper aquifer ground-water discharge, are classified as third- or fourth-order springs.

ALLUVIAL VALLEY AQUIFERS AND LOCAL CONFINING UNITS

Wide, low-lying alluvial plains have formed near the mouths of the large, perennial, northward-flowing rivers that transverse the North Coast ground-water province. Large alluvial plains are associated with the Ríos Grande de Arecibo, Grande de Manatí, de la Plata, and Bayamón. These alluvial deposits are comprised largely of sand, silt, clay, and minor gravel deposits and function as important local aquifers. However, only limited information is available regarding the extent and the distribution of coarser sediment within these aquifers. In the lower reaches of the Río Grande de Arecibo Valley, the average thickness of alluvial deposits is 40 m and an extensive clay layer within the alluvial aquifer tends to separate it into upper and lower water-bearing units. Deposits exceed 90 m at the river's entrance into a narrow, incised upland channel (fig. 58). Coastal reaches of the Río Grande de Manatí alluvial valley also contain relatively thick deposits of alluvium. Deposits locally exceed 80 m in thickness and consist of fine sand, silt, clay, and minor lenses of fine to medium gravel.

Marsh and swamp deposits are in many coastal areas of the North Coast ground-water province and consist of sandy clay, sandy mud, and clayey sand. Although the thickness of these deposits has not been well-mapped, they function locally as a confining unit.

Ground water occurs largely under unconfined conditions within alluvial valley aquifers of Puerto Rico's North Coast and often the aquifer is hydraulically interconnected to underlying carbonate strata of the upper limestone aquifer. Recharge to the alluvial aquifer is possible by stream seepage, infiltration of precipitation, or from the movement of ground water from the underlying and adjoining upper limestone aquifer. In most circumstances, the streams act as a drain for the regional flow system; however, some recent investigations indicate that, in places, the Ríos Grande de Arecibo, Tanamá, and Cibuco lose surface flow to the aquifer (Quiñones-Aponte, 1986a; Gómez-Gómez and Torres-Sierra, 1988). Discharge from the alluvial aquifer occurs by ground-water flow to the sea and nearby coastal lagoons, by well withdrawals, and by evapotranspiration.

The hydraulic conductivity of the Arecibo and Manatí alluvial valley aquifers are reported to range from 6 to 12 m/d (Quiñones-Aponte, 1986a; Gómez-Gómez and Torres-Sierra, 1988). The transmissivity of the Río Cibuco and Río de la Plata alluvial valley aquifers is estimated to range from 10 to 1,000 m^2/d (Torres-González and Díaz, 1984).

UPPER AQUIFER

The upper aquifer is made up of carbonate strata that are part of the Aymamón Limestone, the underlying Aguada (Los Puertos) Limestone, and in some areas of the North Coast ground-water province, the uppermost clastic beds of the Cibao Formation. The Quebradillas Limestone, a foraminiferal-algal limestone, crops out and overlies the Aymamón Limestone along a narrow belt that extends 60 km westward from the Río Grande de Arecibo to Punta Borinquen in the northwestern corner of Puerto Rico. The Quebradillas Limestone is not considered an important part of the upper aquifer, because its lower contact generally lies above the water table.

The upper aquifer is subaerially exposed in most of the study area. It has been subject to extensive karstification and is riddled with numerous solution passages. Precipitation,

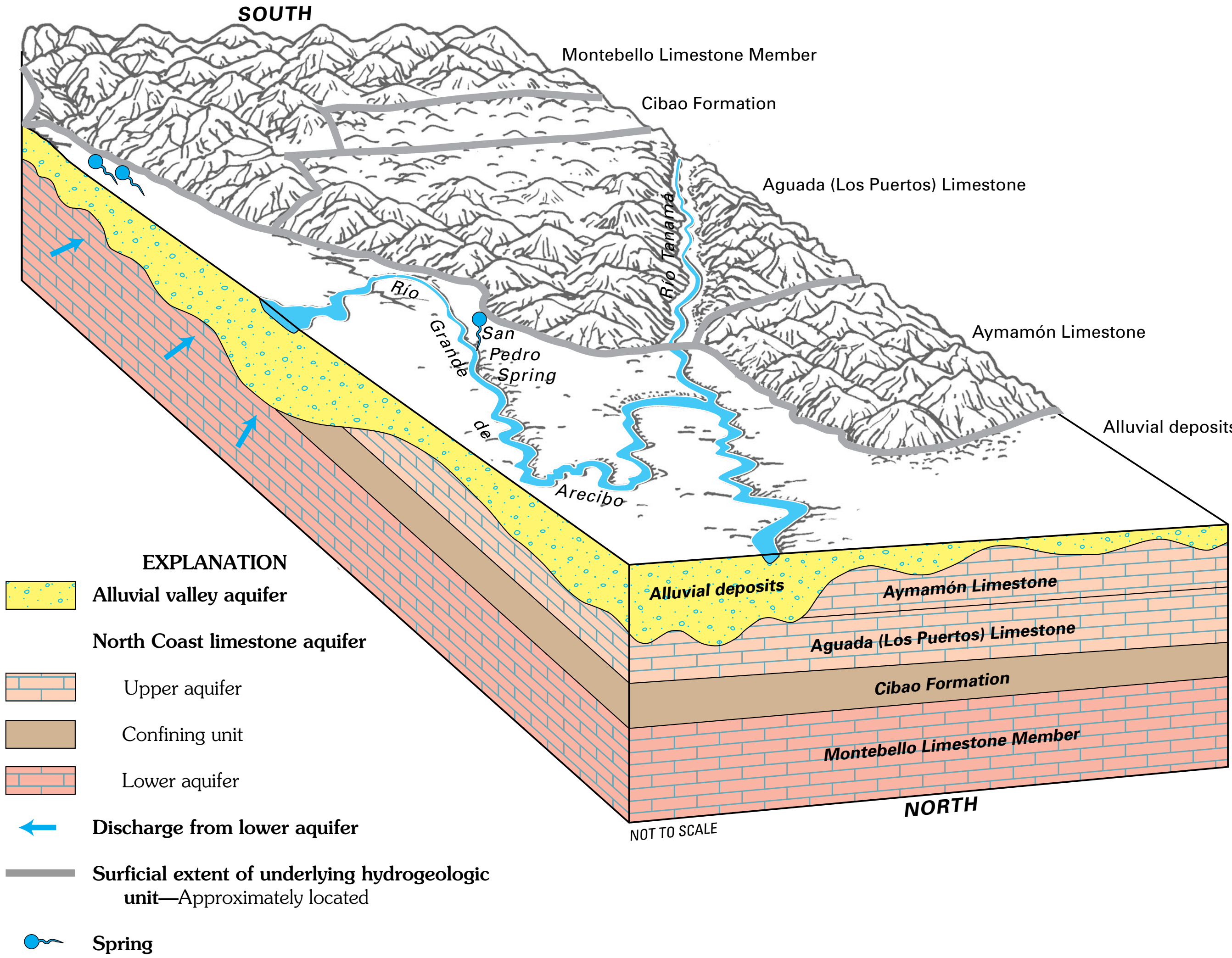


FIGURE 56.—Area of probable discharge from lower aquifer to the alluvial aquifer in the Río Grande de Arecibo valley, northern Puerto Rico (modified from Renken and Gómez-Gómez, 1994).

which is the ultimate source of water to the North Coast limestone aquifer system, enters the upper aquifer by infiltrating through the overlying surficial deposits or as runoff that enters the system directly through karstic conduits (sinkholes, dolines, dry valleys, and zanjones). Unconfined ground-water conditions within the upper aquifer are pervasive in most of the North Coast area with confined conditions present where the aquifer extends beneath poorly permeable clayey sand, silt, clay, and clayey mud deposited along marshy coastal areas. Water that enters the unconfined flow system of the upper aquifer flows northward toward the Atlantic Ocean and discharges to wetlands along the coast; to coastal, near-shore and offshore springs; or to the ocean as diffuse seabed seepage. Ground water is discharged also along the inland reach of north-flowing rivers.

Regional synoptic measurement of water levels in the upper and lower aquifers has never been conducted within the North Coast ground-water province. However, a potentiometric surface map that shows the ground-water conditions in the late 1960’s was presented by Guisti (1978). Unfortunately, Guisti’s maps did not separate the flow system into upper and lower aquifers.

The reader is cautioned to interpret potentiometric maps of the North Coast limestone aquifer system shown herein and in Renken and Gómez-Gómez (1994) with care; some of the maps are based on water-level measurements made over a long period of time and, in some instances, in wells installed in different stratigraphic horizons within the aquifer. Despite these limitations, the maps are considered to be reasonable estimates of regional predevelopment hydrologic conditions for the lower aquifer and postdevelopment conditions in for the upper and lower aquifers. Seasonal water-level fluctua-

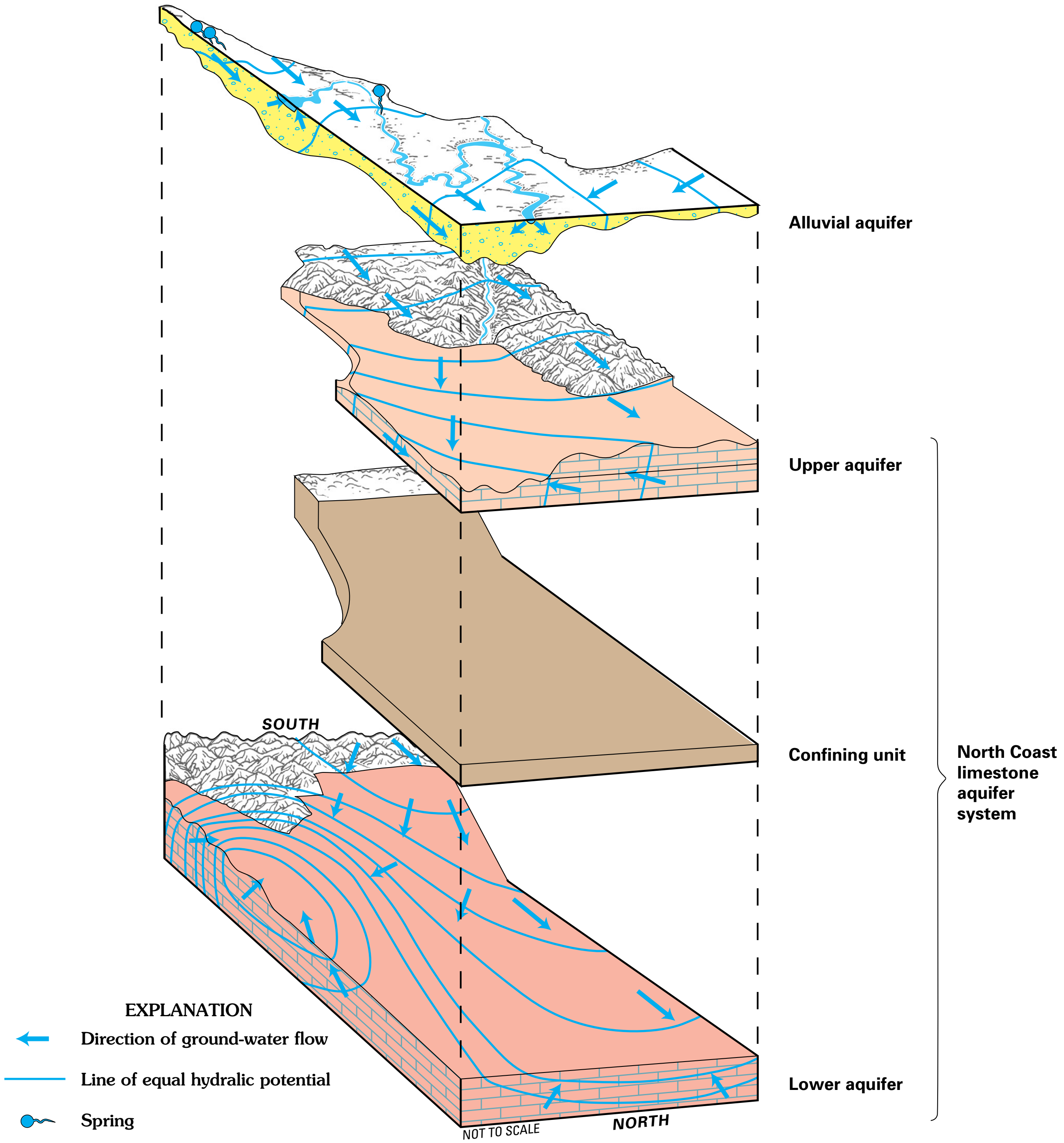


FIGURE 57.—Exploded view of aquifers in the Rio Grande de Arecibo valley and patterns of ground-water flow, northern Puerto Rico (modified from Renken and Gómez-Gómez, 1994).

tions are small in many wells that are cased in the aquifer system (Torres-Gonzáles, 1991), and stress on the system due to pumping is largely restricted to certain areas of the North Coast. Water-level measurements used to draw the development potentiometric-surface map for the upper aquifer (pl. 5*B*) were collected between 1980 and 1990 and are considered to be a reasonable representation of conditions during 1987, when most of the measurements were collected for the lower aquifer. Data were not available to construct a regionwide predevelopment map of the upper aquifer because development of the upper aquifer preceded hydrologic data collection efforts in Puerto Rico by the U.S.G.S. In

Table 1. Principal springs within the North Coast limeston aquifer system

[Data from Persious (1971), Gómez-Gómez (1984), Quiñones-Aponte (1986), Gómez-Gómez and Torres-Sierra (1988), and Guzmán-Ríos (1988). Spring order (Meinzer, 1927) refers to discharge; 2nd order, 280 to 2,800 L/s; 3rd order, 30 to 280 L/s; 4th order, 6 to 30 L/s; 5th order, .6 to 6 L/s]

Spring number	Spring name	Spring order
	Upper aquifer	
1	Maguayo spring near Dorado	3rd-4th.
2	Ojo de Agua spring at Vega Baja	Do.
3	Ojo de Agua Guillo spring near Manatí	3rd.
4	Palo de Pana and Mamey spring	4th.
5	Isadora spring	Do.
6	La Cambija spring at Caño Tiburones	2nd.
7	Zanja Fría at Caño Tiburones	2nd-3rd.
8	El Dique spring near Río Tanamá	4th.
9	Sonadora spring near Camuy	4th-5th.
10	Tiburón spring near Camuy	4th.
11	Sumbadora spring at Los Puertos near Camuy	Do.
12	Ojo de Agua spring at Aguadilla	3rd.
13	Nearshore, offshore, and shoreline springs	Do.
a	Borinquen Beach	
b	U.S. Coast Guard lighthouse	
c	Colonel B. Smith's house	
14	Unnamed spring near Río Cibuco	No information.
15	Ojo de Valencia near Municipio de Moca	Do.
	Lower aquifer	
1	Ojo de Agua at Torrecillas near Morovis	5th.
2	Represa Sonadora de Ciales at Ciales	3rd-4th.
3	Aguas Frías spring near Ciales resurgence of Río Encantado	2nd-3rd.
4	San Pedro spring near Río Arecibo	Do.
5	Hato Viejo spring near Río Arecibo	4th.
6	Zanja spring	No information.
7	Los Chorros spring near Dos Bocas dam	3rd-4th.
8	Unnamed spring along Río Tanamá	Do.
a		3rd.
b		Do.
9	Salto Collazo spring near San Sebastián	Do.

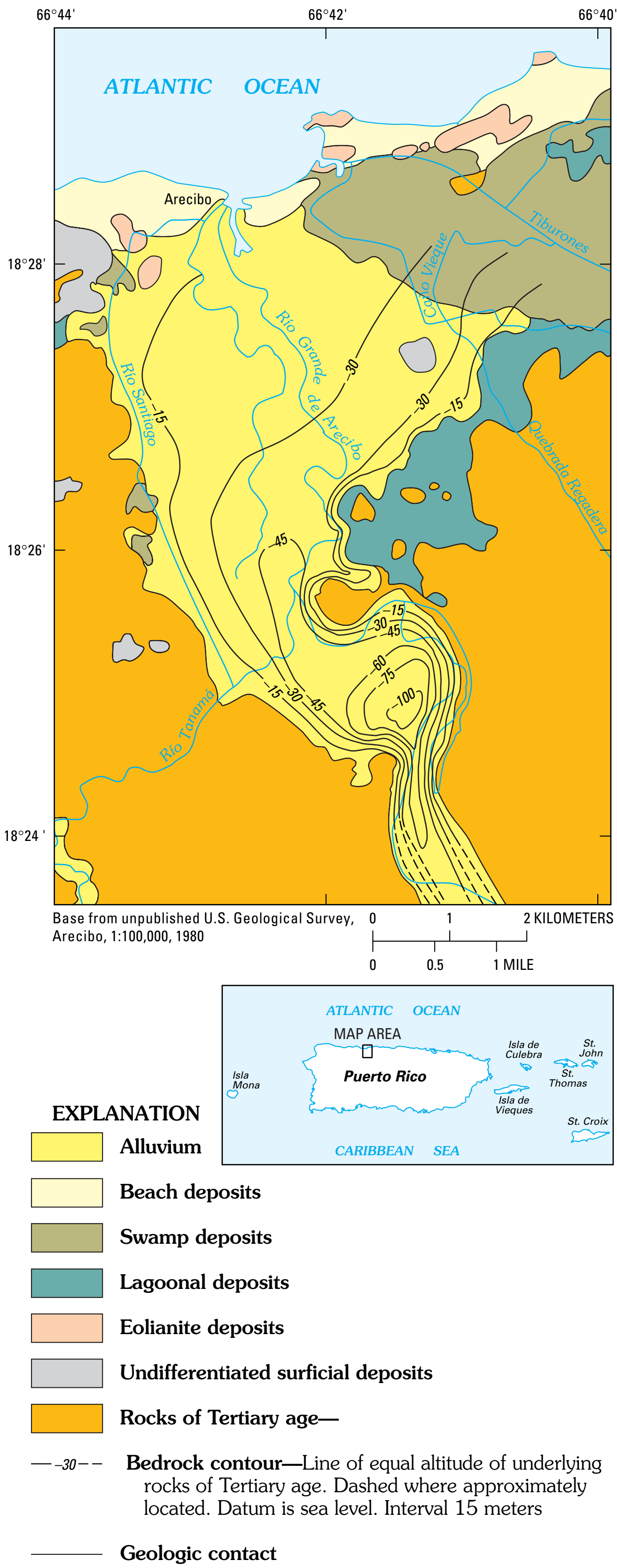


FIGURE 58.—Basal configuration of Arecibo alluvial valley aquifer, northern Puerto Rico (modified from Quiñones-Aponte, 1986a).

some areas, agricultural dewatering and pumping of wells caused change in upper aquifer water levels as early as 1909 (Zack and Class-Cacho, 1984).

A potentiometric map of the upper aquifer (Renken and Gómez-Gómez, 1994), which is based on water-level measurements made between 1980 and 1990, shows that principal recharge areas are in topographically elevated, inland parts of the aquifer (pl. 5*B*). Limited water level data are available for the southernmost areas underlain by the upper aquifer, which creates some uncertainty regarding the altitude of the potentiometric surface in these areas (pl. 5*B*). East of Río Grande de Arecibo, the landwardmost contour is 30 m above sea level. Additional data are needed to accurately assess the occurrence of water in the upper aquifer within upgradient areas; however, ground water may occur at higher altitudes as a thin freshwater lens or saturated zone located at the base of the aquifer.

Only limited water-level data are available for the upper aquifer in areas east of the Río Bayamón. Future groundwater development in the Metropolitan San Juan area is limited by an upper aquifer that is thin or may be entirely absent in some areas (fig. 55; pl. 5*A*) and is reported to mostly contain brackish or saline water.

Marl, mudstone, and clayey wackestone of the middle confining unit that separates the upper and lower aquifers grades by facies change to terrigenous sediments in the Metropolitan San Juan area. These sediments, which include sandstone and sandy limestone, are more permeable and permit greater hydraulic interconnection between the two aquifers. Sparse hydrologic and geologic control in Metropolitan San Juan limit detailed mapping of water levels in the area. The configuration of the lower and upper potentiometric surfaces in this area were assumed to be similar in form; it seems likely that there is potential for upward ground water discharge from the lower aquifer to upper aquifer (compare pls. 5*B* and 5*C*).

East of the Río Grande de Arecibo, the upper aquifer discharges ground water mainly to springs and coastal wetland areas. West of the Río Grande de Arecibo, the aquifer discharges to wetland areas near the shoreline; to nearshore, offshore, and shoreline springs such as those located along the northwest coast of the island (Percious, 1971); or to the ocean as seabed seepage. Future investigations could focus on identifying other coastal freshwater springs that may lie offshore. Percious (1971) suggested the possibility of offshore spring discharge at three site—one near the western end of Punta Peñón, one near the inlet at Hatillo, one near and off the point near the Río Guajataca (known locally as El tunel).

Contours on the upper aquifer potentiometric-surface map (pl. 5*B*) curve upstream in many interstream areas; ground water discharges along inland, upstream reaches of rivers and streams that include the Ríos Guajataca, Camuy, Tanamá, Grande de Arecibo, Grande Manatí, Cibuco, and de la

Plata. Near the coast, however, some rivers lose water to the upper aquifer during most of the year (Quiñones-Aponte, 1986, p. 26). Simulation of ground-water movement in the lower Grande de Arecibo valley indicates that ground water discharges from the upper aquifer along the western limestone channel bank and moves across a highly stratified alluvial aquifer. Ground water reenters the upper aquifer along the eastern margin of the alluvial valley (Quiñones-Aponte, 1986, p. 24). Stratification of the alluvial aquifer by clay and silt in the lower reach of the Río Grande de Arecibo valley has resulted in local confinement of the upper limestone aquifer. Movement of water from the aquifer to the river and back into the aquifer and the northward and northeastward direction of regional ground-water flow toward Caño Tiburones is illustrated in plate 5B. Local confinement of alluvium and the underlying upper aquifer also helps explain why lines of equal hydraulic head on the potentiometric-surface maps do not show strong hydraulic interconnection between the upper aquifer and the river. Simulation of ground-water flow near the Río Cibuco indicates that the river could contribute as much as 15 percent of the water that enters the aquifer in that area (Gómez-Gómez and Torres-Sierra, 1988).

Ground water does not discharge to the upper reaches of all major rivers that traverse the upper aquifer. For example, water-level measurements and streambed altitude data indicate that there is limited ground water discharge along a reach of the Río Camuy. Similar hydrologic conditions could exist along the Río Guajataca. The Quebrada de los Cedros, which is in the northwestern part of the study area, is an ephemeral stream. The water table in the basin lies below the streambed much of the area. In areas of northwestern Puerto Rico drained by such streams, regional ground-water discharge from the upper aquifer probably is to the ocean or springs, rather than to streams (Guisti and Bennett, 1976, p. 27).

The potentiometric surface of the upper aquifer has one large and one small potentiometric depression (pl. 5*B*). The large depression, which extends over an area of 36 km^2, is in the swampy coastal depression at Caño Tiburones is located between the Ríos Grande de Arecibo and Grande de Manatí. The smaller, but locally significant potentiometric depression (also shown in pl. 5*B*) is the Colonia Combate-Colonia Coto Sur area, which is located about 6.1 km south of Laguna Tortuguero.

Caño Tiburones is the site of a former shallow brackish water coastal lagoon that accumulated freshwater from adjacent springs and rivers. Under natural conditions, Caño Tiburones drained to the ocean by subterranean caverns and conduits. Before agricultural devel-opment of the area (1909), saltwater entered the lagoon during high tides or by up-stream migration during periods of low flow. The large present-day (1980-90) potentiometric low at Caño Tiburones is attributed to agricultural dewatering. Drainage of the area for agriculture contributed to soil shrinkage and land subsidence and gradually lowered the water table to sea level. By 1949, gravity drainage became less effective and a drainage system of canals, laterals, tidal gates, and coastal pump stations had been installed to lower water levels to below sea level. Spring-head levels of 0.6 m below sea level in this area have been reported by Zack and Class-Cacho (1984). One major side-effect of lowering the water levels to below sea level was that it reversed the local hydraulic gradient and caused intrusion of seawater into Caño Tiburones. Much of this seawater intrusion was the result of seawater moving into the aquifer through caverns that had previously drained freshwater to the sea.

In 1987, ground-water withdrawals of near 7,570 m^3/d concentrated in a 5.2 km^2 area at the Colonia Combate-Colonia Sur location locally lowered the potentiometric surface below sea level (U.S. Geological Survey, unpub. data, 1993). Three pumped wells in this area were abandoned in 1989 because they yielded water with a nitrate-nitrogen concentration that exceeded 10 mg/L. Before 1989, the depression in the potentiometric surface at this site may have been as much as 3 m below sea level.

Freshwater within the upper aquifer is underlain by a basal zone of salt water along the coastal margins of the North Coast ground-water province. This saltwater zone can extend up to 7 km inland of the Atlantic Ocean coastline (pl. 5*E*).

The thickness of the freshwater lens was, in part, determined following the approach described and applied to the South Coast aquifer. However, the specific conductivity of ground water in the upper aquifer was measured in selected wells at different depth intervals (Gómez-Gómez, written commun., 1993) and served as principal control points. The thickness map was constructed by comparing the saltwater interface depth map (ground-water with estimated dissolved solids exceeding 35,000 mg/L) with the map that shows the average potentiometric surface between 1980 and 1990 (Renken and Gómez-Gómez, 1994).

Within the homoclinal, seaward-thickening wedge of permeable stratum, the thickest part of a freshwater lens generally lies along a zone where the landward limit of the freshwater-saltwater interface intersects the base of the aquifer. In northern Puerto Rico, this area generally coincides with the interstream areas that lie between several major rivers that include the Ríos Grande de Arecibo, Grande de Manatí, and de la Plata (exceeding 100 m). The thickest parts of the lens appear to lie between the Río Grande de Arecibo and the westernmost coastline of Puerto Rico (exceeding 150 m thickness). East of the Río de la Plata, the freshwater lens is thin or absent; the upper aquifer is reported to locally contain brackish water in metropolitan San Juan.

MIDDLE CONFINING UNIT

The middle confining unit extends throughout the North Coast ground-water province (pl. 5*F*) and consists largely of marl, calcareous mudstone, and clayey wackestone and wackestone-packstone of the Cibao Formation. The top of the middle confining unit generally conforms the position of the contact between the Aguada (Los Puertos) Limestone and the Cibao Formation and is shown as such in figure 55 and plate 5A. However, the top of the confining unit may lie below a 5 to 30 m thick layer of dolomitic limestone and dolomite that represent the uppermost beds of the Cibao Formation. In the Isabella-Hatillo area, the top of the confining unit is similarly difficult to define, but may coincide with the lowermost boundary of a karstic zone that is located within the lowermost Aguada (Los Puertos) Limestone and generally considered to be the base of the upper aquifer. Additional hydrologic data are needed to better define the relation between the hydrogeologic and rock-stratigraphic boundaries.

West of the Río Grande de Arecibo, the Montebello Limestone Member and Lares Formation grade to poorly permeable, red algal wackestone and minor packstone that is lithologically indistinguishable from the Cibao Formation. Here, the base of the middle confining unit is difficult to determine. Whereas underlying strata are poorly permeable, they locally contain minor water-bearing zones separated by less permeable strata. A minor water-bearing zone is contained within the confining unit in an area that extends from Arecibo to Vega Alta and could be equivalent to the Quebrada Arenas Limestone Member. Permeable wackestone-packstone of the Montebello Limestone grade to a less permeable clay, marl, mudstone, and siltstone sequence in the Río Grande de Manatí and Río Cibuco area. Here, the bottom of the middle confining unit occurs at the base of the mudstone unit. In the Manatí-Vega Baja area, the middle confining unit includes subsurface rocks that are part of the Quebrada Arenas and Río Indio Limestone Members. The same limestone strata could be part of the lower aquifer where they crop out or lie in the shallow subsurface. The contact between the Cibao Formation and the Lares Limestone conforms well with the middle confining unit's lower boundary in the areas east of the Río Cibuco and with the Cibao Formation and Mucarabones Sand Member east of the Río Bayamón. Additional well data are needed to more fully understand the character, thickness, and extent of the middle confining unit, particularly in the western part of the North Coast ground-water province.

Hydrologic data suggest that the middle confining unit is leaky in restricted updip localities (Renken and Gómez-Gómez, 1994). This is probably due to two factors. In these areas, the confining unit, which is the Cibao Formation, consists primarily of poorly permeable clay, marl, and mudstone that interfingers with comparatively permeable siliciclastic and limestone strata, thereby increasing vertical hydraulic conductivity. The second geologic factor relates to a poorly defined fracture system (Ward and others, 1990; Ward, this report). In areas where the Cibao Formation lies near the surface, fractures are more likely to be open and more numerous. In the deeper subsurface, they tend to be closed due to lithostatic pressure caused by the weight of overlying rock and soil. The confining unit is entirely absent at outcrop between the Ríos Grande de Arecibo and Grande de Manatí due to a facies change. Here, the clay, marl, and mudstone confining unit grades to the Montebello Limestone Member that forms part of the lower aquifer. However, the effectiveness of the confining unit can be readily demonstrated in middip and downdip areas where the difference between potentiometric heads of the upper and lower aquifers locally exceeds 90 m.

LOWER AQUIFER

Ground water within the lower aquifer occurs under confined and unconfined conditions. Unconfined conditions occur where the principal carbonate-rock units that make up the aquifer crop out or lie in the shallow subsurface. Confined conditions occur in areas where the aquifer extends northward and dips beneath the Cibao Formation's poorly permeable claystone, wackestone, and marl that are a major part of the middle confining unit.

The lower aquifer includes skeletal wackestone-packstone and foraminiferal-red algal packstone-grainstone of the Montebello Member, dolomitic red algal *Lepidocyclina* packstone and wackestone of the Lares Limestone, and in some updip northwestern localities, conglomeratic sandstone of the San Sebastián Formation. The lower aquifer may include rocks of the Río Indio and Quebrada Arenas Limestone Members that crop out or lie in the shallow subsurface. To the east, the lower aquifer includes sandstone, conglomerate, siltstone, and silty clay of the Mucarabones Sand. Marl and claystone of the lower part of the Cibao Formation and the upper Lares Limestone grade into the Mucarabones Sand, which becomes part of the lower aquifer in those subsurface areas that lie east of the Río de la Plata and where it crops out east of Río Grande de Manatí. This change in lithofacies also occurs to a limited extent in the upper part of the Cibao Formation and could account for greater upward leakage from the lower aquifer. The lower aquifer's freshwater lens probably does not extend much beyond the Río Piedras to Carolina area of metropolitan San Juan where it becomes poorly permeable and contains water of poor quality farther eastward.

In deep subsurface areas west of the Río Grande de Arecibo, the stratigraphic and hydraulic nature of the lower aquifer is increasingly complex. East of the river, the lower aquifer consists of the Montebello Limestone Member and the Lares Limestone. West of the river, the aquifer grades by facies change to poorly permeable wackestone, wackestone-packstone, and minor dolomite. Here, the lower aquifer is discontinuous and probably is made up of several different water-bearing zones that are restricted in areal extent. Therefore, the boundary of the lower aquifer can not confidently be extended westward very far beyond the NC 6 deep test well in section *A–A´* (fig. 55; pl. 5*A*).

The Lares Limestone does crop out and is thought to underlie the extreme updip, shallow subsurface areas west of the Río Grande de Arecibo before it pinches out or grades westward and northward to less permeable rocks, or both. In updip areas, the lower aquifer includes water-bearing rocks of the Lares Limestone, but also contains local beds of sand, sandstone, and conglomerate of the San Sebastián Formation. Downdip in this area, the Lares Limestone grades into the lower part of the Cibao Formation.

Water level measurements of wells completed in the lower aquifer were used to construct potentiometric-surface maps that show predevelopment (pl. 5*C*) and 1987 (pl. 5*D*) hydrologic conditions (Renken and Gómez-Gómez, 1994). Additional information regarding predevelopment conditions, mostly within a small subbasin in the upper reach of the Río Tanamá Basin, is presented by Jordan (1970, 1977).

The lower aquifer is exposed as a 3- to 11-km wide band along the southern one-third of the North Coast ground-water province. The lower aquifer is recharged by infiltration of precipitation through soil cover or as runoff that enters the aquifer through numerous sinkholes, solution trenches (zanjones), and dry streambeds in the outcrop areas. The predevelopment and 1987 potentiometric-surface maps for the lower aquifer indicate that the principal areas of recharge are in topographically elevated interstream areas where the aquifer crops out. Much of the water that enters the shallow part of the flow system moves to the principal north-flowing rivers and some water enters deeper confined parts of the flow system. Many areas where the potentiometric surface is elevated are located along the northern boundary of the outcrop belt. Other areas where the potentiometric surface is elevated are located downdip where the lower aquifer is in the shallow subsurface (pls. 5*C*, 5*D*). The elevated potentiometric surface in these areas indicates that the lower aquifer is probably recharged by the downward leakage of water from the upper aquifer through a leaky confining unit.

Areas where the potentiometric surface of the lower aquifer is low generally coincide with principal stream valleys and north-flowing rivers. The upstream V-contour pattern of potentiometric-surface contours in predevelopment and 1987 potentiometric-surface maps (pls. 5*C*, 5*D*) indicates that the lower aquifer discharges water upward to shallower units in the major river valleys. Large potentiometric lows associated with major river valleys probably coincide with areas where the middle confining unit was breached by deep channels during Pleistocene sea-level lowstands. Two of Puerto Rico's largest springs (San Pedro and Aguas Fría) are located within the Ríos Grande de Arecibo and Grande de Manatí potentiometric lows. Southwestward movement of ground water to the Río Culebrinas indicates that this river is a major area of discharge from the lower aquifer in the outcrop belt (pl. 5*C*). Ground water from the lower aquifer also discharges to the Ríos Limon, Cialitos, Manvilla, and Mucarabones in the outcrop belt. Although these rivers receive discharge from the lower aquifer, the amount of ground water discharged is not considered to be significant in terms of the total ground-water budget.

Large cave systems represent major ground-water drains in areas where the lower aquifer crops out. This is evident in the Río Camuy cave system where potentiometric-surface contours show a characteristic up-stream V-contour pattern indicative of ground-water discharge (pl. 5*C*). Ground-water also discharges to the Río Encantado cave system located in the Florida-Montebello area (pls. 5*C*, 5*D*). A large number of water-level measurements in this area were used to constrain the position of the lines of equal hydraulic head (water-level contours) and help define the probable extent of the subterranean passageway. Potentiometric surface data also indicate the possible presence of another major cavernous drainage feature that lies to the north and appears to parallel the Río Encantado cave system. However, further study is needed to confirm the presence of this possible subterranean drainage feature.

In the Ríos Grande de Arecibo-Grande de Manatí area, ground-water movement in the deeper parts of the flow system is coastward along a circuitous path to the principal river drains. East of the Río Grande de Manatí, some ground water flows eastward toward the Levittown and Metropolitan San Juan area. Test drilling indicates that the upper aquifer is thin or absent in the Metropolitan San Juan area (fig. 55; pl. 5*A*) and that the confining unit (Cibao Formation) overlying the lower aquifer is leaky. The pattern of ground-water flow indicates that the San Juan area may be a site of regional discharge from the lower aquifer. However, surficial deposits in the San Juan area form a local confining unit that tends to impede upward leakage. West of the Río Grande de Arecibo, ground-water flow is largely coastward within the lower aquifer; however, some upward ground-water discharge to north-flowing streams is possible. In the westernmost part of the island, ground-water flow is locally westward. Ground-water flow in deep confined parts of the lower aquifer is poorly understood because of a lack of data. As described above, test drilling near Camuy and Isabella indicates that the stratigraphic and hydraulic nature of the lower aquifer is increasingly complex. Ground-water is contained under fragmented, heterogeneous artesian conditions made up of different water-bearing and confining zones of limited extent. Freshwater was encountered at depth in this western area, but facies relations within the Lares Limestone and Cibao Formation suggest strata equivalent to the lower aquifer are poorly permeable.

Ground-water development within confined parts of the lower aquifer is limited to the north-central part of the coastal plain, which extends eastward from the Ríos Grande de Arecibo to the Laguna Tortuguero and southward to Florida and Montebello. This area corresponds to the area where water-level declines in the lower aquifer have been greatest. Little has changed in water levels within the lower aquifer elsewhere, although ground-water withdrawals and possible leakage from wells southwest of the Laguna Tortuguero have locally lowered water levels as much as 40 m in some places (fig. 59). The greatest decline in the potentiometric surface was in the area between the Ríos Grande de Arecibo and Grande de Manatí. In 1987, the potentiometric surface in this area was more than 45 m lower than predevelopment levels in some wells. This is largely attributed to industrial ground-water withdrawals, mainly from the Montebello Limestone Member near Barceloneta, and the pumping of public water supply wells from equivalent strata near Florida. Upward leakage of water from the lower aquifer around poorly constructed wells in the Barceloneta area have also contributed to a decline in heads (Conde-Costas and Torres-González, written commun., 1990; Conde-Costas, written commun., 1991; Hydro Geo Chem., 1991).

BASAL CONFINING UNIT

The basal confining unit of the North Coast limestone aquifer system is made up of poorly permeable, lithified, volcaniclastic and igneous bedrock of Cretaceous and early Tertiary age that underlie the central mountains of the island and extend beneath the northern coastal plain. In the deeper subsurface, mudstone, clay, marl, and silt of the San Sebastián Formation compose the basal confining unit.

DISTRIBUTION OF TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY

A number of factors influence the distribution of transmissivity or hydraulic conductivity within the North Coast Limestone aquifer system. Some of the factors that govern the regional distribution of hydraulic conductivity include the original lithologic character of the carbonate rock, carbonate depositional patterns, subsequent diagenesis, and the array of fractures and joints that facilitate dissolution and karstification (see Ward, this report). Transmissivity patterns within the upper aquifer are also regulated by a diminishing thickness of the freshwater lens where the aquifer extends seaward or reaches southward and thins to a featheredge; and the degree of interconnection between surface and subterranean drainage systems.

Estimates of transmissivity for the North Coast Limestone aquifer system were determined by the analysis of aquifer test and specific capacity data (Torres-Gonzáles, written commun., 1990). Specific capacity-derived transmissivity estimates were provided using the empirical equations developed by Theis (1963) and Brown (1963) and parallels the approach previously described for the South Coast aquifer. The distribution of apparent hydraulic conductivity (K') was computed by dividing apparent transmissivity estimates (T') by the thickness of the aquifer that was penetrated by the well. These maps are subject to similar qualifications described earlier. They are based on specific-capacity methods that assume 100 percent well efficiency, full penetration of the aquifer, 30 cm well diameter, a storage coefficient of $1x10^{-4}$ for wells subject to artesian conditions or 0.10 for wells subject to water-table conditions, and a 24-hour pumping time. Two important qualifications of the transmissivity and hydraulic conductivity maps is that most wells only partly penetrate the aquifer and represent only the freshwater part of the section. It is assumed that the hydraulic properties of these partial penetrating wells were representative for the entire aquifer and, therefore, estimated transmissivity values were not adjusted.

In the region west of Río Guajataca, hydraulic data for the upper aquifer are sparse, and transmissivity and hydraulic conductivity patterns are, in general, poorly known or understood (pls. 5*G*, 5*H*). On the basis of two wells, the transmissivity of the upper aquifer in the northwestern Puerto Rico is reported to range from 1,000 to more than 10,000 m^2/d. However, hydraulic data collected for these two wells are not considered to be representative of regional transmissivity. One well near the northwestern coast may be screened in coastal deposits (1,499 to 2,360 m^2/d). The other well, locally known as the Monte Encantado well, is drilled into a subterranean stream. Here, transmissivity is reported to range from 6,618 to 10,051 m^2/d. The wide variability in transmissivity and great distance between wells suggests that it is not possible to map the regional distribution of transmissivity in this area. Similarly, few data are available east of Río de la Plata for the upper aquifer. The upper aquifer contains minor freshwater within a small area east of the Río de la Plata; transmissivity is reported to exceed 4,000 m^2/d locally, but averages 75 to 90 m^2/d (I. Padilla, USGS, written commun., 1990).

The upper aquifer is most transmissive in middip regions of the north coast that lie between the Río Camuy and Río de la Plata (pl. 5*G*). The transmissivity of the upper aquifer is reported to exceed 10,000 m^2/d in several locations, including areas that lie southwest of Arecibo, west of Barceloneta, east-southeast of Laguna Tortugero, and in the Los Puertos-Regadera area. Transmissivity of the upper aquifer is reported to be as much as 68,000 m^2/d. Highly transmissive rocks within the upper aquifer are commonly, but not exclusively, associated with a freshwater lens that is greater than 50 to 100 m thick. As previously discussed, the thickest part of the freshwater lens is in interstream areas between major stream valleys, but is proximate to the landwardmost extent of saltwater and usually is the zone of highest transmissivity. Highly transmissive

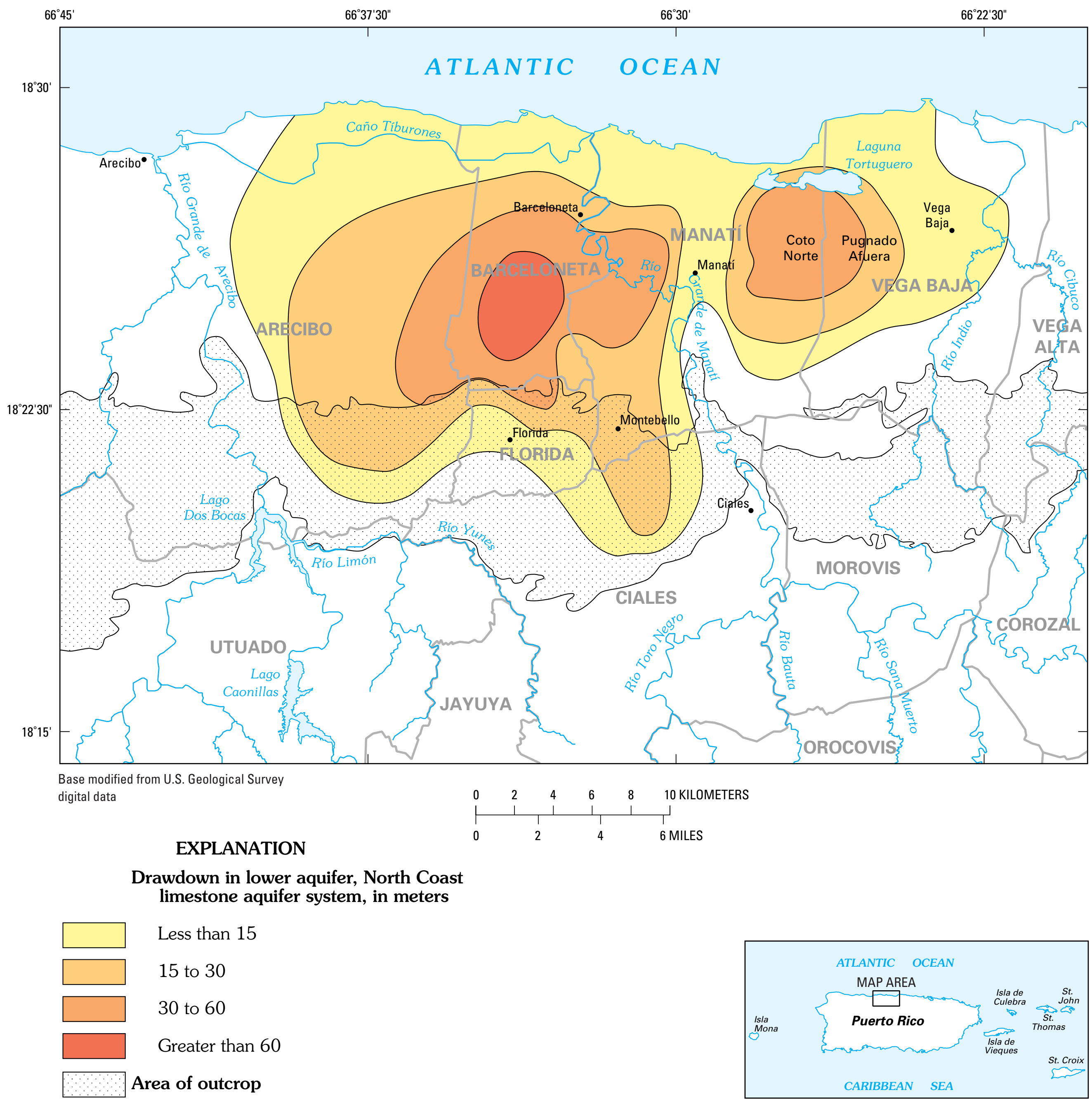


FIGURE 59.—Drawdown in the lower aquifer between 1968 and 1987, north-central Puerto Rico.

rocks are also in coastward localities where the freshwater lens is considerably thinner; extremely vuggy or cavernous limestone can account for these high transmissivities. In general, transmissivity within the upper aquifer diminishes coastward (northward) and landward (southward), and in interstream areas as a result of thinning of the freshwater lens. In these areas, transmissivity within the upper aquifer is often less than 1,000 m^2/d.

When compared to stratigraphic depth, there is wide variability in hydraulic conductivity within the upper aquifer (Guisti, 1978) and is indicative of the aquifer's heterogeneity. Hydraulic conductivity within the Aymamón Limestone appears to diminish with stratigraphic depth, a decrease in permeability that is probably associated with a maximum effective depth to which karstification will occur within the aquifer. In some localities, values of hydraulic conductivity or transmissivity may not appear to fit the regional pattern and is probably due to the erratic distribution of cavernous porosity.

On the basis of specific-capacity data, hydraulic conductivity of the upper aquifer is estimated to range from less than 1 to more than 2,000 m/d (pl. 5*H*). In general, hydraulic conductivity of the upper aquifer increases northward (coastward) with the least permeable parts of the aquifer inland (less than 30 m/d) or west of the Río Camuy. Highest hydraulic conductivities (greater than 300 m/d) occur along a narrow coastal band that extends eastward from the Río Grande de Arecibo to the Río Grande de Manatí. Highly permeable carbonate rocks are also near Laguna Tortugero.

Several factors contribute to the pattern of permeability within the upper aquifer. Ward and others (1990; this report) suggest that porosity within the Aguada (Los Puertos) Limestone and the lower part of the Aymamón Limestone could be lithologically controlled by the occurrence and distribution of dolomite and of formerly aragonitic fossils contained within these strata. Conversely, porosity within the upper 30 to 100 m of the Aymamón Limestones appear to be related more to processes of karstification and the associated development of cavernous porosity.

If uniform solubility within the carbonate rocks that make up the aquifer is assumed, the coastward increase in permeability appears, at first glance, to be at odds with geochemical data for the North Coast of Puerto Rico (Román-Mas and Lee, 1987) that show carbonic acid is consumed as meteoric waters that recharge the aquifer move downgradient. Under this scenario, one would expect permeability to diminish coastward. However, mixing of freshwater and seawater at the coast may help enhance processes of dissolution (Plummer, 1975). Such mixing could help explain the apparent coastward increase in porosity and permeability as well as the occurrence of cavernous zones and subterranean conduits near Caño Tiburones (Zack and Class-Cacho,1984).

The transmissivity of the lower aquifer is reported to range from less than 1 to more than 1,300 m^2/d (pl. 5*I*). Reported transmissivity values that fall within the upper range are unusual, however, and transmissivity within the most productive part of the lower aquifer generally ranges from 50 to 800 m^2/d. The lower aquifer is most transmissive in an area that includes outcropping rocks of the Montebello Limestone Member and the Lares Limestone and equivalent subsurface strata that extend coastward and lie between the Río Grande de Arecibo and Río Grande de Manatí. Highest transmissivity corresponds to areas of greatest aquifer thickness. Transmissivity of the lower aquifer diminishes to the west and east in conjunction with facies changes occurring within the rocks composing the aquifer. For example, the Montebello Limestone Member grades eastward to the poorly permeable “mudstone unit,” and the aquifer is comprised only of the less transmissive Lares Limestone. In the easternmost part of the study area, transmissivity within the lower aquifer increases and is reported to be as much as 56 m^2/d, largely attributed to a clastic facies change to rocks of the Mucarabones Sand. As the lower aquifer extends westward, the Lares Limestone and Montebello Limestone Member both grade to a poorly permeable facies of either the San Sebastián Formation or the Cibao Formation.

CONTROLS ON POROSITY AND PERMEABILITY IN CARBONATE AQUIFERS OF NORTHERN PUERTO RICO

BY W.C. WARD[1]

The principal aquifers of the North Coast limestone aquifer system consist of open-platform limestones and dolomites of the Aymamón and Aguada Limestones and the Montebello Limestone Member and Lares Limestone. The new subsurface data provided by core drilling demonstrate that the distribution and quality of the carbonate-rock aquifers are directly related to (1) the regional stratigraphic framework, (2) local lithologic and diagenetic facies, and (3) fracture systems (Ward and others, 1990).

Stratigraphic Control

To a large degree, the principal hydrogeologic units of the North Coast limestone aquifer system coincide closely with major middle Tertiary geologic units of northern Puerto Rico. The North Coast limestone aquifer system’s upper aquifer is within the Aymamón Limestone and Aguada (Los Puertos) Limestone carbonate rocks and the Montebello Limestone Member and Lares Limestone rocks form the lower aquifer (Renken and Gómez-Gómez, 1994; Renken, Gómez-Gómez, and Rodríguez-Martínez, this report).

From a hydrogeologic perspective, the upper aquifer is a relatively uniform limestone sequence; the Aguada (Los Puertos) Limestone and Aymamón Limestone include bedded skeletal packstone-wackestone, and packstone-grainstone with lesser dolomitic beds. The two limestone units combine to form one aquifer that cannot be regionally separated on the basis of potentiometric data.

The lower aquifer is confined by less permeable marl, limestone, and mudstone of the overlying Cibao Formation and by poorly permeable mudstones of the underlying San Sebastián Formation. The lower aquifer also is confined below in easternmost areas by Upper Cretaceous and lower Tertiary rocks where the San Sebastián Formation is either missing or grades updip to permeable conglomeratic beds. The Cibao confining unit that separates the upper and lower aquifers appears to be hydraulically less effective in some

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updip localities (Renken and Gómez-Gómez, 1994). In the western part of the basin, this may partly be due to interfingering of the Cibao with terrigenous sediment.

The relatively high potentiometric head and low specific conductance measured during drilling within Lares Limestone and Montebello Limestone Member carbonate rocks (Renken and Gómez-Gómez, 1994) indicate that these strata contain freshwater under confined conditions in an area that lies north of its outcrop belt (north of approximately latitude 18°23'; fig. 3). The most productive part of the aquifer is in an area between the Río Grande de Manatí and Río Grande de Arecibo, an area that corresponds to where the Montebello Limestone Member is relatively thick and widespread. On the western side of the basin, the Lares and Montebello Limestones interfinger with poorly permeable and porous marl and limestone of the undifferentiated Cibao Formation and San Sebastián Formation. East of the Río Grande de Manatí, porosity and permeability within the aquifer diminish as the Montebello grades into undifferentiated Cibao and the mudstone unit. On the eastern side of the basin, however, sandstone and conglomerate of the Mucarabones Sand are more permeable and may provide avenues for diffuse upward flow of ground water from the lower aquifer.

Lithologic and Diagenetic Control

Porosity and permeability within the major aquifers are highly variable, largely because of lateral and vertical variations in depositional textures and in diagenetic features. In general, porosity is highest in coarser and better-sorted grainstone-packstone and lowest in wackestone and marl (clayey wackestone or highly calcareous claystone). Primary intergranular porosity is retained in some grainstone and packstone layers. More commonly, however, porosity is secondary, resulting from dissolution of original skeletal constituents or from dissolution of calcium carbonate during dolomitization, or both. The most abundant type of secondary porosity in these rocks is moldic porosity, most of which occurs where aragonitic fossils, particularly mollusk and corals, were dissolved. Although moldic porosity is abundant in some mollusk- and coral-rich wackestones, permeability in these rocks is generally low. Moldic porosity is most effective in grainstone-packstone layers that retain intergranular porosity or that have been dolomitized. Dolomitized zones commonly have fossil-moldic porosity and intercrystalline porosity. Porosity and permeability is significantly reduced where calcite cement fills intergranular and moldic pores.

Upper Aquifer

Enhanced porosity and permeability in the upper part of the Aymamón Limestone are predominantly the products of late Miocene and Quaternary karstification. The upper 30 to 100 m of the Aymamón Limestone are dense recrystallized limestone and chalky limestone with cavernous porosity. The cavernous and vuggy porosity is concentrated in zones, which become more numerous upward. Many of the large vugs, however, are filled or partly filled with red-brown mud.

In the lower part of the Aymamón and in the Aguada (Los Puertos) Limestone, porosity is highly variable, being controlled principally by the distribution of dolomite and of originally aragonitic fossils. Numerous thin units of dolomitized coral-rich grainstone-packstone and coral boundstone have up to 25 percent moldic and intercrystalline porosity (Hartley, 1989, Scharlach, 1990).

Porosity in the lower Aymamón is locally as much as 15 percent (estimated in thin section) in mollusk- and coral-rich layers, and where these are dolomitized, as much as 30 percent. Dolomite in the Aymamón Limestone increases downdip (Scharlach, 1990). In poorly indurated coarser grainstone-packstone, intergranular and moldic porosity may be up to 25 percent.

Porosity of the Aguada (Los Puertos) Limestone is best in dolomitized units, which commonly have an estimated 10 to 20 percent moldic, intercrystalline and intergranular porosity. Dolomite in this formation also apparently increases downdip. Some poorly cemented soritid-mollusk packstone-grainstone and coral-mollusk wackestone-packstone have greater than 10 percent intergranular and moldic porosity. Calichified zones and the upper karsted interval may have as much as 20 percent vuggy and moldic porosity.

Middle Confining Unit

Coarser skeletal packstone-grainstones of the undifferentiated Cibao Formation generally have the highest porosity, up to about 10 percent moldic and intergranular. Dolomitic layers in the upper and lower parts of this member have 5 to 10 percent moldic, intergranular, and intercrystalline porosity. Porosity generally increases updip because of fewer clayey intervals and more packstone-grainstone intervals.

Porosity in the mudstone unit is low. Moldic porosity is uncommon because of the scarcity of larger mollusks and other originally aragonitic fossils. The finely crystalline dolomite has less than 5 percent (estimated in thin section and hand specimen) intercrystalline porosity. At the top and bottom of the unit, dolomitized skeletal wackestones have 5 to 10 percent moldic and intercrystalline porosity (Scharlach, 1990).

The fossiliferous coarser terrigenous rocks of the Quebrada Arenas and Río Indio Limestones cored in NC 2 have estimated 5 to 7 percent intergranular porosity with lesser moldic and intraparticle porosity. Sandy large-foraminifer packstone-grainstone in NC 8 has 5 to 15 percent porosity, mostly intergranular with moldic and intraparticle. The upper

15 m of this member has low porosity because the rocks are better cemented.

Lower Aquifer

Porosity in the Montebello Limestone Member is highly variable. Intergranular and moldic porosity in skeletal packstone commonly is 5 to 10 percent and may be as high as 15 percent (Hartley, 1989). Mollusk- and coral-rich units may have up to 25 percent moldic porosity. Porosity decreases downdip as the Montebello Limestone grades into clayey wackestone-packstone and claystone.

Porosity in the Lares Limestone also is highly variable, depending on depositional texture, original mineralogy of the skeletal fragments, and dolomitization. Mollusk- and coral-rich layers of coarser packstone have moldic and intergranular porosity estimated to be as much as 15 percent. In large-foraminifer packstone-grainstone estimated porosity is 12 percent, mostly intergranular with lesser moldic and intraparticle. Dolomite has much as 10 to 15 percent moldic and intercrystalline porosity. In the eastern part of the basin (NC 2; fig.21), 65 to 70 percent of the Lares limestone and dolomite has less than 5 percent porosity, the rest having 10 to 15 percent (Scharlach, 1990).

Intergranular porosity of the Mucarabones Sand is generally less than 5 to 10 percent because many sandstones are clayey. Some thin moderate- to well-sorted sandstones have greater than 10 percent intergranular porosity (Scharlach, 1990).

The most productive part of the lower aquifer lies largely in an area between the Río Grande de Arecibo and the Río Grande de Manatí. Porosity and permeability in the lower aquifer in the vicinity of NC 5 is best developed in coarse grainstone-packstone and coral-patch-reef limestone (Hartley, 1989). These rocks typically have about 10 to 15 percent moldic and intergranular porosity with minor zones of mollusk- and coral-moldic porosity as high as 25 percent (Hartley, 1989). Patches of dolomitized grainstone in the middle Lares have 5 to 10 percent intercrystalline-intergranular porosity. An estimated 65 percent of the Lares section and 45 percent of the Montebello section in wells NC 5 and NC 10 have low permeability with less than 5 percent porosity.

Basal Confining Unit

Estimated porosity in San Sebastián Formation limestones and sandstones is variable, but generally no more than a few percent. Characteristically, the carbonate rocks of the San Sebastián Formation have less than 5 percent (estimated in thin section) intergranular and moldic porosity.

Fracture Control

The Tertiary limestone outcrop belt in northern Puerto Rico is a well-developed karst terrain (Monroe, 1976). Karst features of the North Coast ground-water province has been ascribed to a variety of tectonic, geomorphic, hydrologic (climatic), and geochemical factors. Some straight dry valley segments have been attributed to dissolution along joint systems, whereas other dry valleys have been attributed to superposed drainage (Monroe, 1976, p. 27). Preferential alignment of cones or cockpit karst has been alternatively ascribed to preferential drainage patterns as the Puerto Rico platform emerged with a supposed eastward tilt (Lobeck, 1922; Meyerhoff, 1933; Guisti, 1978) or to dissolution along joint or fractures (Lehmann, 1954). Monroe (1976, p. 38) believed there was such variability within these alignments as to preclude joint control. Joint control on the arrangement of mogotes (steep-sided karst hills) was inferred by Hubbard (1923) and Kaye (1957), whereas Monroe (1976, p. 47-48) believed this also might be the result of trade winds effects, late Tertiary drainage patterns, or fluvial flow during a Pleistocene interglacial stage. There does seem to be general agreement that the linear solution trenches or zanjones are joint-related karst features (Sweeting, 1972; Monroe, 1976, p. 48).

Assuming that most straight segments of karst valleys in this region represent dissolution along major fractures, the topography in the limestone hills shows the strong influence of several sets of regional fractures. For example, between the Río Grande de Arecibo and the Río Grande de Manatí, major trends of karst valleys (fracture systems) are N55°-60°E, N10°-N5°W, N15°-20° W, N30°-40°E, and approximately E-W (fig. 60). Although the upper aquifer seems to be best characterized as a diffuse-flow carbonate aquifer, it seems likely that ground-water flow in the upper aquifer is controlled, at least in part, by regional fractures. Ground-water flow in karst systems is often channeled through caverns and along solution-enhanced fractures (White, 1969, 1988).

The lower aquifer is characterized by vertically and laterally discontinuous porosity and permeability, suggesting that porous zones may be connected by fractures. The comparatively low transmissivity of the lower aquifer (pl. 5*I*), however, suggests that permeability within Montebello Limestone Member and Lares Limestone carbonate rocks is not substantially enhanced by fractures.

U.S. VIRGIN ISLANDS

By R. A. Renken[1]

St. Croix is the only island of the three U.S. Virgin Islands that is underlain by poorly lithified or unconsolidated sedi-

[1] U.S. Geological Survey

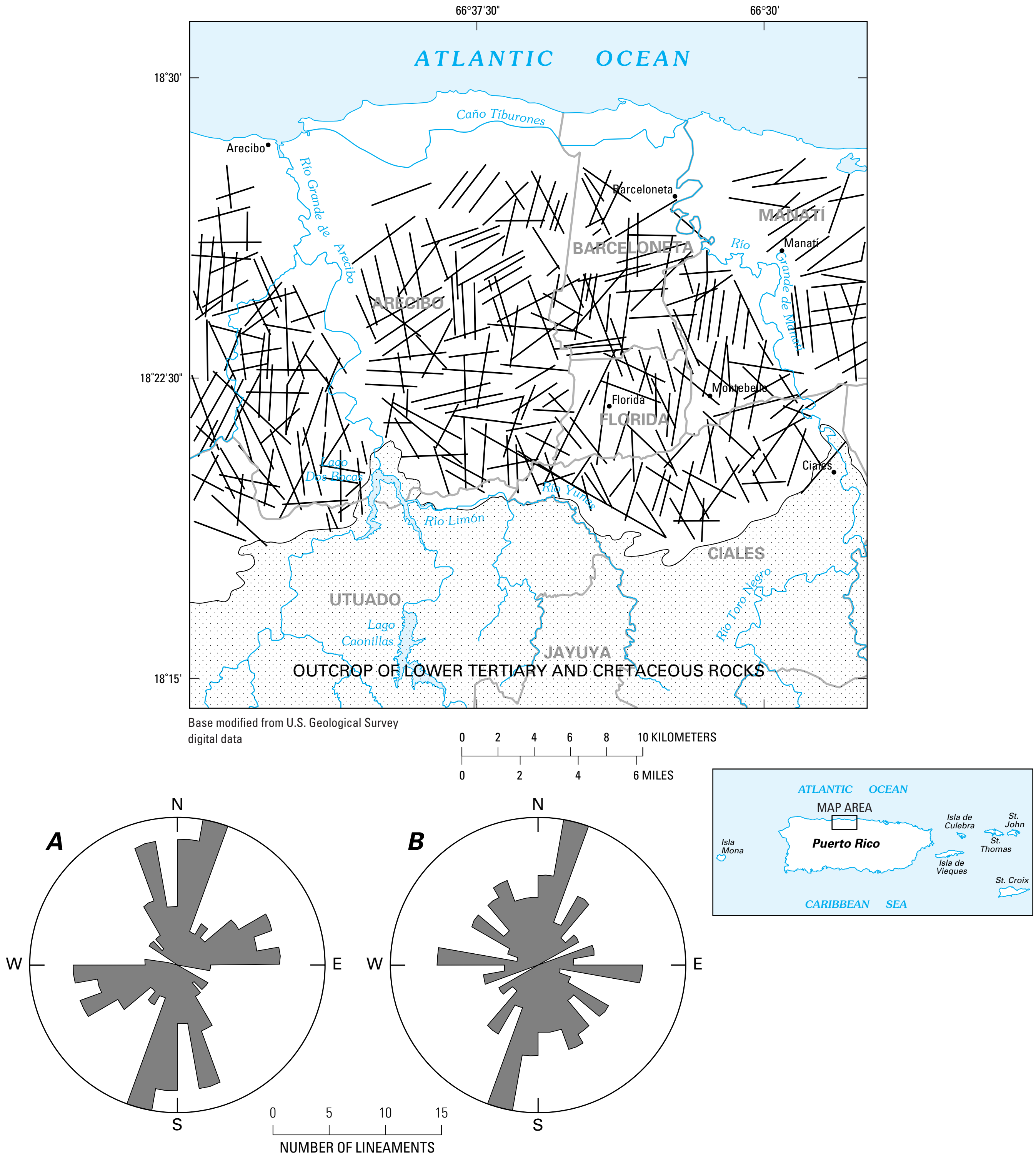

FIGURE 60.—Major fracture patterns inferred from strike of surface lineaments in karst topography between the Río Grande de Arecibo and Río Grande de Manatí, northern Puerto Rico. Rose diagrams, constructed using 10-degree sectors, show the orientation of 99 lineaments from the Aymamón and Aguada Limestones (*A*) and orientation of 100 lineaments from the Montebello Limestone Member and the Lares Limestone (*B*) (reprinted from Ward and others, 1990, and published with permission).

mentary strata that function as a source of ground-water and have "regionally-significant" areal extent. Even then, the areal extent of the Kingshill aquifer is small, underlying a total area of only 78 km^2. The Kingshill aquifer, by definition, is comprised of the Kingshill Limestone and overlying carbonate rocks of the Blessing Formation. Underlying rocks of the Jealousy Formation are considered to form the hydrologic basement, in large part due to the progressively poorer chemical quality of water with increasing depth (Robison, 1972, p.3). Combined with its poorly transmissive nature in most places (less than 3 m^2/d reported for wells that penetrate only the Kingshill Limestone) (Torres-González, written commun., 1990), the Kingshill aquifer's importance is strictly a function of the lack of an alternative source of groundwater. Most of the large-yield wells reported to be screened in the Kingshill aquifer are also screened in more permeable alluvium. The karstic Blessing Formation is more permeable, but its thickest extent is restricted to St. Croix's heavily industrialized south-central coast area, an area subject to industrial contamination or to salt-water intrusion if pumped heavily.

A veneer of alluvial sediment that locally overlies the Kingshill aquifer and Cretaceous bedrock of St. Croix's highland ranges forms a patchy, discontinuous alluvial aquifer. Whereas alluvial deposits in St. Croix and in St. Thomas and St. John are more permeable than most underlying strata, their restricted extent limits their use as a reliable source of ground water. Production from wells that penetrate fractured bedrock in the U.S. Virgin Islands has met limited success, and reported sustainable yields are usually less than 1.0 L/s.

DISTRIBUTION AND TYPES OF POROSITY WITHIN THE KINGSHILL AQUIFER

BY I.P. GILL[1], D.K. HUBBARD[2], P.P. MCLAUGHLIN[3], AND C.H. MOORE[4]

Porosity types in carbonate rocks of St. Croix central basin are varied and complex. This complexity is a result of the range of primary pore types and partly a result of dissolution, cementation, and recrystallization. The distribution and nature of the porosity is variable geographically and stratigraphically.

Kingshill Limestone in the Central and Northern Basin

The Kingshill Limestone, exclusive of the overlying Mannings Bay Member, is dominated by fine-grained, basinal deposits, and is rich in planktonic foraminifera and other pelagic biota. The unit is poorly lithified in the subsurface, with lithification evident mainly in the coarser grained, shelf-derived beds that interstratify the pelagic accumulations. Because of the lack of lithification, primary porosity in much of the Kingshill Limestone is preserved as intergranular pores and as pore space within the grains themselves. Circulation of ground water has leached the fine-grained sediments and produced recrystallization and minor cementation. In general, however, permeability within the Kingshill Limestone is commonly poor, with much of the pore space being microscopic.

In the coarser-grained sediment-gravity flows (sand- to boulder-sized constituents) that are common throughout the Kingshill Limestone, interspersed between the pelagic accumulations discussed above, much of the primary porosity has been destroyed by cementation and recrystallization. These beds generally show intergranular and intragranular pores occluded by calcite cementation and are mostly impermeable.

Although the Kingshill Limestone is widespread in the Central Plain region (fig. 5), water production is patchy and is poor in large areas. Production in the Kingshill Limestone is limited to areas where terrigenous components have allowed porosity to be preserved, or production stems from incursion of alluvial aquifers on top of the Kingshill Limestone. Fractures within the poorly lithified Kingshill Limestone are also a potential source of water and have been developed in water-supply drilling during the 1980's (Jesús Rodríguez, oral commun., 1989). The large number of wells in the Kingshill Limestone attests mostly to its areal extent and to the limited supply available from other sources rather than its production capabilities.

The porosity of the Jealousy Formation is similar in many respects to that in the Kingshill Limestone. In many cases, the Jealousy Formation can be considered the hydrologic basement, and is not a significant water producer.

Mannings Bay Member and the Blessing Formation along the southern coastline

The Mannings Bay Member of the Kingshill Limestone and the overlying Blessing Formation are coarser-grained than the La Reine Member and are far more affected by diagenetic alteration. Both units are correspondingly more porous than the lower Kingshill Limestone. These two units are thickest and best exposed in the southeastern coastal section of the Kingshill Basin area, where they contain permeable sections that are the sources of both industrial and public water supply. Because of their greater porosity and the wider variety of diagenetic alteration affecting them, these units are important to the discussion of this paper.

Porosity in the Mannings Bay Member and the Blessing Formation ranges from microscopic intergranular pores to large voids up to a meter across. The voids are evident in out-

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crop and in the subsurface when the drill bit penetrates empty space. Megascopic porosity in the post-Kingshill units is restricted to the coastal region, and is in many cases represented by the wholesale removal of unstable minerals. In this case, many of the voids observed in outcrop are external molds of cobble- to boulder-sized coral heads, some with molds of the coral calyxes preserved (Gill and others, 1989).

Corals, originally composed of aragonite, are easily dissolved by the circulation of waters undersaturated with respect to calcium carbonate. Throughout the Blessing Formation rocks, large voids have been produced by selective dissolution of aragonite and high-magnesium calcite, or through wholesale dissolution due to karsting or a similar process. Non-fabric selective dissolution can be observed in outcrop as caliche zones and solution pits (Lidz, 1982; Gill and Hubbard, 1987; Gill and others, 1989).

The Blessing Formation and the Mannings Bay Member are the host rocks for localized dolomitization (fig. 49). Accompanying the dolomitization process is a large-scale increase in porosity due to the selective leaching of bioclasts as well as an increase in intercrystalline porosity. In heavily dolomitized strata, aragonitic and calcitic bioclasts originally in the formation have dissolved, leaving a matrix of dolomite rhombs with moldic porosity. The selective removal of calcitic and aragonitic bioclasts is due presumably to differential solubility. The net result of the dissolution accompanying dolomitization is high porosity and transmissivity as much as 370 m^2/d in localized areas.

Dissolution and karsting

Large-scale dissolution in the Blessing Formation and Mannings Bay Member has resulted in megascopic voids, accompanied in outcrop by evidence of subaerial exposure of the limestone and leaching by meteoric waters. This evidence includes caliche layers and soil horizons (Behrens, 1976; Lidz, 1982; Gill 1989), as well as significant shifts in the stable isotopic ratios of the remaining limestone (Gill and others, 1989; Gill, 1989). In the subsurface samples, insufficient data have been obtained to judge the causes of cavernous porosity production. However, the outcrop exposures and caves point to modest karst development, and it is reasonable to extend this interpretation to the subsurface as well.

The restriction of cavernous porosity to locations along the coastline might indicate an alternative hypothesis to subaerial exposure and leaching: the dissolution and megascopic porosity in the upper Kingshill and Blessing Formation rocks is due to the circulation of fresh ground water and seawater in a coastal mixing zone (Back and Hanshaw, 1983).

In St. Croix, chemical equilibria calculations show that some of the coastal ground waters are undersaturated with respect to calcite, and the pattern of salinity in coastal zones indicate that mixing is taking place today (Gill and Hubbard, 1986; Gill, 1989). Although equilibria calculations show that modern hydrological conditions are presently favorable to limestone dissolution within the coastal portion of the aquifers, this does not prove that this process was important during the geologic past. The coastal distribution of the porosity could indicate a lithologic control, rather than a geochemical control, on the dissolution of the coastal limestone units. In short, although ground-water mixing is a viable hypothesis to explain the development of porosity in the upper Kingshill and Blessing Formation rock units, its effects are impossible to separate from those of localized karsting and leaching by meteoric water. Both of the latter processes are common in exposed limestone areas, and both can be demonstrated to have occurred in the upper Kingshill and Blessing Formation limestones.

Dolomitization

The localized dolomitization of parts of the Blessing Formation and the Mannings Bay Member has produced a significant amount of porosity in these units. Although highly localized on St. Croix, the dolomitization process is an important mechanism of porosity development.

Combining the evidence from both the oxygen and strontium isotopes (Gill and Hubbard, 1987; Gill 1989), the main conclusions are that the highly porous zones of dolomitization were the result of a ground-water system that (1) allowed the mixing of ground water and seawater to produce a fluid with a strontium isotopic composition intermediate between modern marine water and ground water and (2) allowed the evaporation to produce a fluid with an oxygen isotopic composition enriched in ^{18}O relative to normal seawater.

This scenario is consistent with the geological distribution of the dolomitized zones on St. Croix. The dolomite occurs only in shallow marine strata very close to the paleocoastline of St. Croix, and only within a block that has been downfaulted relative to the surrounding rock. The location of the dolomitized strata is thus consistent with the requirement that mixing takes place between the seawater and the ground water; coastal regions are the only place on St. Croix where mixing would be possible, and it can be shown that some coastal mixing occurs today (Gill and Hubbard, 1987; Gill 1989). The dolomitized strata occur only in a structurally controlled embayment or lagoon that could have allowed extensive evaporation to take place. Similar lagoons and embayments exist on St. Croix today, and the salinity and oxygen isotopic composition of their waters shows that extensive evaporation is taking place (Gill, 1989).

More generalized porosity patterns, such as the karst-related and selective dissolution porosity in other areas underlying St. Croix's central plain are lithologically and geographically restricted to the Blessing Formation and Mannings Bay Member carbonates as well. The distribution of these porosity types can be predicted to occur on the basis of lithology, and can therefore be expected to occur in a narrow band around the coastline from the southern to the western end of St. Croix. The Mannings Bay Member and the Blessing Formation can be expected to contain these porosity types because of their original mineralogies, their geographic location close to the coastline, and their higher initial porosity and permeabilities

ALLUVIAL AQUIFERS

ROBERT A. RENKEN[1]

Unconsolidated clastic detritus in St. Croix deposited as part of alluvial fan, slope wash, debris flow, lagoonal muds, and stream alluvium are, for purposes of this discussion, collectively grouped as part of U.S. Virgin Islands alluvial aquifers. Restricted in its physical extent, the alluvial aquifer is moderately permeable, serving as an aquifer and as a temporary storage zone for rainfall and stream runoff. Where these deposits overlie the Kingshill aquifer, ground water is slowly released to the underlying, poorly transmissive Kingshill aquifer.

Unconsolidated clastic detritus in the Central Limestone Plain of St. Croix consist of moderately thin, alluvial fan and slope wash deposits, or occur as stream alluvium that has infilled overdeepened valleys now drained by ephemeral to intermittent streams. Alluvial-fan deposits along the Northside Range appear to be dominated by silt- or clay-rich material and usually less than 10 m thick. Deposits of coarse alluvial detritus (sand-size or larger) that exceed 20 m thick lie within river guts that incise the Kingshill aquifer north of Krause Lagoon (fig. 61). The alluvial aquifer is thickest along the south-central coast of St. Croix (greater than 40 m) where alluvium and lagoonal sediments underlie Krause Lagoon. The thickness of alluvial deposits in eastern St. Croix is poorly known due to limited well data, but is reported to be as much as 25 m thick (Cederstrom, 1950, p. 28). Here, alluvial deposits consist of alluvial fan and matrix-supported boulder-conglomerate debris fan deposits. The poorly sorted nature of the debris flow deposits probably limits their utility as an alluvial aquifer. Silt and clay make up a part of the alluvial section in many areas. Sand and gravel deposits are thin and interbedded with silt and clay. Alluvial deposits are reported to yield 2 to 10 L/s to some wells. Estimates of transmissivity for alluvial sediments in St. Croix are difficult to obtain as many wells screened in such deposits also tend to be screened in the underlying Kingshill Limestone or older volcaniclastic bedrock units. The transmissivity of the alluvial deposits contained within the River Gut area is reported to range from 20 to 450 m^2/d. The transmissivity of wells screened in the alluvium and Kingshill Limestone in the Bethlehem Gut area north of Krause Lagoon is reported to range from 20 to 650 m^2/d (Torres-González, written commun., 1990).

Alluvium and beach deposits of Holocene and Pleistocene (?) age occur in a number of coastal embayments in St. Croix, St. Thomas, and St. John. They are only of local importance and not areally extensive (figs. 5, 6). The alluvial aquifer that lies within the lower reach of Turpentine Run in eastern St. Thomas, extends only as a narrow, 60 m-wide band that is no more than 12 m thick. Alluvium in St. Thomas and St. John consist largely of silt, clay, sand and gravel lenses that grade coastward to sandy carbonate beach sands. Recharge to these alluvial aquifers occurs by seepage of storm runoff or water gained from the adjoining bedrock aquifer. The yield of the alluvial aquifers of St. Thomas and St. John is small. Sustainable withdrawals from Turpentine Run's alluvial aquifer exceeding more than 0.4 L/s could cause an encroachment of saltwater (Jordan and Cosner, 1973).

WEATHERED MANTLE-BEDROCK AQUIFER

Limited supplies of ground water are available in St. Croix, St. Thomas, and St. John contained within the Cretaceous volcaniclastic bedrock and volcanic (gabbro and diorite) rocks of Tertiary and Cretaceous age. Movement of ground water within these rocks is largely limited to weathered and open joints and fractures not subjected to secondary mineralization, or along fault zones not sealed with gouge. In St. Croix, the depth of the weathered fracture and joint bedrock aquifer does not extend more than 30 to 45 m below land surface. The bedrock aquifer of St. John has been separated into three hydrogeologic units and probably parallels the physical character of bedrock aquifers in St. Thomas and St. Croix: (1) a thin soil zone and saprolite zone capable of absorbing large amounts of rainfall, (2) a weathered bedrock zone (1 to 15m thick and rarely as much as 55 m thick), and (3) unweathered bedrock containing joints that are more numerous and more open at shallower depths (Cosner, 1972). Bedrock fractures and joint weakness are best expressed in valleys and provide the greatest opportunity for additional ground-water supplies, particularly in the lower part of the valley, where overlying alluvium often acts as a source of recharge. In St. John and St. Thomas, drainage basins and minor valleys have formed along fault and fracture zones that, in general, function as conduits. Antecedent soil-moisture conditions are important to recharge of the bedrock aquifers on each of the U.S. Virgin Islands. The bedrock aquifer is infrequently recharged and usually only after heavy rainfalls or a series of storms that generate 50 mm of rain (Jordan, 1975).

The hydraulic conductivity of the bedrock aquifer in St. Thomas near Charlotte Amalie ranges from 0.3 to 2.7 m/d. Hydraulic conductivity of a well located within a nearby fault zone ranged from less than 21 to 46 m/d (Jordan and Cosner,

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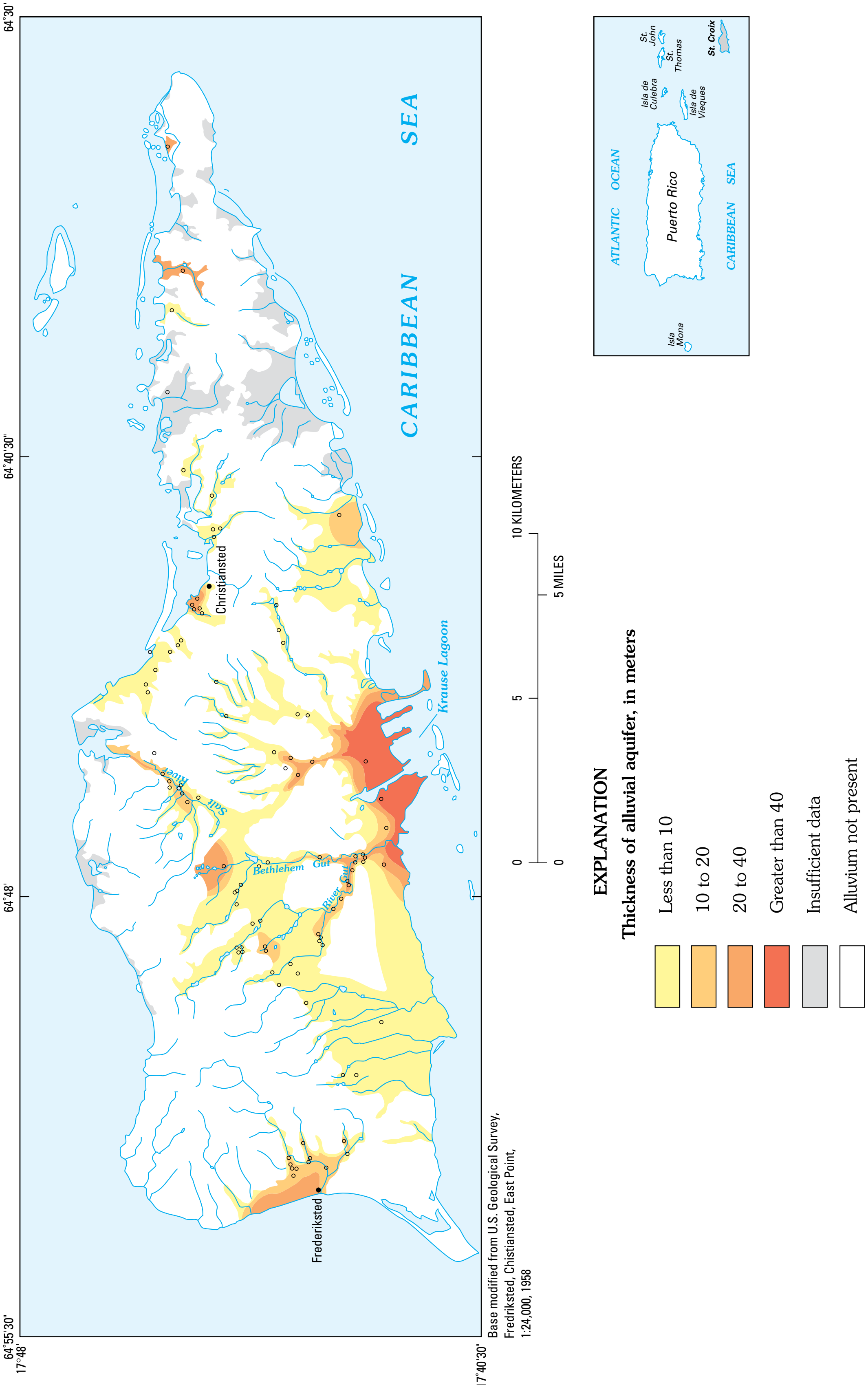

FIGURE 61.—Thickness of the alluvial aquifer in St. Croix, U.S. Virgin Islands.

1973). In St. Croix, the specific capacity of wells screened in the bedrock aquifer is reported to range from 0.02 to 1 [(L/s/m)] with highest values generally associated with bedrock-valley areas overlain by alluvium. Water obtained from the Mahogany Road well field near Frederiksted is obtained mostly from weathered bedrock underlying alluvium (Hendrickson, 1963). Transmissivity in this well field is estimated to range from 4 to 150 m^2/d (Torres-González, written commun., 1990).

VIEQUES ISLAND

Alluvial fan deposits and/or alluvium underlies Esperanza alluvial valley in south-central Vieques and Resolución alluvial valley in northwestern Vieques. Consisting of largely sand, silt, clay, and rock fragments, they represent the principal aquifers on the island (fig. 4).

The thickness of the Esperanza alluvial valley aquifer is as much as 30 m. In much of Esperanza alluvial valley, a 3-m-thick clay layer or weathered bedrock zone overlies dioritic bedrock (fig. 62). The clay layer is, in turn, overlain by a 18 m-thick coarsening upward zone of fine sand, rock fragments, and clay. In general, the amount of clay within the aquifer increases with depth. A 1.5-m-thick clay layer occurs less than 8 m below land surface. The clay layer functions as a leaky confining bed and hydraulically separates a lower confined zone from an upper water-table aquifer comprised of sand and silt (Torres-González, 1989). The transmissivity of the Esperanza alluvial valley aquifer reportedly ranges from 19 to 186 m^2/d with hydraulic conductivity of the aquifer ranging from less than 1 to 11 m/d (Torres-González, 1989).

The Resolución alluvial valley aquifer is a 9-m-thick alluvial aquifer which overlies a clay or weathered bedrock zone similar to that underlying the Esperanza alluvial valley aquifer. Estimates of transmissivity and hydraulic conductivity within the Resolución alluvial valley aquifer are not available but probably are similar to the Esperanza alluvial valley aquifer.

SUMMARY

Poorly lithified to unlithified carbonate and clastic sedimentary rocks of late Tertiary and Quaternary age comprise an aquifer system and two regional aquifers of the U.S. Caribbean Islands. The South Coast aquifer and the North Coast limestone aquifer system underlies the southern and northern coastal plains of Puerto Rico and accounts for approximately 80 percent of the total amount of ground-water withdrawn from the U.S. Caribbean Island Regional Aquifer-System Analysis (CI-RASA) study area. The Kingshill aquifer of St. Croix is the most extensive aquifer of the U.S. Virgin Islands. However, the importance of the Kingshill aquifer is more a function of its physical extent and the lack of alternative water supplies; it supplied less than 1 percent of the total amount of ground water withdrawn from the U.S. Caribbean islands in 1985.

Rocks that underlie the South Coast ground-water province of Puerto Rico range from Oligocene to Holocene in age. Much of the South Coast ground-water province is underlain by a southward thickening coastal plain wedge that has been interrupted by fault movement; this coastal plain sequence infills a large sedimentary basin that, in places, contains more than 1,000 m of clastic and carbonate sediment. These sedimentary rocks and unconsolidated sediments are underlain by, and in places fault-juxtaposed with, Cretaceous and early Tertiary bedrock that underlie the central mountainous core of Puerto Rico.

The Juana Díaz Formation consists of a basal clastic sequence of late-early Oligocene age and grades upward to shelf and island-slope carbonate rocks of late Oligocene age. In places, the Juana Díaz Formation is, in turn, unconformably overlain by an unnamed sequence of pelagic slope and deep shelf chalk and limestone of early Miocene age. Elsewhere, the Ponce Limestone of middle Miocene to early Pliocene (?) age directly overlies the Juana Díaz Formation. The Ponce Limestone is dominated by a shallow-water reef and carbonate shelf limestone where it crops out west and north of the city of Ponce and where it extends beneath the Quaternary-age fan-delta plain south of the city. However, the Ponce Limestone grades eastward to a thick sequence of clastic nearshore marine, alluvial and fan-delta deposits. Clastic and minor limestone deposits equivalent to the Ponce Limestone are thickest (more than 800 m) where they lie buried beneath the Quaternary fan-delta plain in south-central Puerto Rico.

A 10- to greater than 100-m thick unlithified sequence formed by five large coalescing fan-deltas and minor nearshore marine clastic sediment of Quaternary age (Pleistocene to Holocene age) extends eastward 70 km from Ponce to Patillas. These fan-delta deposits make up the bulk of the stratigraphic sequence that functions as a freshwater aquifer. Fan-delta deposits unconformably (?) overlie the Juana Díaz Formation and Ponce Limestone and equivalents in the central part of the South Coast ground-water province, but directly overlie Cretaceous and early Tertiary rocks in the eastern part of this area. Geologic mapping indicates that the varied thickness of these Quaternary fan deposits is a result of pre-fan preferential denudation and erosion along fractures and faults of the great southern Puerto Rico fault zone. Oligocene sinistral and Miocene normal fault movement appears to have played a significant role affecting the pattern of lithofacies contained within the Juana Díaz Formation and the Ponce Limestone. Paleofloods, Quaternary eustatic changes in base level, and associated changes in paleoclimate played a more important role in terms of controlling the cyclic distribution and thickness of coarse- and fine-grained beds within the fan-

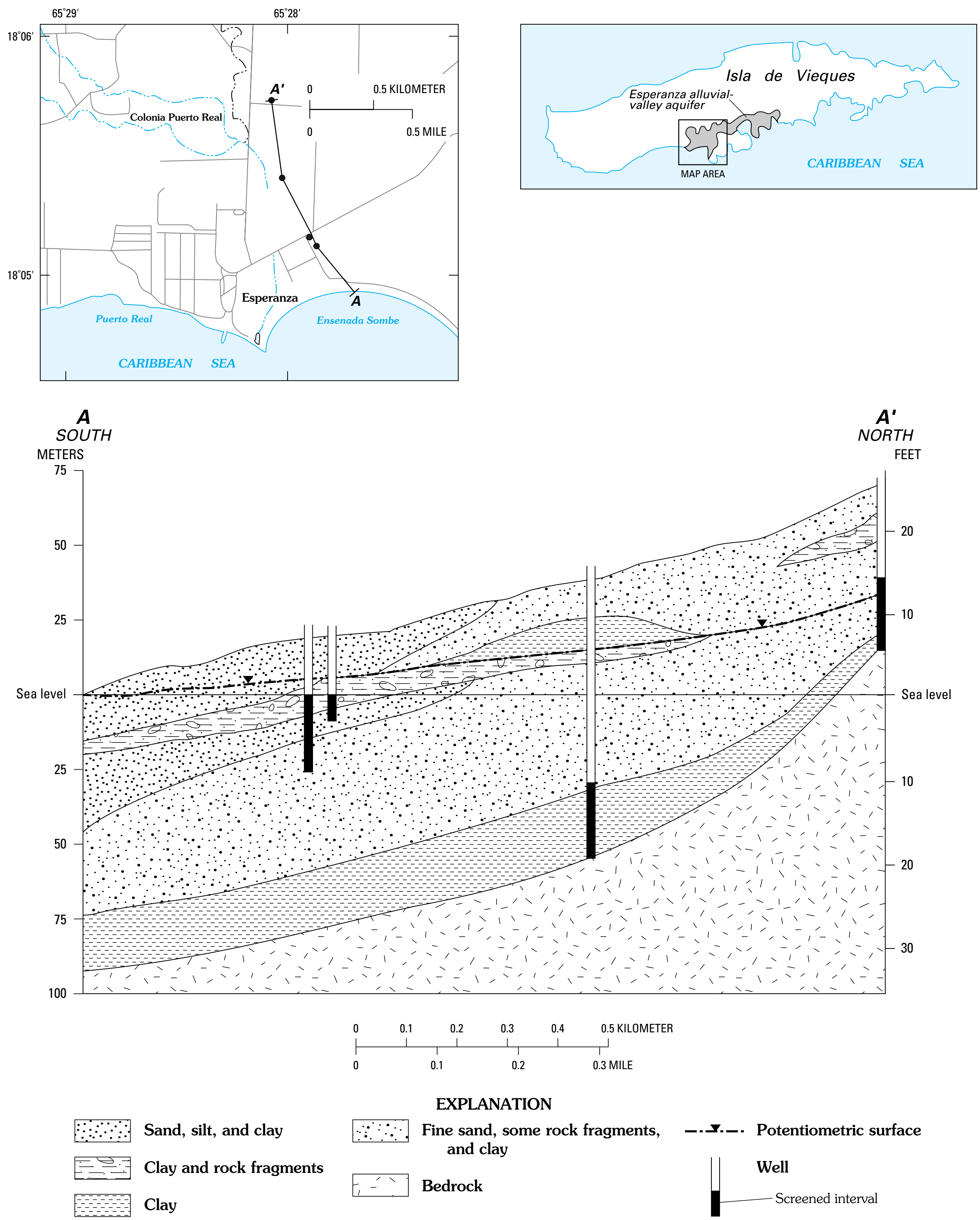

FIGURE 62.—Section *A–A′* showing hydrogeology of the Esperanza alluvial valley aquifer, Isla de Vieques (modified from Torres-Gonzáles, 1989).

delta plain. Surficial and sand-and-gravel percentage maps show that sediments within the fan-delta sequence are deposited as a series of depositional lobes where coarse detritus is concentrated as a lobe and laterally separated from one another by areas underlain by fine sediment.

The South Coast ground-water province of Puerto Rico is separated into three hydrogeologic units that include the South Coast aquifer, alluvial valley aquifers located in the western part of the province, and the Ponce-Juana Díaz aquifer. Boulder- to sand-size detritus constitute the major water-bearing units within the South Coast fan-delta plain and alluvial valley aquifers, and are intercalated with thick beds of silt that impede vertical ground-water movement. Given limited well data, separation of the numerous beds of coarse-grained detritus (1 to 20 m-thick) into distinct, mappable water-bearing units is difficult, if not impossible. However, several intermediate-scale (30- to 40-m thick) depositional cycles containing bedded sequences of sand, pebbles, and cobbles within the distal parts the fan-delta sequence can be viewed as mappable hydrogeologic units.

The pattern of deposition within the fan-delta and alluvial valley sequence appears to directly control the distribution of hydraulic conductivity within these aquifers. Diagenesis is not important to the distribution of porosity or permeability within this sequence. Sand-and-gravel lithofacies maps were used to corroborate the distribution of hydraulic conductivity based on specific capacity data. Highest conductivities are associated with proximal and midfan parts of each fan delta with smallest conductivities corresponding with the interfan and distal parts of the fan. Transmissivity and hydraulic conductivity data of alluvial valley deposits that are present in the western part of the South Coast ground-water province is highest in upland channel areas; the permeability of these sediments diminishes considerably as they extend coastward.

The Ponce-Juana Díaz aquifer is poorly permeable and not considered to be a reliable source of water. Conglomeratic beds are partially-cemented, and limestone beds, for the most part, do not exhibit extensive dissolution features. Secondary permeability within the limestone of the Ponce-Juana Díaz aquifer is found only along fractures and faults that lie buried beneath unconsolidated alluvial deposits.

The South Coast aquifer contains water under unconfined and confined conditions. Unconfined conditions generally occur in the coarse-grained proximal and midfan areas where the aquifer is recharged by irrigation water (surface and ground water), infrequent rain, and streambed seepage from streams entering the fan-delta plain. Regional discharge occurs as seabed and coastal wetland seepage, base flow discharge near the coast, evapotranspiration from the shallow water table, and by well withdrawals. Well withdrawals currently represent the principal mechanism of ground-water discharge. During the 1960's and 1970's, an increase in net ground-water withdrawals led to a decrease in discharge to coastal drains. From 1970 to 1980, a decrease in irrigation deliveries and well withdrawals resulted in a decline in coastal drain ground-water discharge to near predevelopment rates. Regional ground-water flow is largely coastward from the fan apex and foothills with local movement to well fields. Confined conditions are associated with more deeply buried sediments or those that lie in interfan or coastal areas. The intercalated nature of sediments helps explain the confinement in these areas where discontinuous fine-grained beds retard vertical ground-water movement.

The North Coast ground-water province of Puerto Rico is underlain by a northward-dipping coastal plain wedge of carbonate and minor siliciclastic sediments that thicken to as much as 1,700 m near the coast and infills the North Coast Tertiary Basin. The sedimentary rocks of the north coast can be separated into a relatively thin basal section of siliciclastic sedimentary rocks of late Oligocene age and thick upper section of mostly carbonate rocks late Oligocene to middle Miocene in age. The lowermost San Sebastián Formation records a change from nonmarine to shallow-marine deposition in which the thickness of the formation reflects an irregular paleotopography and paralic depositional system. The San Sebastián grades upward to the Lares Limestone, a unit that is thickest in the central part of the basin between the Río Grande de Arecibo and Río Cibuco. The lower and middle parts of the Lares Limestone consist of a cyclic sequence of skeletal wackestone, packstone, grainstone and record a deepening of the carbonate sea. The upper part of the formation consists of dolomitic to clayey wackestone, skeletal wackestone and packstone, and reflects a shallowing of the sea.

In the extreme western part of the basin, the Lares Limestone is absent. Equivalent rocks grade to clayey wackestone and dolomitized wackestone that are similar to the Cibao Formation downdip or to mudstone strata that characterize the San Sebastián Formation. In the eastern part of the basin, the Lares Limestone and overlying Cibao Formation interfinger with sandstone, conglomerate, siltstone, and claystone of the Mucarabones Sand. The Cibao Formation is a complex facies of carbonate, mixed carbonate-siliciclastic, and siliciclastic rocks that reflect differential uplift or subsidence, or both, in highland and marine platform areas. The Montebello Limestone Member of the Cibao Formation, the most permeable part of the North Coast limestone aquifer system's lower aquifer, consists of a packstone-wackestone facies that contains large foraminifera and coral- and algal-rich layers. In adjacent subsurface areas, the mudstone unit consists of calcareous mudstone that contains planktonic foraminifera and may have been deposited within a restricted part of the basin that had undergone preferential subsidence during the early Miocene. At the same time, carbonates of the Montebello Limestone Member built up directly over paleohighs that were subsiding at a slower rate. To the east, carbonate and terrigenous sedimentary rocks of the Río Indio and Quebradas Arenas Limestone Members were deposited within the inner- to middle-platform environments. An uppermost undifferentiated sequence of marl, calcareous mudstone, and clayey wackestone makes up the typical Cibao Formation lithology; this sequence ranges from more than 300 m thick in the western part of the basin to tens of meters thick in the eastern part of the basin.

The Aguada (Los Puertos) Limestone consists of shoaling-upward cycles of skeletal wackestone to packstone and ranges from 60 to nearly 180 m thick. The Aymamón Limestone consists of skeletal wackestone, packstone, lesser grainstone, minor mudstone and coral-algal boundstone. The upper 60 to 90 m is highly karsted with large dissolution holes. The Quebradillas Limestone consists of a globergerinid packstone that is restricted in extent, cropping out or lying in the shallow subsurface in northwestern part of the basin. This formation is unimportant hydrologically as much of it lies above the water table and is unsaturated.

Oligocene to middle Miocene sedimentary rocks of northern Puerto Rico are tentatively divided into five depositional sequences and associated systems tracts. The oldest sequence is not exposed but lies deeply buried and records an early onlap of the basement complex; much of the strata that were deposited as part of this sequence could have been removed by erosion. A second depositional sequence that includes the San Sebastián Formation and Lares Limestone records onlap during a rise in relative sea level. The overlying Cibao Formation represents the third depositional sequence and shows evidence of a transgression following a lowstand that marked the end of Lares Limestone deposition. Uppermost Cibao Formation rocks and the Aquada (Los Puertos) Limestone make up the fourth sequence that include transgressive and high stand systems tracts. A karst surface separates the fourth sequence from overlying fifth depositional sequence, the transgressive Aymamón Limestone.

The North Coast limestone aquifer system can be separated into an upper aquifer, an intervening confining unit, a lower aquifer, and a basal confining unit. The upper aquifer is comprised of the karstic Aymamón Limestone and the underlying Aguada Limestone and contains a basal zone of saltwater that lies as much as 7 km inland from the coast. The middle confining unit consists of clay, mudstone, and marl of the Cibao Formation. The lower aquifer is made up of the Montebello Limestone Member of the Cibao Formation, the Lares Limestone, clastic sediments of the Mucarabones Sand, and in the more inland, updip areas, conglomerate and sandstone beds of the San Sebastián Formation and clastic and carbonate beds of the Quebrada Arenas and Río Indio Limestone Members. The North Coast limestone aquifer system is underlain by a confining unit that consists of poorly permeable mudstone and marl of the deeply buried San Sebastián Formation and lithified volcanogenic and igneous bedrock of early Tertiary and Cretaceous age that underlie and form the mountainous core of Puerto Rico. A number of alluvial valley aquifers overlie the North Coast limestone aquifer system where major rivers extend northward from the central highlands. These alluvial valley aquifers consist of cobbles, pebbles, and sand where present in the narrow, deeply incised upland valleys, but fine coastward to sand, silt, and clay forming wide alluvial plains near the mouths of several major rivers.

Topographic relief and incision of carbonate coastal plain rocks by streams are the principal factors that control the direction of ground-water flow where the upper and lower aquifers crop out. Northward-flowing rivers were deeply incised during Pleistocene sea level lowstands. Subsequently, mechanical erosion breached middip parts of the confining unit. These deeply incised areas are now covered by thick alluvial deposits that were deposited in response to the interglacial rise in sea level. The occurrence of large springs and low potentiometric surfaces within these valley-fill areas indicates that ground water from the lower aquifer probably discharges upward into the alluvium overlying the breached part of the middle confining unit.

The North Coast limestone aquifer system is recharged in topographically-elevated interstream areas and water flows northward toward the Atlantic Ocean, discharging to the major rivers, coastal wetlands, coastal, nearshore, or offshore springs, or as seabed seepage. In the San Juan area, which is likely an area of regional ground-water discharge from the lower aquifer, the upper aquifer is thin or absent and mixed siliciclastic sediments of the Cibao Formation provide an avenue for diffuse upward flow of ground water from the Mucarabones Sand. Ground-water withdrawals and agricultural drainage have locally lowered water levels in the upper aquifer. Ground-water development within the confined part of the lower aquifer is limited to the north-central part of the coastal plain and corresponds to areas where water-level declines have been greatest. This decline is attributed to industrial withdrawals near Barceloneta, upward leakage from poorly constructed wells, and pumping of public supply wells in updip areas near Florida.

Factors that govern the distribution of permeability and porosity within the North Coast limestone aquifer system include the original character of the carbonate rocks, depositional patterns, diagenesis, dissolution along fractures, and processes of karstification. Permeability of the upper aquifer is controlled largely by the distribution of dolomite and formerly aragonitic fossils and, in part, by processes of karstification. It is also possible that recent mixing of meteoric and saltwater lowered calcium carbonate saturation of ground water near the coast causing additional dissolution of limestone and possibly promoting increased permeability in that area. Dissolution along fractures may also have enhanced permeability along fractures within the North Coast limestone aquifer system. Topographic relief and major segments of karst valleys show the strong influence of several regional fracture sets.

Transmissivity of the upper aquifer is also controlled by the thickness of the freshwater lens that thins landward and coastward. The freshwater lens is thickest (100 to 150 m) in regional interstream areas along a zone that roughly corresponds to the point where the saltwater interface intersects the aquifer's lowermost contact. The upper aquifer is most transmissive in these same interstream areas and locally may exceed 10,000 m^2/d. A hydraulic conductivity map of the upper aquifer indicates that permeability of the aquifer increase coastward, with least permeable parts of the aquifer landward and west of Camuy. Transmissivity of the lower aquifer is, in general, an order of magnitude or more lower than that of the upper aquifer and usually ranges from 50 to 800 m^2/d. Greatest transmissivity of the lower aquifer appears to correspond to an area where the Montebello Limestone Member crops out and lies in the subsurface. Transmissivity diminishes to the east and west, paralleling facies changes within these same rocks.

Porosity is highest in coarse grainstone-packstone and low in wackestone and marl. Although moldic porosity is common in mollusk- and coral-rich wackestones, permeability of these rocks is low. Dolomitized zones and moldic grainstone-packstones are some of the most porous and permeable carbonate strata. The dense, recrystallized Aymamón Limestone (upper aquifer) is highly karstic within the upper 30 to 100 m of land surface, and caverous zones and large mud-filled vugs are common. Porosity and permeability of the lower aquifer is developed best within grainstone-packstone and coral-patch-reef limestone. However, these porous zones are usually no more than a few meters thick and most of the section has a low permeability.

The island of St. Croix is bordered to the northwest and east by low hills and mountains underlain by Cretaceous volcaniclastic and minor igneous rocks. These highland areas are separated by a central graben structure largely infilled with early Miocene to Pliocene age pelagic and hemipelagic limestone (Jealousy Formation and the Kingshill Limestone). The Jealousy Formation is the oldest stratigraphic unit in the basin and ranges from early Miocene to early-middle Miocene age and is comprised of a planktonic foraminifera-rich mud. The diachronous contact between the Kingshill Limestone and Jealousy Formation is recognized by a distinctive, but unexplained change in color from light buff to blue-grey or gray. The La Reine Member of Kingshill Limestone (early Miocene to Pliocene age) is lithologically more diverse than the Jealousy Formation and includes packstone (planktonic foraminifera-rich carbonate mud with some lithic grains and pebbles), wackestone, polymictic packstone facies, as well as debris flow beds of coral and terrigenous gravel. Uppermost Kingshill Limestone of thinly-bedded limestone containing greater amounts of shelf-derived carbonate clasts, and foraminiferal faunal remains constitute the Manning Bay Member.

The Mannings Bay Member is a limestone characterized by large benthic foraminifera and skeletal debris, locally dolomitized, and leached by meteoric weathering. The Blessing Formation unconformably overlies the Mannings Bay Member and is thickest in an area formed by a subsidiary Pliocene age graben structure located along St. Croix's south-central coast near Krause Lagoon. Also occurring along the southwest and western coasts, the Blessing Formation of Pliocene age differs considerably from older pelagic limestones of St. Croix. The Blessing Formation consists of reef and shallow lagoon limestone with minor patchy zones of dolomitization.

The Kingshill aquifer consists of the Kingshill Limestone and the Blessing Formation and contains ground water under unconfined conditions. The Jealousy Formation is not considered to be part of the aquifer largely because of the poor hydrochemical character of ground water it contains. Although most of the primary porosity of the Kingshill Limestone aquifer is preserved, it is microscopic. In coarser sediments of the Kingshill Limestone, cementation and recrystallization have destroyed original permeability. Limestone of the Blessing Formation and the Mannings Bay Member of the Kingshill Limestone are more permeable and porous than the underlying units. Diagenesis directly controls permeability and porosity within the Mannings Bay Member and the Blessing Formation and vertical tectonic movement near Krause Lagoon during Pliocene time contributed to the limited geographic distribution of dolomite within these two rock units. Diagenetic factors affecting permeability of the upper Kingshill aquifer include dissolution of unstable minerals, karstification, and possible coastal mixing zone dissolution. Localized dolomitization within the graben structure north of Krause Lagoon has resulted in a localized increase in intercrystalline and moldic porosity. The dolomitization process is attributed to the mixing of evaporated sea and ground water within a structurally-controlled embayment. The moderately permeable alluvial aquifer in St. Croix comprises alluvial fan, debris flow, slope wash, stream alluvium, and lagoonal mud deposits. Restricted in extent, the alluvial aquifer serves as a temporary storage zone for rainfall and runoff, allowing ground water to be slowly released to underlying carbonate aquifers. Many of the large-yield wells reported to be tapping in the Kingshill aquifer are also screened in the alluvium.

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