Hydrogeology of the North Coast Limestone Aquifer System of Puerto Rico

By Jesús Rodríguez-Martínez

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CONTENTS

FIGURES

TABLE

CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND ACRONYMS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
mile (mi)	1.609	kilometer
square foot (ft^2)	929.0	square centimeter
square mile (mi^2)	2.590	square kilometer

Temperature: Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8 \times °C + 32$$

Transmissivity: the standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form of this unit, foot squared per day (ft^2/d), is used for convenience.

Abbreviated water-quality units used in this report:

mg/L milligrams per liter
µS/cm microsiemens per centimeter at 25 degrees Celsius

Acronyms used in this report:

MSL Mean Sea Level
USGS U.S. Geological Survey

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Abstract

The North Coast Limestone aquifer system of Puerto Rico is composed of three regional hydrogeologic units: an upper aquifer that contains an underlying saltwater zone near the coast, a middle confining unit, and a lower aquifer. The upper aquifer is unconfined, except in coastal areas where it is locally confined by fine-grained surficial deposits. The upper aquifer is mostly absent in the Río Piedras area of northeastern Puerto Rico. The confining unit is composed of calcareous claystone, marl, chalky and silicified limestone, and locally clayey fine-grained sandstone. Test hole data indicate that the confining unit is locally leaky in the San Juan metropolitan area. An artesian zone of limited areal extent exists within the middle confining unit, in the central part of the study area. The lower aquifer mostly contains ground water under confined conditions except in the outcrop areas, where it is unconfined. The lower aquifer is thickest and most transmissive in the north-central part of the study area. Water in the lower aquifer is fresh throughout much of the area, but is brackish in some areas near San Juan and Guaynabo.

West of the Río Grande de Arecibo, the extent of the lower aquifer is uncertain. Data are insufficient to determine whether or not the existing multiple water-bearing units in this area are an extension of the more productive lower aquifer in the Manatí to Arecibo area. Zones of moderate permeability exist within small lenses of volcanic conglomerate and sandstone of the San Sebastián Formation, but in general this formation is not a productive aquifer.

Transmissivity values for the upper aquifer range from 200 to more than 280,000 feet squared per day. The transmissivity values for the upper aquifer generally are highest in the area between the Río de la Plata and Río Grande de Arecibo, where transmissivity values have been reported to exceed 100,000 feet squared per day in six locations. Transmissivity estimates for the lower aquifer are highest in north central Puerto Rico, where the Lares Limestone and the Montebello Limestone Member of the Cibao Formation have transmissivities as high as 500 and 3,600 feet squared per day, respectively.

INTRODUCTION

The North Coast Limestone aquifer system is an important source of ground water in Puerto Rico. It consists of a highly karstified carbonate platform sequence of middle Tertiary age and extends eastward 85 miles (mi) from Rincón, in western Puerto Rico, to Loíza in northeastern Puerto Rico (fig. 1).

This aquifer system is composed of three main hydrogeologic units: an upper aquifer and a lower aquifer, separated by a confining unit of variable thickness (Giusti, 1978). Although the upper aquifer has been developed extensively in some areas, relatively little is known about the aquifer system, particularly the lower aquifer. To gain a better understanding of this regional aquifer system, the U.S. Geological Survey (USGS), in cooperation with the Commonwealth of Puerto Rico Department of Natural and Environmental Resources, conducted a study of the hydrogeology of the North Coast Limestone aquifer system from 1983 to 1988.

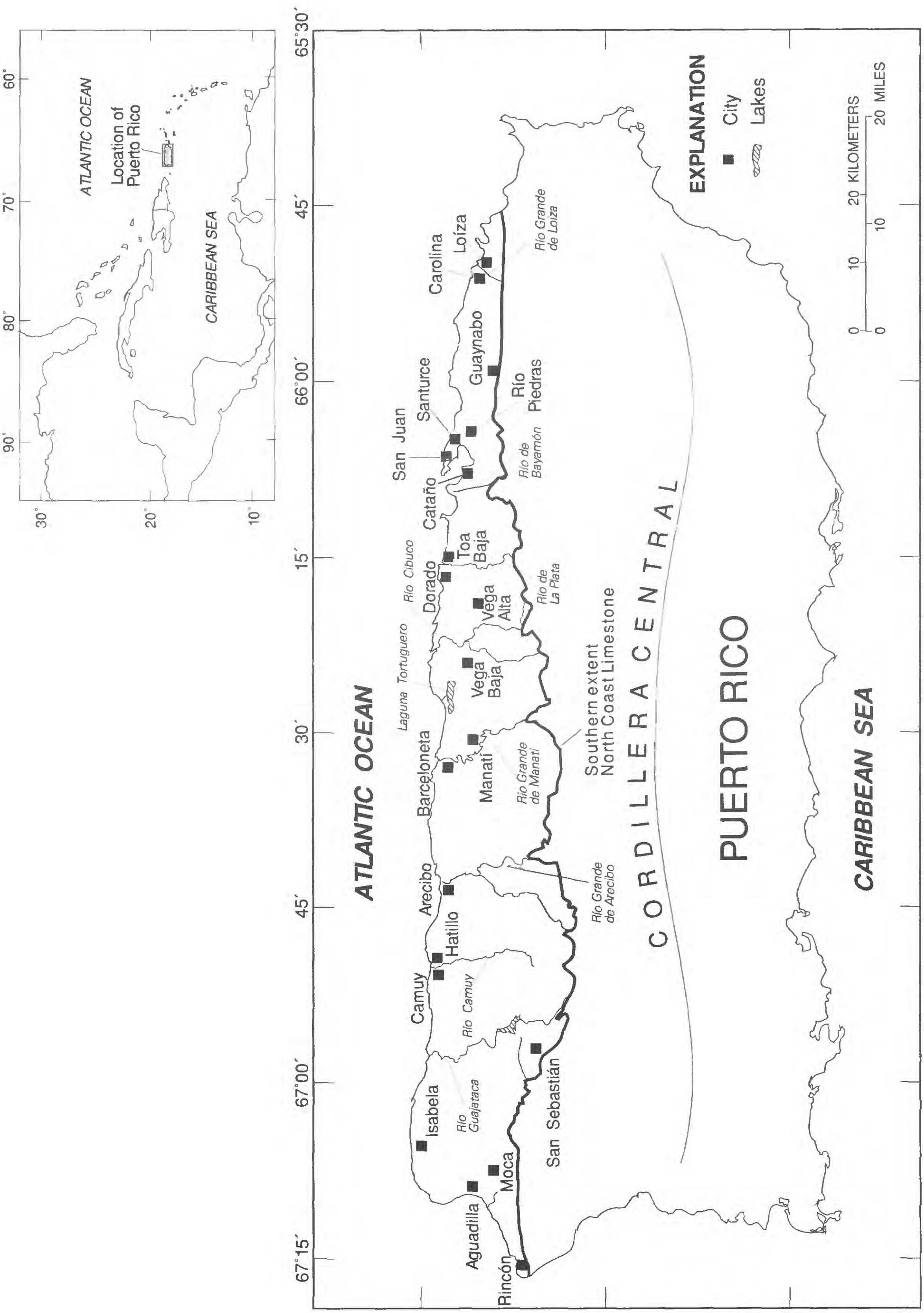

Figure 1. Areal extent of the North Coast Limestone of Puerto Rico.

Purpose and Scope

The purpose of this report is to describe the regional hydrogeologic units and the hydrogeologic framework of the North Coast Limestone aquifer system. The regional aquifers and confining units have been mapped on the basis of relative permeability and hydraulic continuity of geologic materials penetrated by a series of deep test wells and test holes drilled during the study (fig. 2). Lithologic, geophysical, and hydraulic data for the test wells and test holes and from other wells in the area were also used to prepare a series of hydrogeologic sections showing the variations in the lithology and thickness of the main hydrogeologic units in the study area. These hydrogeologic sections are presented in this report, along with maps showing the distribution of estimated ranges of transmissivity for the major aquifers in the North Coast Limestone.

Geographic Setting

The North Coast Limestone of Puerto Rico underlies about 700 mi^2 in the northern one-third of Puerto Rico and extends eastward from Rincón in the western part of the island to Loíza (fig. 1), a distance of about 85 mi. The North Coast Limestone extends from the Atlantic Ocean southward to a central east-west ridge that is part of the Cordillera Central Mountain Region. The outcrop area of North Coast Limestone is approximately 11 mi wide near Camuy and narrows to 2.25 mi near San Juan.

The North Coast Limestone is drained by eight major rivers that originate in the mountainous volcanic terrane to the south. These rivers flow predominantly north to the Atlantic Ocean.

The surface exposure sequence of middle Tertiary age is characterized by tropical karst topography. In the northwestern part of Puerto Rico, the karst topography is characterized by high relief and deeply entrenched river channels or rivers with subterranean courses in some areas. In the north-central part of the island, the land surface is characterized by numerous karst features including sinkholes and limestone hills (mogotes). In this part of the island, dissolution processes generally are still very active in the intermogotal areas. The karst topography in the eastern part of the island, which includes the municipalities of San Juan and Loíza, is in an older stage of development. There, the karst development is characterized by low topographic relief with little or no active dissolution of limestone, and by surface, rather than underground drainage (Monroe, 1976).

Previous Hydrogeologic Studies

The first study of the North Coast Limestone was conducted by McGuinness (1948), as part of a general reconnaissance of the ground-water resources of Puerto Rico. Subsequent hydrogeologic studies in the North Coast Limestone, prior to 1973, are summarized by Giusti (1978). In his report, Giusti discussed the hydrogeology of the North Coast Limestone karst, placing emphasis on the upper aquifer. Since 1973, a series of hydrologic investigations in parts of the North Coast Limestone have been carried out by the USGS in cooperation with various agencies of the Commonwealth of Puerto Rico (Anderson, 1976; Gómez-Gómez, 1984; Torres-González and Wolansky, 1984; Torres-González, 1985a and 1985b; Quiñones-Aponte, 1986; Gómez-Gómez and Torres-Sierra, 1988). None of these studies, however, described the hydrogeologic framework of the lower part of the aquifer system in detail.

Method of Study

The geologic and hydrogeologic framework of Puerto Rico's North Coast Limestone belt is based largely on core and hydrologic data collected from 15 deep test wells, mostly drilled to depths exceeding 1,500 ft (fig. 2 and table 1), and on lithologic as well as hydrologic data from three other existing wells. These deep test wells were drilled as part of a cooperative Commonwealth of Puerto Rico-USGS investigation to evaluate the water-resources 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 can be used to collect continuous core samples of 10-cm diameter. Limestone core samples considered

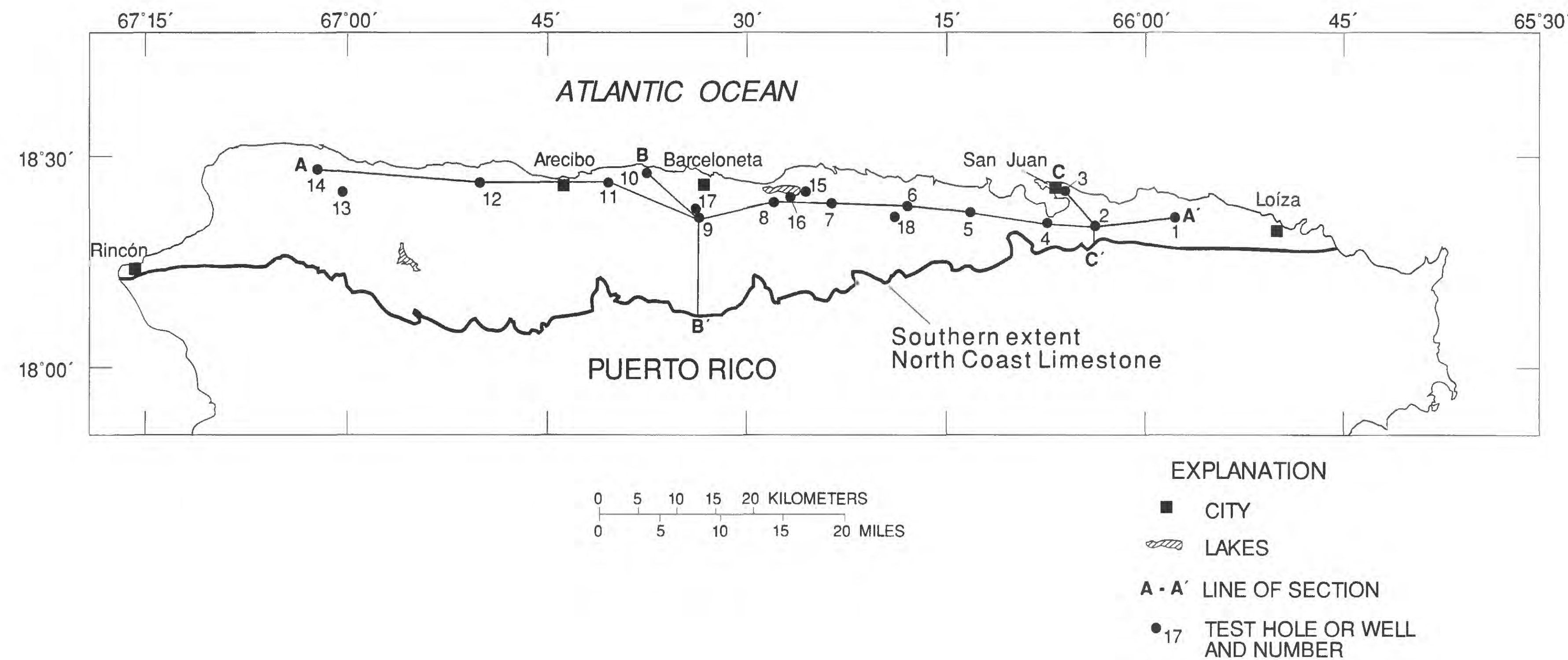

Figure 2. Location of test wells, test holes, and lines of section within the extent of the North Coast Limestone of Puerto Rico (the location and description of the test holes and wells are shown in table 1).

Table 1. Location and description of test holes, test wells, and supply wells in the study area used in this report
[--, indicates no data available; °, degrees; ', minutes; ", seconds]

Test well or hole number in figure 2	Location in figure 1	Local well or hole designation	Latitude	Longitude	Casing depth below land surface (feet)	Total depth below land surface (feet)
1	Loíza	NC-12	18°26'44"	65°55'31"	--	1,450
2	Río Piedras	NC-3	18°24'32"	66°02'33"	--	375
3	Santurce	NC-15	18°26'37"	66°04'22"	--	1,268
4	Guaynabo	NC-1	18°25'33"	66°06'45"	--	635
5	Toa Baja	NC-13	18°26'30"	66°12'23"	--	1,506
6	Dorado	NC-2	18°27'01"	66°18'22"	--	2,128
7	Vega Baja	NC-9	18°27'35"	66°23'43"	--	1,725
8	Interaquifer System (Manatí)	[1]IAS-1	18°27'32"	66°28'13"	--	2,700
9	Cruce Dávila (Barceloneta)	[2]NC-5	18°25'38"	66°34'12"	1,750	2,564
10	Islote, Arecibo	[3]CPR-4	18°29'29"	66°36'13"	--	6,934
11	Santana, Arecibo	--	18°27'01"	66°38'58"	--	1,520
12	Hatillo	NC-6	18°27'57"	66°49'26"	--	2,574
13	Isabela	NC-7	18°28'05"	67°02'58"	--	760
14	Isabela	NC-11	18°29'19"	67°03'13"	--	2,120
15	Manatí	NC-14	18°27'43"	66°25'22"	--	1,898
16	Manatí	NC-4	18°26'33"	66°26'26"	--	1,837
17	Barceloneta	NC-10	18°26'05"	66°34'44"	--	1,516
18	Vega Alta	NC-8	18°25'18"	66°19'43"	--	1,736

[1] Test hole drilled as part of the Interaquifer Project (C. Conde, U.S. Geological Survey, written commun., 1990).

[2] Test well drilled as part of the North Coast Limestone study and used as an observation well completed in the lower confined aquifer.

[3] Oil test well.

representative of a certain bed, or sequence of beds, were selected, slabbed and thin sectioned for study at the University of New Orleans. Analyses included the study of carbonate rock texture, porosity, fossil content, bedding, and identification of other possible depositional and diagenetic features.

The geologic framework for major rock units that lie buried in the subsurface (Ward and others, 1991) serves as the physical basis for the hydrogeologic framework described in this report. Major hydrogeologic units of the North Coast Limestone aquifer system were separated on the basis of relative permeability and hydraulic continuity. Field data from these 18 test wells and existing wells were used to compile maps that show the distribution of transmissivity within major aquifers and the position of the freshwater-saltwater interface. These data also were used to prepare hydrogeologic sections that show the thickness of the freshwater lens contained within the upper aquifer.

A chloride concentration of 500 milligrams per liter (mg/L) was used to delineate the boundary between the saltwater and freshwater zones of the upper aquifer. This concentration represents slightly saline water. Because of the absence of data on chloride concentrations in certain areas of the north coast, both surface resistivity and borehole geophysical data obtained from the test holes drilled for this study and from existing wells were also used in the delineation of the saltwater zone. The mixing zone of freshwater and saltwater where chloride concentrations exceed 500 mg/L is considered part of the saltwater zone in this report.

GEOLOGIC SETTING

The stratigraphic nomenclature of the middle Tertiary age sequence of rocks of the North Coast Limestone belt used in earlier USGS reports is that proposed by Monroe (1980). In a more recent study, Seiglie and Moussa (1984) proposed a somewhat different stratigraphic nomenclature that is based on paleontologic and lithologic data collected from two water wells in the Manatí area of north central Puerto Rico (fig. 3). However, the nomenclature of Monroe (1980) is largely used in this report because it is based on stratigraphic observations made along the entire north coast of Puerto Rico. One exception is reference to the mudstone unit of Seiglie and Moussa (1984) that occurs only in the subsurface.

A thick sequence of platform carbonates and minor clastics ranging in age from middle Oligocene to Miocene, constitute the sequence of middle Tertiary age rocks of the North Coast Limestone belt (fig. 4). These rock units make up a homoclinal sequence that dips gently northward (Monroe, 1980; Meyerhoff and others, 1983) at an average dip of three to four degrees; the dip ranges from two degrees near the coast to six or seven degrees where these rocks lie in contact with the volcanic core of Puerto Rico (Monroe, 1980). Local faulting and fracturing may be responsible for the apparent alignment of geomorphic features of the province, such as limestone hills (mogotes), sinkholes, and straight rivers segments (Meyerhoff and others, 1983).

The sequence of formations of late-middle Tertiary age of the North Coast Limestone is the product of several minor and major regressions and transgressions of the sea that occurred between Oligocene and Miocene time (Seiglie and Moussa, 1984). A variety of depositional environments are represented in the late Tertiary age sequence: fluvial, coastal marginal marine, and open-marine conditions (Seiglie and Moussa, 1984). Fore-reef and outer-shelf environments, indicative of deep-water conditions, are only locally represented (Seiglie and Moussa, 1984; Hartley, 1989; Scharlach, 1990).

A generalized east-west geologic section showing the major rock units of the north coast province is shown in figure 5. In ascending order these units are: the San Sebastián Formation, the Lares Limestone, the Mucarabones Sand, the Cibao Formation, the Aguada Limestone, the Aymamón Limestone, and the Camuy Limestone. The San Sebastián Formation consists of coastal and fluvial clastics, marginal marine clay, and inner platform limestone. The Lares Limestone consists of mid-platform, and minor inner- and outer-platform carbonate rocks. The Mucarabones Sand, which is in part chronostratigraphically equivalent to the Lares Limestone and the lower part of the Cibao Formation, consists of marginal marine quartz sand and minor fluvial clastics. The Cibao Formation is separated into the Montebello Limestone Member, an unnamed mudstone unit of Seiglie and Moussa (1984) and an unnamed upper part. The Montebello Limestone Member, the Río Indio Limestone Member, and the Quebrada Arenas Limestone Member consists of mid-platform limestones. The Río Indio Limestone and the Quebrada Arenas Limestone Members are made-up of inner and mid-platform carbonates containing terrigenous material. The mudstone unit consists of deep-water claystone and marl, and the uppermost part of the Cibao Formation consists of claystone, marl, and limestone containing terrigenous material. The Aguada Limestone is composed of inner- to middle-platform carbonates. The Aymamón Limestone is a mid-platform coral-rich limestone; and the Camuy Formation, the youngest unit, is mostly an inner platform chalk but locally includes minor terrigenous material.

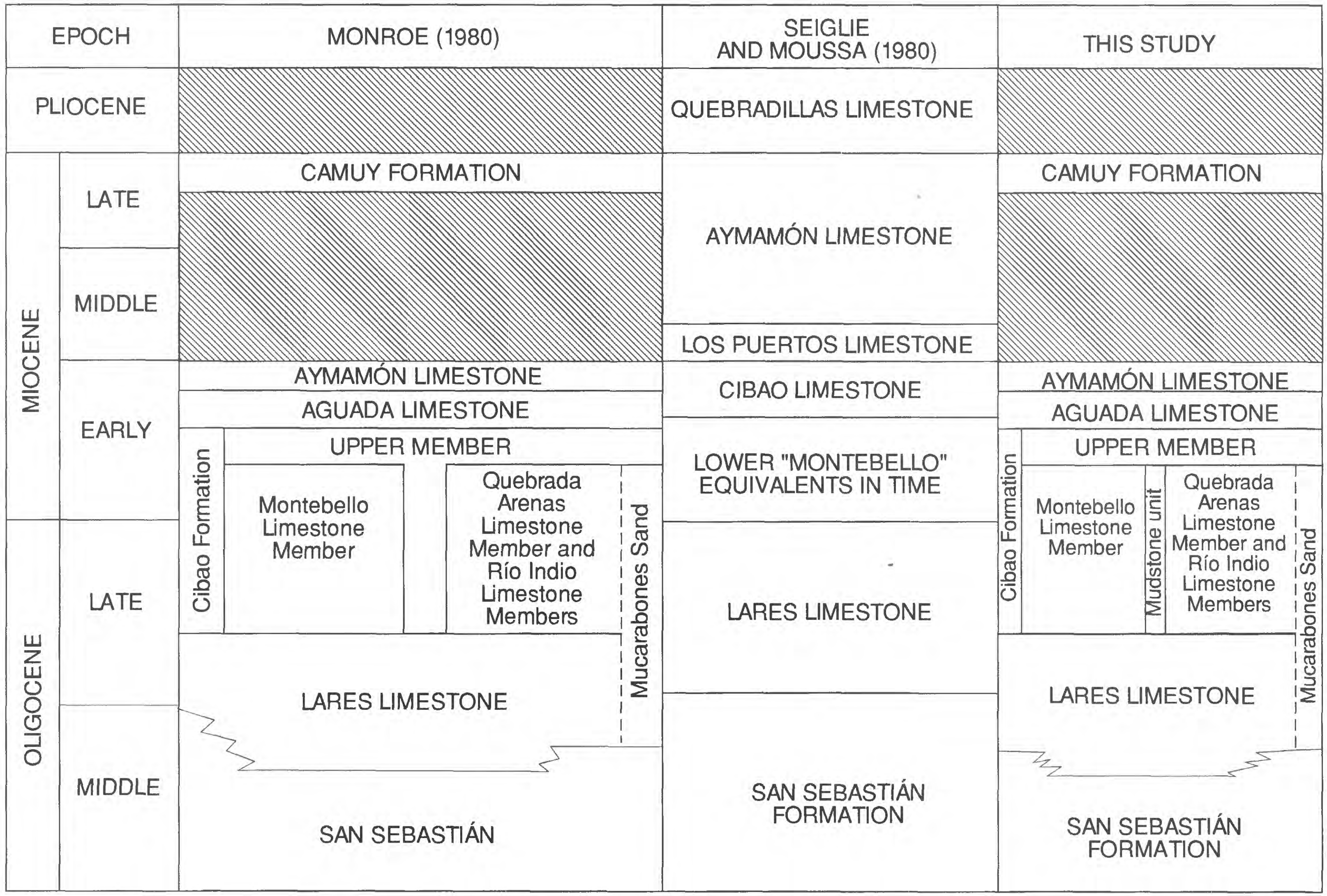

Figure 3. Stratigraphic nomenclature sequence of middle Tertiary age of the North Coast Limestone of Puerto Rico.

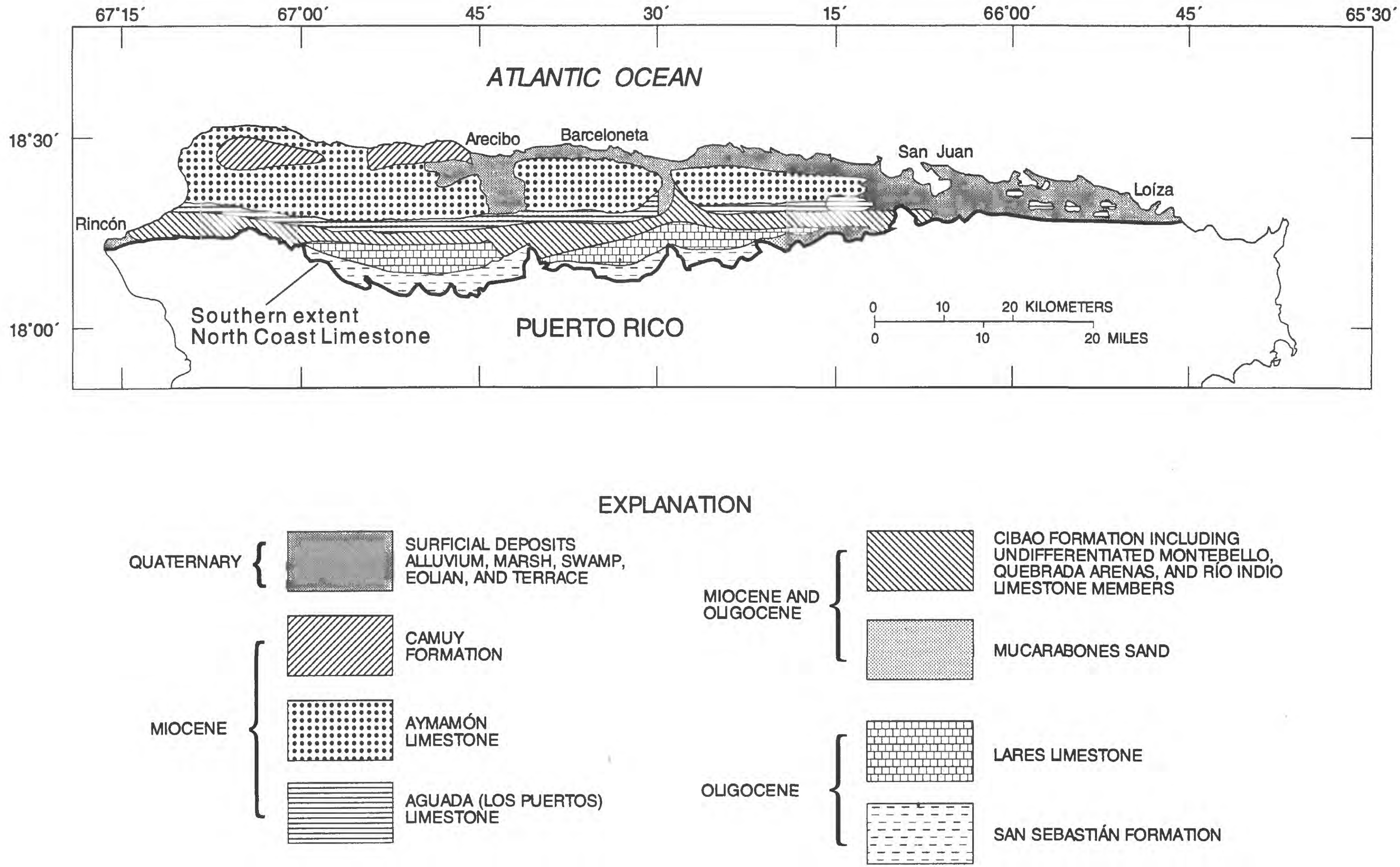

Figure 4. Generalized geologic map of the North Coast Limestone belt of Puerto Rico (modified from Monroe, 1980).

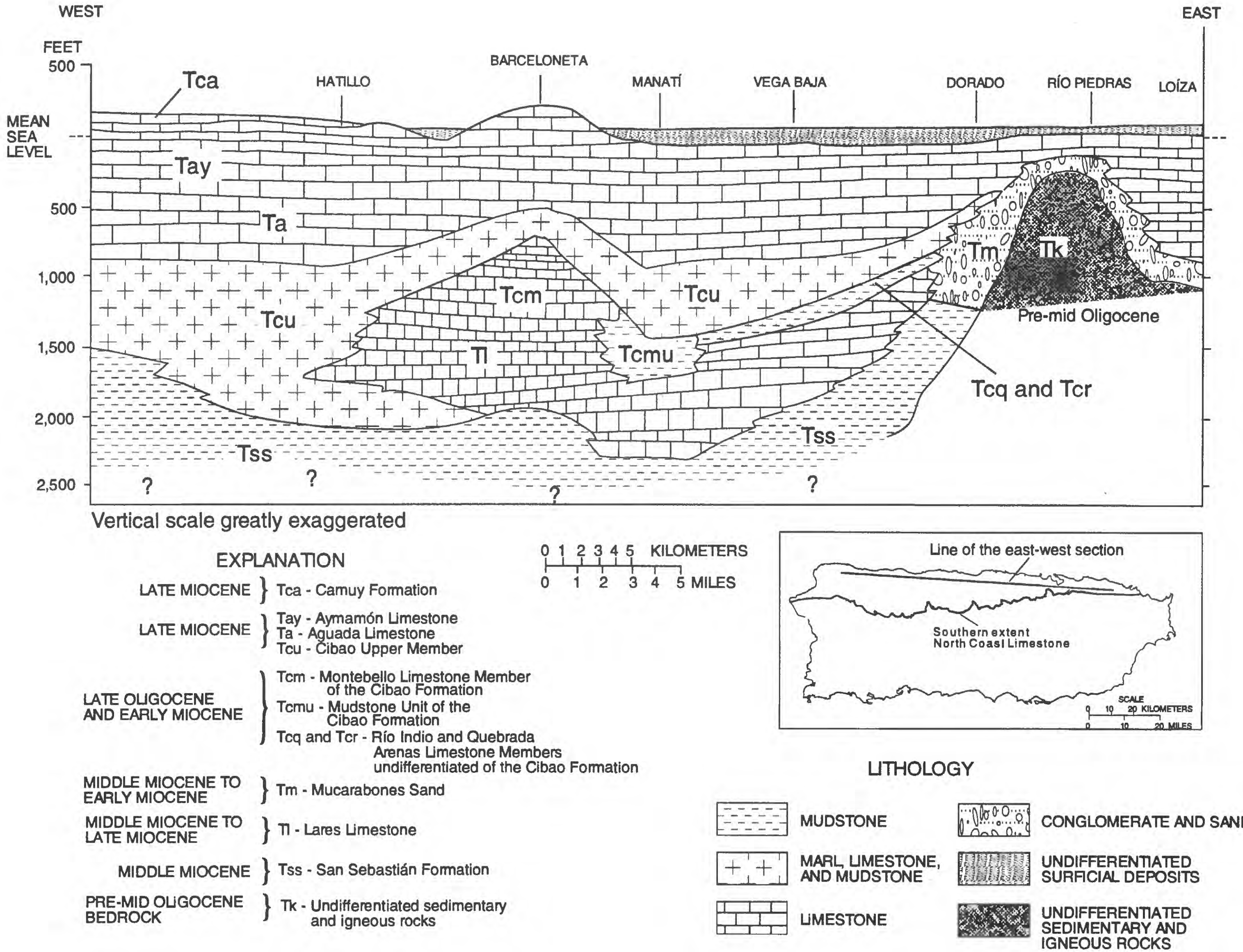

Figure 5. Generalized east-west geologic section sequence of middle Tertiary age of the North Coast Limestone belt of Puerto Rico.

Underlying basement rocks consist of Late Cretaceous and early Tertiary volcaniclastics (siltstone, sandstone, breccia, and conglomerate), minor limestone and minor amounts of igneous intrusive rocks (Monroe, 1980; Meyerhoff and others, 1983). Geophysical and geological evidence indicate that a number of structural highs have compartmentalized the middle Tertiary basin into a series of sub-basins (Meyerhoff and others, 1983; fig. 6). The vertical and lateral relations between the various sedimentary formations observed in the lower part sequence of middle Tertiary age; the San Sebastián Formation, the Lares Limestone, and the Cibao Formation seem to be controlled by the presence of these sub-basins (Meyerhoff and others, 1983; Hartley, 1989). The sedimentary facies of the Aguada (Los Puertos) and Aymamón Limestones and the Camuy Formation do not seem to be controlled by these sub-basins.

REGIONAL HYDROGEOLOGIC UNITS

The North Coast Limestone aquifer system is divided into three regional hydrogeologic units: an upper aquifer containing a basal saltwater zone in the coastal region, an intervening confining unit, and a lower aquifer. A local artesian zone also has been identified within the confining unit in some areas. The upper aquifer, which includes the freshwater part and the underlying saltwater zone near the coast, the confining unit, and the lower aquifer are discussed in the following sections.

Upper Aquifer

The upper aquifer mainly consists of the Aymamón Limestone and underlying Aguada (Los Puertos) Limestone, however, in some areas the upper aquifer also includes the uppermost permeable beds of the upper member of the Cibao Formation and overlying permeable surficial deposits (fig. 7). The upper aquifer contains water under unconfined conditions, except in coastal areas where it is locally confined by overlying silty and clayey surficial deposits. The upper aquifer contains a basal saltwater zone in much of the coastal areas of northern Puerto Rico (figs. 7 and 8).

The thickness of the upper aquifer along section A-A' (fig. 7) ranges from about 450 ft in the Arecibo and Barceloneta area to about 1,075 ft in the Isabela area to the west and about 925 ft near Manatí to the east. East of Vega Baja it decreases to about 650 ft in the Toa Baja area. The upper aquifer is absent in some parts of the Río Piedras area. In the San Juan metropolitan area, the upper aquifer where locally present, is thin and well yields are small. The Aymamón and the Aguada (Los Puertos) Limestones have been extensively eroded by karstification east of Toa Baja, and many of the thin erosional remnants have little hydrologic importance. In the area of Loíza, the upper aquifer is present as a continuous unit and has a thickness of about 750 ft.

The base of the upper aquifer is primarily defined by the uppermost strata of terrestrial clastics and argillaceous limestone of the upper member of the Cibao Formation. However, in the Hatillo-Isabela area the base of the upper aquifer seems to coincide with the lower boundary of the karstic zone located in the Aguada Limestone where this geologic unit is characterized by a significant decrease in porosity and increase in the clayey content of the rocks.

The freshwater zone on section A-A' of the upper aquifer is thickest in the area between the Río Grande de Arecibo and Río Grande de Manatí with a maximum thickness of about 500 ft (fig. 7). The freshwater part in the coastal zones of the San Juan metropolitan and Loíza areas is either absent or present with a thickness that does not exceed 30 ft. In the Guaynabo area, along section A-A', the upper aquifer is mostly brackish and saline. In north-south sections B-B' and C-C', the maximum thickness of the freshwater zone is greatest in the interstream areas of the southern extent of the freshwater-saltwater interface (figs. 8 and 9).

The freshwater zone of the upper aquifer is underlain by a basal zone of saltwater along the coast. The landward extent of this saltwater zone is not known for the entire north coast, but is about 6 mi in the Barceloneta area (fig. 8). In the Santurce-San Juan area, the landward extent could be about 3 mi (fig. 9). The position of the

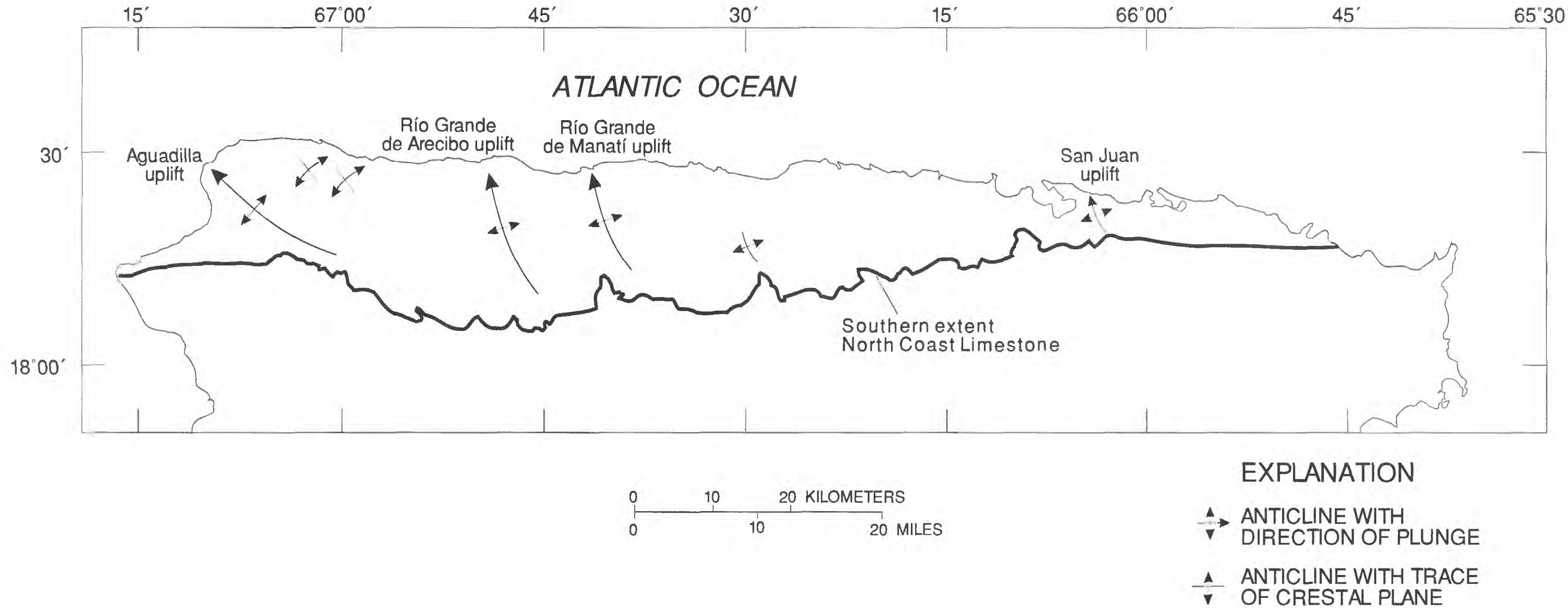

Figure 6. Major structural features of the North Coast Limestone belt of Puerto Rico (modified from Meyerhoff and others, 1983).

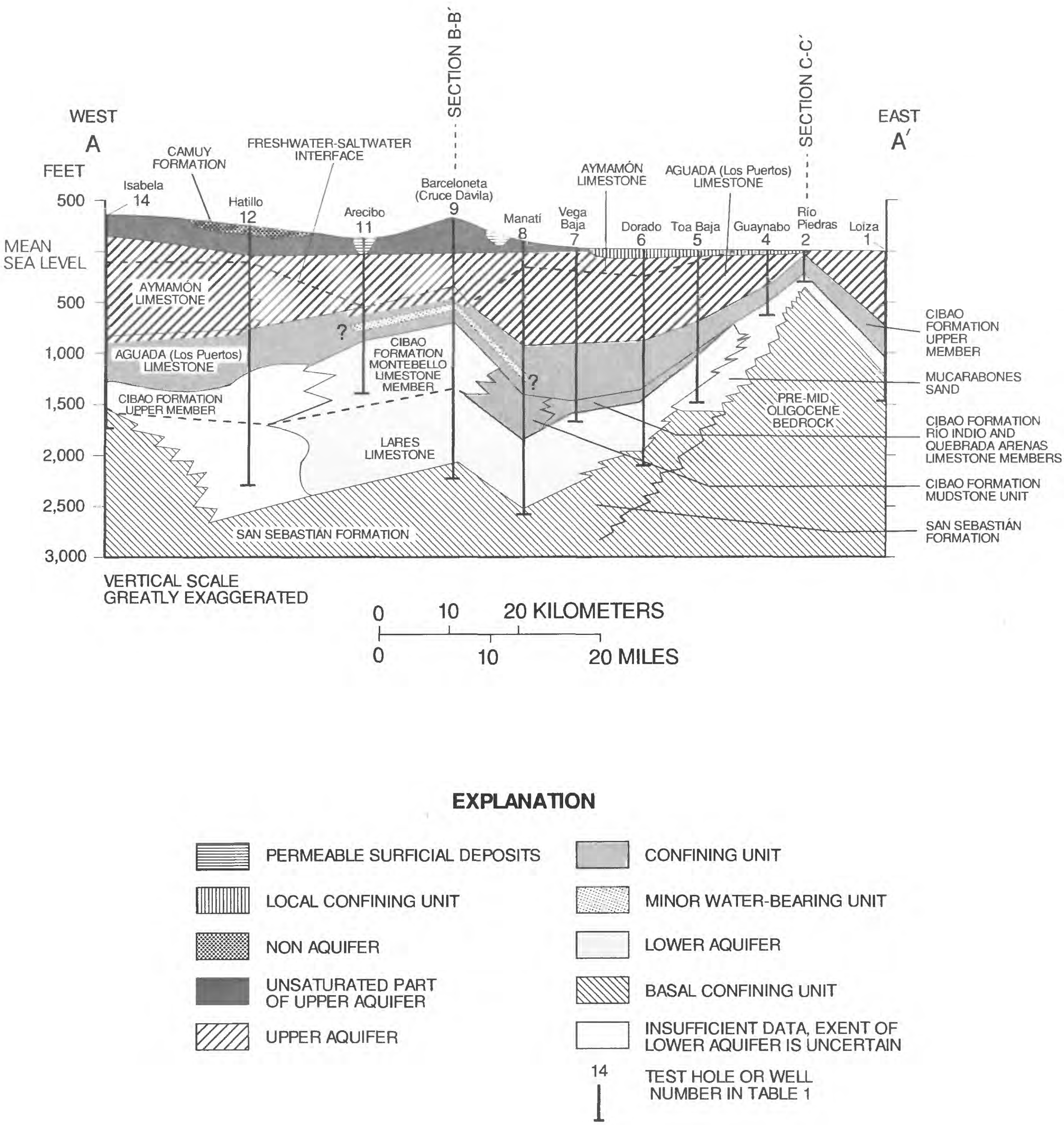

Figure 7. Hydrogeologic section A-A' (section line shown in figure 1).

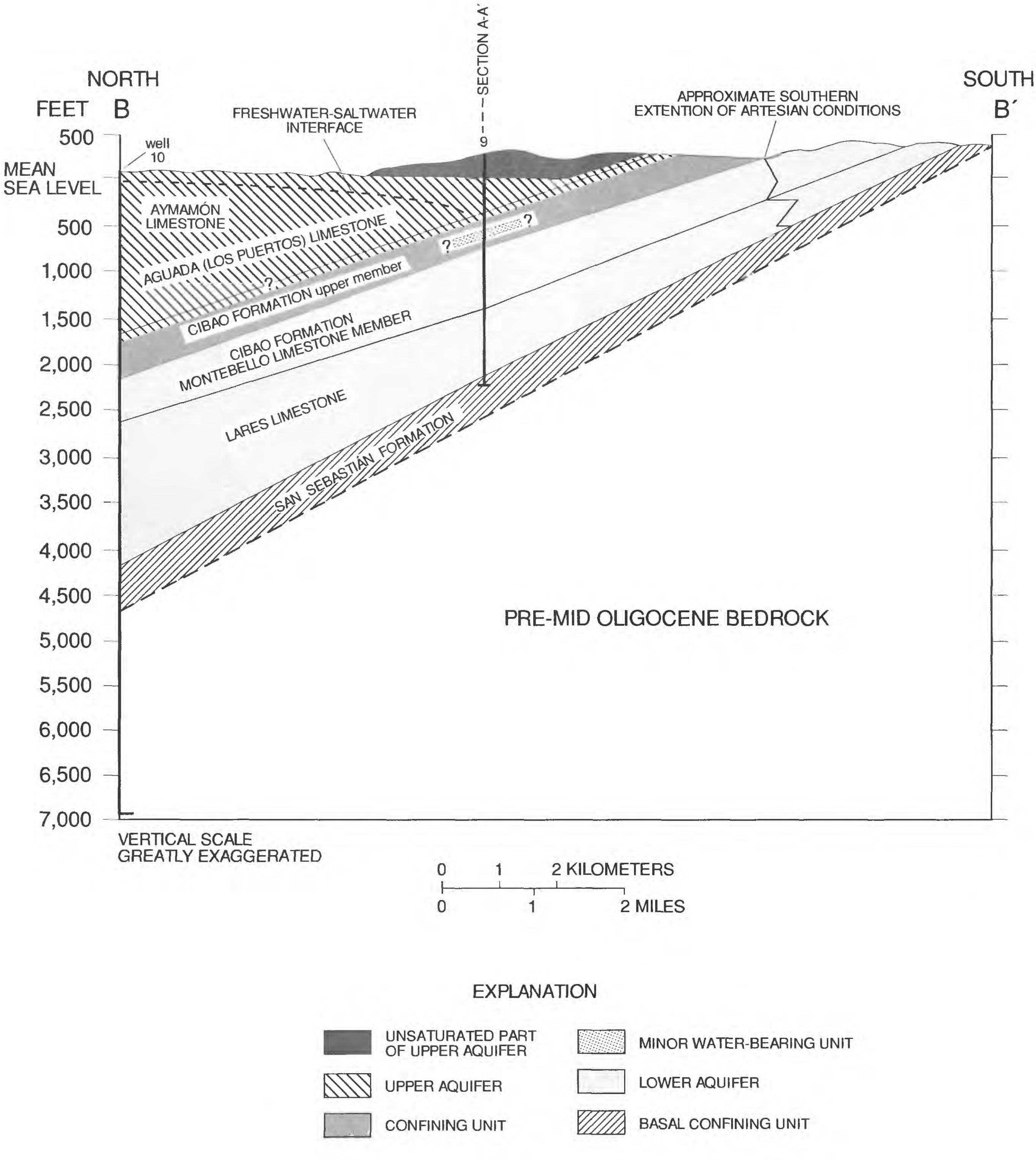

Figure 8. Hydrogeologic section B-B' (section line shown in figure 2).

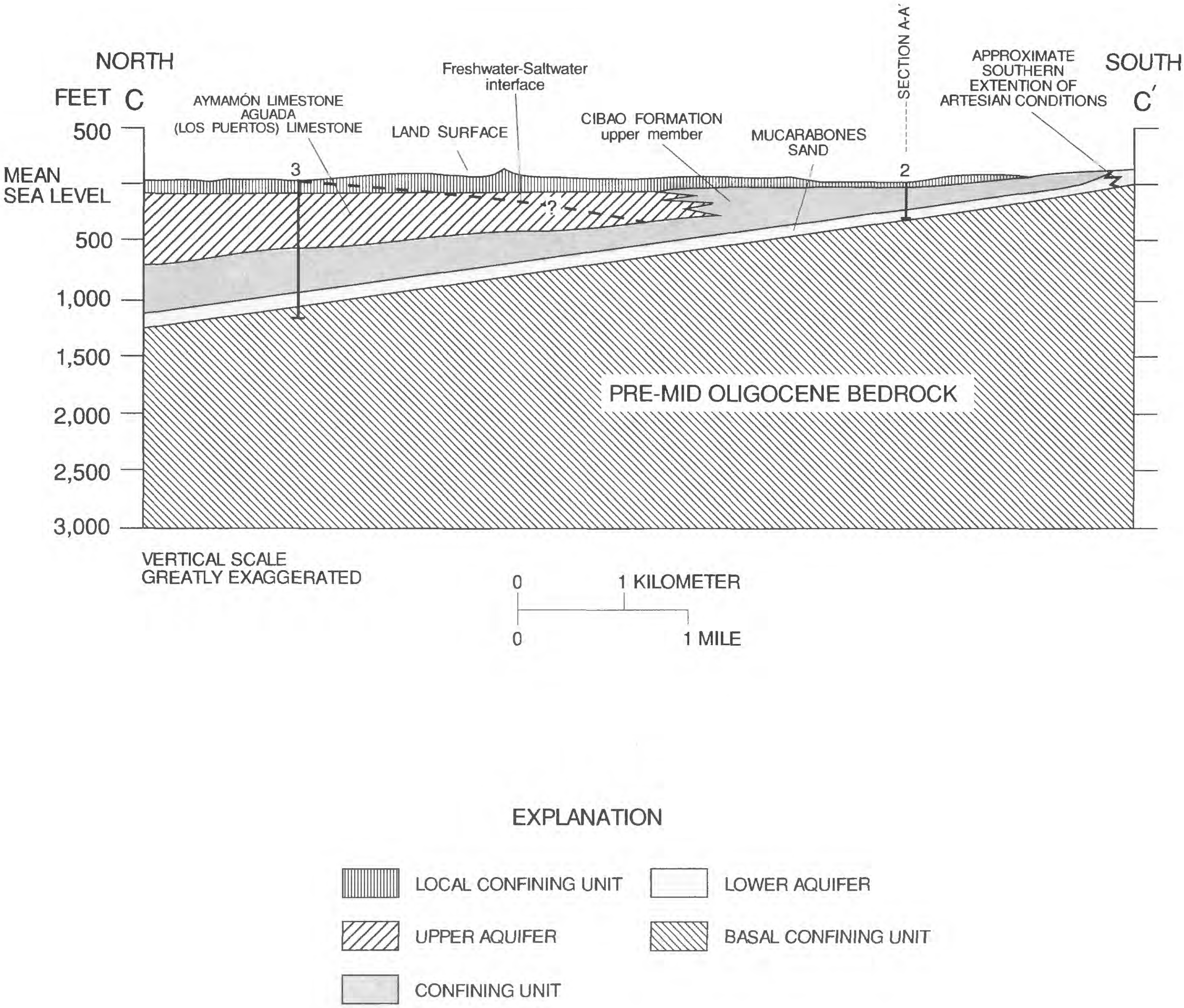

Figure 9. Hydrogeologic section C-C' (section line shown in figure 2).

freshwater-saltwater interface (fig. 10) is a function of the hydraulic properties of the aquifer, the effects of pumping, and large rivers that function as drains.

The most permeable of the geologic units that constitute the upper aquifer is the Aymamón Limestone (Giusti, 1978). The estimated hydraulic conductivity of this geologic unit ranges from 57 to 570 ft/day (Giusti, 1978). The hydraulic conductivity within the Aymamón Limestone generally diminishes with depth. The decrease in hydraulic conductivity is probably related to a maximum effective depth to which karstification will occur within the aquifer. Because hydraulic conductivity can vary with depth, use of site specific values of hydraulic conductivities to determine the transmissivity of the upper aquifer is not appropriate. Transmissivity values determined from aquifer tests or specific capacity data reflect the vertical variations in hydraulic conductivity and are used in this report to describe the regional transmissive properties of the freshwater zone of the upper aquifer. In some localities, site specific values of transmissivity may not be in good agreement with regional transmissivity, because locally transmissivity can reflect the irregular distribution of cavernous porosity.

The areal distribution of transmissivity in the freshwater zone of the upper aquifer is controlled, in part, by the depositional environment, diagenesis, and fractures in the Aymamón and Aguada (Los Puertos) Limestones. Another factor controlling transmissivity is the thickness of the freshwater lens.

Transmissivity estimates are available in most areas underlain by the freshwater zone of the upper aquifer. Estimates are sparse, however, for the areas east of the Río de La Plata and west of the Río Camuy. The transmissivity and hydraulic conductivity of the aquifer are not well documented for these areas. Available transmissivity estimates for the freshwater zone of the upper aquifer range from 200 to more than 280,000 ft^2/d (F. Gómez-Gómez and S. Torres-González, U.S. Geological Survey, written commun., 1990; fig. 11).

The maximum transmissivity of the freshwater zone of the upper aquifer (more than 280,000 ft^2/d) is in the area between the Río Grande de Arecibo and the Río de La Plata, where the transmissivity of this zone is reported to exceed 100,000 ft^2/d at six locations in this area. These high transmissivity values probably are the result of the cavernous porosity and enhanced dissolution along bedding planes, joints, and fractures. Also in this area the Aymamón Limestone is mostly a grainstone-packstone and coral boundstone and has as much as 25 percent total porosity (Hartley, 1989; Scharlach, 1990). Locally, the transmissivity of minor water-bearing units underlying the San Juan metropolitan area range from 200 ft^2/d (Rullán well) to 500 ft^2/d (Banco de Ponce well) (I. Padilla, U.S. Geological Survey, written commun., 1990).

Confining Unit

Although the upper member of the Cibao Formation is the principal rock-stratigraphic unit of the middle confining unit, the upper boundary of the confining unit does not always coincide with its top. For example, the uppermost part of the Cibao Formation is reef limestone (wackestone-packstone) in the Barceloneta and Arecibo areas (test wells 9 and 11, respectively). In these areas, the upper part of the upper member of the Cibao Formation is considered part of the upper aquifer (figs. 7 and 8).

The areal and vertical extent of the confining unit are well known in the Arecibo to Manatí area, but are less precisely known east and west of this area. The confining unit gradually thickens east of Barceloneta (fig. 7). Between Manatí (test well 8) and Vega Baja (test hole 7), the confining unit consists of the upper member of the Cibao Formation, the underlying Quebrada Arenas and Río Indio Limestone Members, and the mudstone unit. In this area, the confining unit ranges in thickness from 250 ft at test well 9 in Barceloneta to about 925 ft at test well 8 in Manatí. At test hole 6 near Dorado, the confining unit includes the Río Indio Limestone and the Quebrada Arenas Limestone Members and the upper member of the Cibao Formation and is about 600 ft thick. The confining unit is about 225 ft at test hole 2 near Río Piedras east of Dorado.

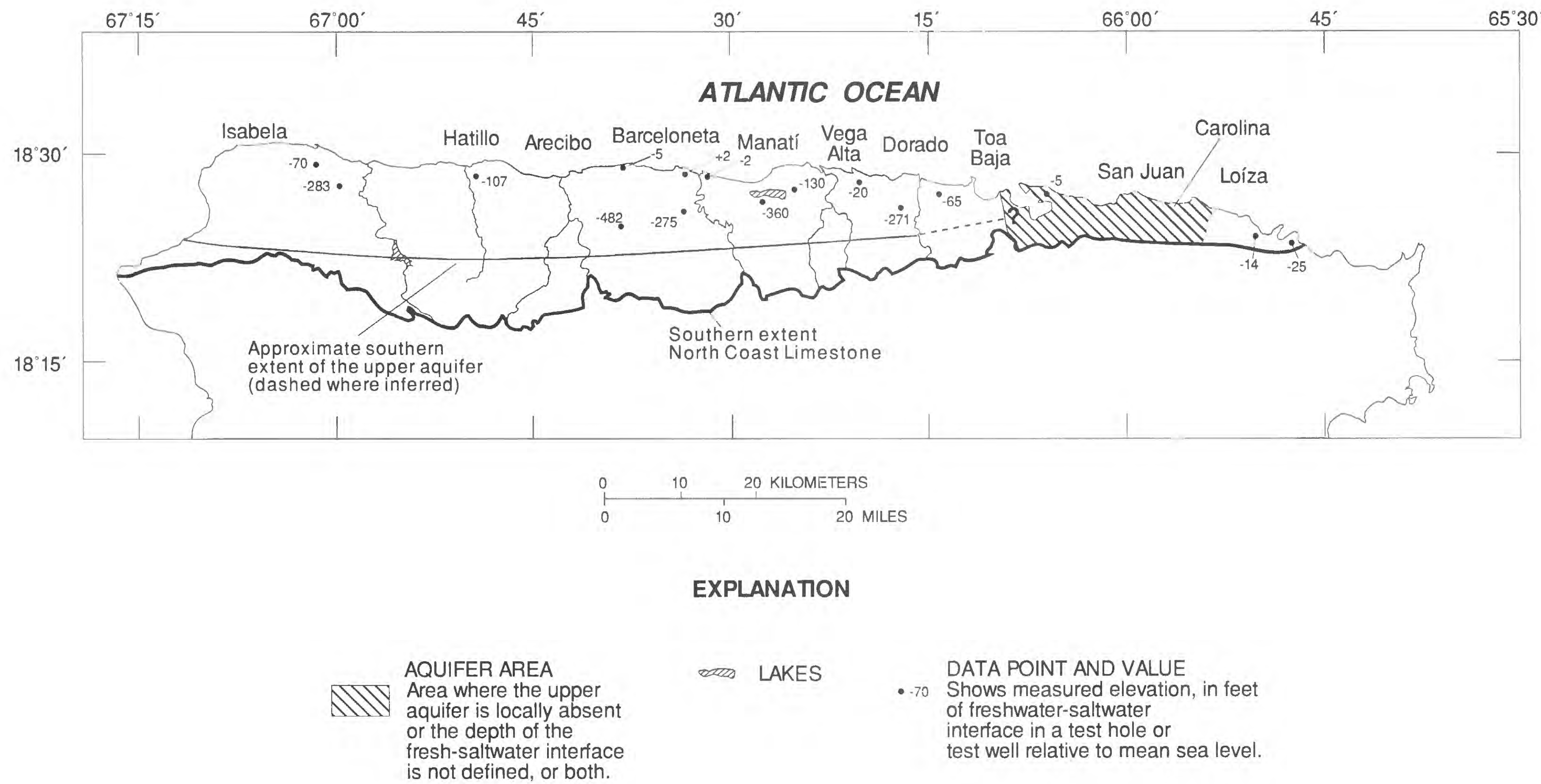

Figure 10. Elevation of the regional freshwater-saltwater interface in the upper aquifer.

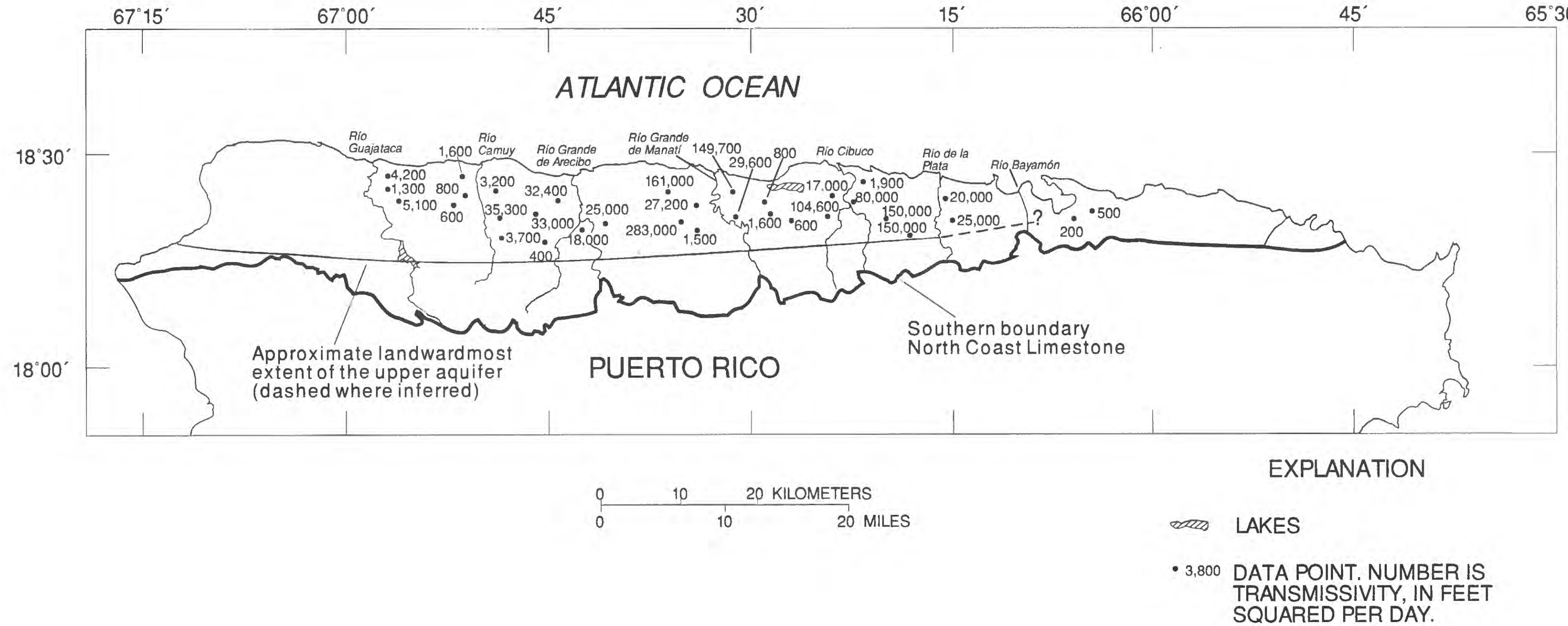

Figure 11. Estimates of transmissivity for the freshwater zone of the upper aquifer F. Gómez-Gómez, U.S. Geological Survey, written commun., 1992.

Hydrologic and lithologic data collected at test holes 3 and 4 indicate the probable leaky nature of the confining unit in the easternmost part of the North Coast Limestone aquifer system. In these test holes, the variations of specific conductance and water level (head) with depth, as well as the lithologic nonhomogeneity of the confining unit, indicate possible upward movement of water from the lower aquifer into the upper aquifer (Rodríguez-Martínez and others, 1991).

An artesian water-bearing zone of local extent exists within the confining unit near water well 11 in Arecibo, observation well 9, and test well 8 south of Manatí (fig. 7). This local water-bearing zone consists mostly of coral-bearing wackestones and packstones and is about 50-ft thick.

Lower Aquifer

The lower aquifer of the North Coast Limestone was first identified in 1968, when two disposal wells were drilled in the Cruce Dávila area of Barceloneta (Giusti, 1978). The aquifer contains water under artesian pressure throughout the area where it is overlain by the middle confining unit. Where the aquifer crops out, in the recharge areas near the southernmost outcrop belt of the mid-Tertiary sequence, however, the lower aquifer contains water under water-table conditions.

The lithology of the lower aquifer is most homogeneous in the area between Arecibo and Manatí. In that area, the aquifer consists of the Lares Limestone and the Montebello Limestone Member of the Cibao Formation (figs. 7 and 8). Core samples collected from observation well 9 indicate that the aquifer consists of skeletal wackestone-packstone and packstone-grainstone that were deposited in a carbonate middle platform environment. The Lares Limestone is generally much finer-grained than the Montebello Limestone Member of the Cibao Formation. The hydraulic conductivity of the lower aquifer, particularly the Montebello Limestone Member, is greater in the Arecibo to Manatí area than elsewhere in the study area. No hydraulic separation between the two limestone units was observed in the Arecibo to Manatí area.

West of Río Grande de Arecibo, the extent of the lower aquifer is uncertain. The terrigenous character of the Lares Limestone in the Hatillo and Isabela areas and the increased stratigraphic complexity of the Cibao Formation west of Arecibo, suggest that multiple confining and water-bearing strata of unknown areal and vertical extent exist in this area. Because only 3 out of the 18 test holes and wells used in this study were drilled west of Río Grande de Arecibo, it is not known if these water-bearing strata are an extension of the more productive lower aquifer in the Manatí to Arecibo area. Zones of moderate permeability are known to exist locally in the westernmost part of the mid-Tertiary age sequence within small lenses of volcanic conglomerates and sandstones of the San Sebastián Formation, but in general, this formation is not a good aquifer.

In the area between Manatí and Dorado, the lower aquifer is composed solely of the Lares Limestone (fig. 7). The Lares Limestone in this area is a moderately to highly terrigenous and mostly fine-grained wackestone-packstone, which is predominantly argillaceous at its base (Scharlach, 1990). The Montebello Limestone Member of the Cibao Formation grades by facies change to an age-equivalent calcareous mudstone, marl, and a highly argillaceous wackestone unit in the area between Manatí and Vega Baja. In this area, the Quebrada Arenas Limestone and the Río Indio Limestone Members of the Cibao Formation are more argillaceous and silty than in their outcrop areas, and consequently, are part of the confining unit (Scharlach, 1990). The Quebrada Arenas and the Río Indio Limestone Members are, in part, stratigraphically equivalent to the Montebello Limestone Member that exists to the west. East of Toa Baja, the Quebrada Arenas Limestone and the Río Indio Limestone Members of the Cibao Formation grade by facies change to the Mucarabones Sand. East of Toa Baja, the lower aquifer includes rocks that are part of the Mucarabones Sand (fig. 7). In this area, the Lares Limestone gradually thins and grades to the Mucarabones Sand, a calcareous marine sandstone with local lenses of volcanic conglomerate (Scharlach, 1990). The lower aquifer also includes permeable units in the upper part of the San Sebastián Formation, in and near the area where the San Sebastián Formation crops out.

In the area of San Juan and Guaynabo (test hole 4) and Río Piedras (test hole 2), the lower aquifer is composed mostly of the Mucarabones Sand (figs. 7 and 9). The Mucarabones Sand in this area consists of sandstone and gravel of terrestrial origin. In San Juan and to the east, the water in the lower aquifer is brackish in some areas.

Transmissivity estimates for the lower aquifer are available from only a few aquifer tests and specific capacity tests (fig. 12). In the Río Grande de Arecibo to Río Grande de Manatí area, the transmissivities of the Lares Limestone at two sites were 150 and 500 ft^2/d (fig. 12). Transmissivity values for the Lares Limestone in other areas range from 20 to 330 ft^2/d (fig. 12). Reported transmissivity values for the Mucarabones Sand, which is stratigraphically equivalent to the Lares Limestone in the San Juan metropolitan area, range from 850 to 1,000 ft^2/d (Anderson, 1976). The transmissivity of the Montebello Limestone Member is highest in the Río Grande de Arecibo to the Río Grande de Manatí area, where it ranges from 625 to 3,600 ft^2/d (fig. 12). West of the Río Grande de Arecibo, the reported transmissivity of the Montebello Limestone Member ranges from 370 to 680 ft^2/d. In this area, the unit becomes increasingly chalky and is similar in lithology to the upper member of the Cibao Formation.

SUMMARY

The hydrogeology of the North Coast Limestone aquifer system was studied by the U.S. Geological Survey in cooperation with the Commonwealth of Puerto Rico Department of Natural and Environmental Resources during 1983 to 1988. During this study, 15 deep test holes and wells were drilled into bedded carbonate and clastics deposits of middle Oligocene to Miocene age that underlie the north coast of Puerto Rico. Lithologic cores collected from these test holes and test wells were analyzed to describe the stratigraphic and hydrogeologic framework of the area. Data from three other existing water wells collected during previous studies also were used in the delineation of the regional hydrogeologic units.

An upper aquifer, a lower aquifer, and a middle confining unit constitute the hydrogeologic units of the North Coast Limestone aquifer system. The upper aquifer consists mainly of the Aymamón Limestone and the Aguada (Los Puertos) Limestone and locally includes part of the upper member of the underlying Cibao Formation and the overlying alluvium. This upper aquifer is present along much of the north coast of Puerto Rico, but is largely absent in the Río Piedras area. A saltwater zone underlies the freshwater zone of the upper aquifer in the coastal region. The upper aquifer contains water under water-table conditions, except in the coastal region where it is locally confined by overlying fine-grained material. The extent of the lower aquifer west of Arecibo is uncertain. It is not known if the existing multiple water-bearing units west of Arecibo are an extension of the more productive aquifer in the Arecibo to Manatí area.

The confining unit consists of the upper member, the Quebrada Arenas Limestone and the Río Indio Limestone Members of the Cibao Formation, and the mudstone unit. The confining unit generally consists of low permeability rocks; however, in an area that extends from Manatí to Arecibo it locally contains a water-bearing zone that is under artesian conditions. Data from test holes 3 and 4 indicate that the confining unit possibly is leaky in the San Juan metropolitan area and that water from the lower aquifer is moving into the upper aquifer in that area.

The lower aquifer is composed of the Lares Limestone, the Montebello Limestone Member of the Cibao Formation, and the outcrop areas and shallow facies of the San Sebastián Formation. The lower aquifer is thickest and most transmissive in the north-central part of the study area. West of the Río Grande de Arecibo, the extent of the lower aquifer is not known. Multiple water-bearing units and intervening confining units of limited extent exist in the Hatillo to Isabela area but it is not known if these water-bearing units are extensions of the lower artesian aquifer in the Manatí to

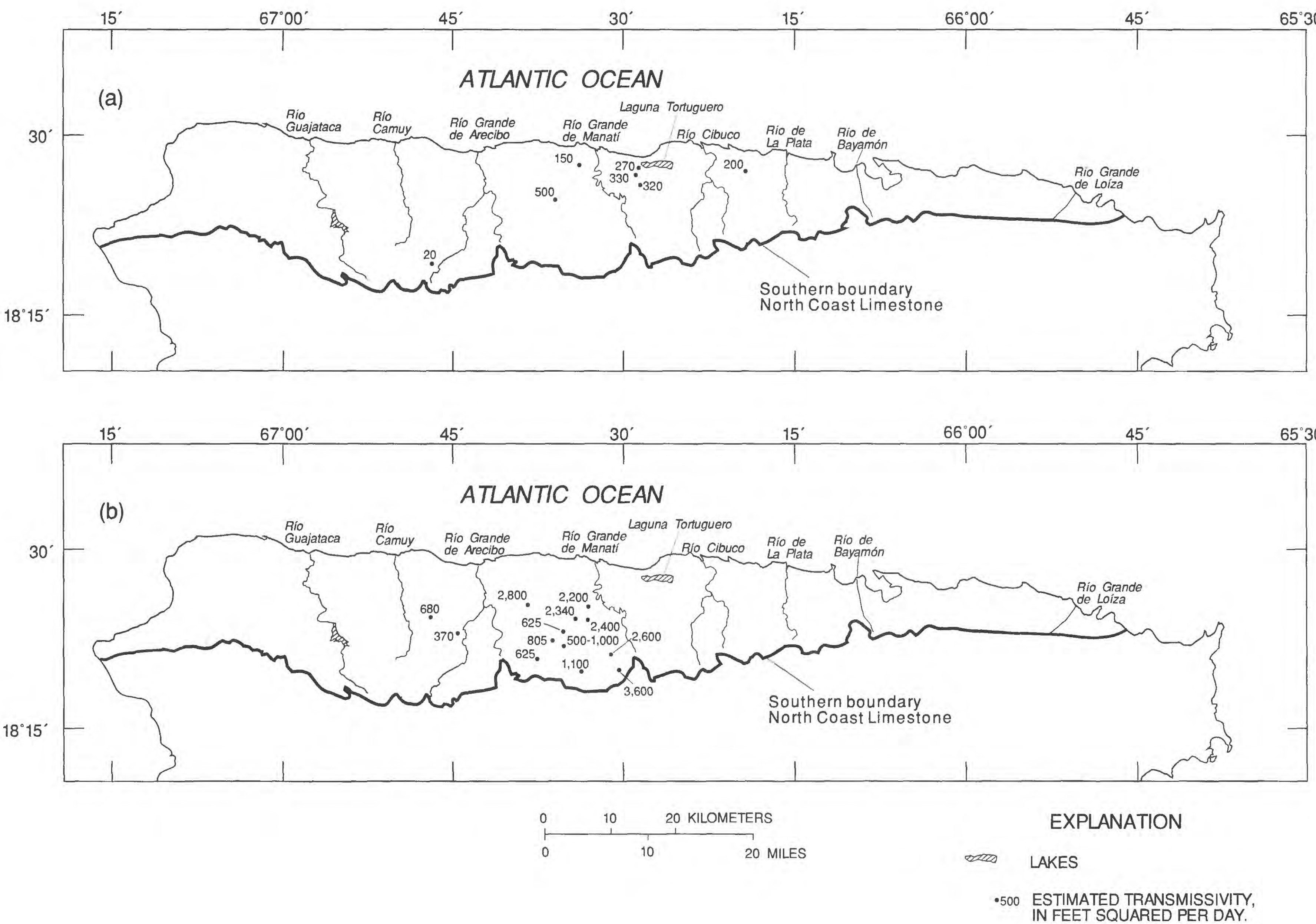

Figure 12. Estimated transmissivity for the lower aquifer in the North Coast Limestone aquifer system of Puerto Rico: (a) the Lares Limestone and (b) the Montebello Limestone Member of the Cibao Formation (F. Gómez-Gómez, U.S. Geological Survey, written commun., 1991).

Arecibo area. In an area that extends from Manatí to Dorado, the lower aquifer is composed of rocks that are part of the Lares Limestone. In the area of Toa Baja and further east, the limestone rocks that make up the lower aquifer grade by facies change to the more terrigenous Mucarabones Sand. East of Toa Baja the lower aquifer consists of the Mucarabones and contains water that ranges from fresh to brackish.

The transmissivity values for the freshwater zone of the upper aquifer are highest in the Río Grande de Arecibo to the Río de La Plata area. Transmissivities values for the upper aquifer exceed 100,000 ft^2/d in six locations in this area and have been reported to exceed 280,000 ft^2/d at one site near Barceloneta. Locally, the transmissivity values of minor water-bearing units within the upper aquifer underlying the San Juan metropolitan area range from 200 to 500 ft^2/d. In the lower aquifer, the Lares Limestone has transmissivity values of 150 and 500 ft^2/d at two sites in the Río Grande de Arecibo to the Río Grande de Manatí area. In other areas the transmissivity values for the Lares Limestone range from 20 to 330 ft^2/d. The estimated transmissivity of the Mucarabones Sand in the San Juan metropolitan area ranges from 850 to 1,000 ft^2/d. The transmissivity values of the Montebello Limestone Member of the Cibao Formation are highest in the Río Grande de Arecibo to Río Grande de Manatí area and range from 625 to 3,600 ft^2/d. West of the Río Grande de Arecibo transmissivity data for the Montebello Limestone Member are sparse, but values at two sites were 370 and 680 ft^2/d.

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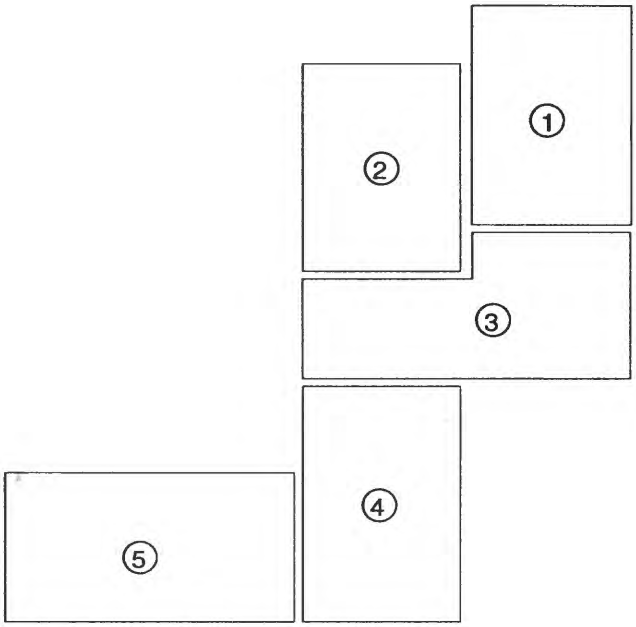

PHOTOS USED ON COVER

1) Cueva Clara de Empalme - one of the entrances to the Río Camuy Cave System, Puerto Rico. (Photo by Arturo Torres-González, USGS)

2) Areal view of the Río Tanamá Canyon and the Arecibo Ionospheric Radiotelescope in the central karst region of Puerto Rico. (Photo by Ramón A. Carrasquillo-Nieves, USGS)

3) View of Laguna Tortuguero on the north coast near Manatí, Puerto Rico. (Photo by Ramón A. Carrasquillo-Nieves, USGS)

4) Explorers floating down the Río Tanamá in the north central karst region of Puerto Rico. (Photo by Arturo Torres-González, USGS)

5) Intermogotal area in the north coast karst limestone belt of Puerto Rico. (Photo by Arturo Torres-González, USGS)