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THE HYDROGEOLOGIC FRAMEWORK OF THE NORTHERN COASTAL PROVINCE AQUIFER SYSTEM OF PUERTO RICO

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ABSTRACT: The Northern Coastal Province aquifer system of Puerto Rico is composed of three regional hydrogeologic units: an upper aquifer that contains saline water in the more coastal areas, an intervening confining unit, and a lower confined aquifer. The upper aquifer is unconfined except in coastal areas and consists mainly of karstic, coral-rich limestone and chalk of the Aymamón and Los Puertos Limestones. Locally, it also may include the uppermost part of the Cibao Formation and the overlying alluvium. The upper aquifer extends along the northwest and north-central coast, but is largely absent in San Juan and areas further east. The upper aquifer contains saline water below freshwater in coastal regions, but is entirely brackish or saline northeast of San Juan. The position of the saline-freshwater interface is a function of both the hydraulic properties of the Aymamón Limestone and Los Puertos Limestone and the degree of development of the upper aquifer. The confining unit is composed of calcareous claystone, marl, chalky and silicified limestone, and localized clayey fine-grained sandstone that are all part of an unnamed upper member of the Cibao Formation. Locally, the confining unit includes the Río Indio and Quebrada Arenas Limestone Members of the Cibao Formation and also part of the Los Puertos Limestone. A local water-bearing zone, found within the unnamed upper member of the Cibao Formation, extends west from Arecibo to Manatí. The lower aquifer attains its maximum transmissivity and homogeneity in the north-central part of the study area, where it consists of the Lares Limestone, the Montebello Limestone Member of the Cibao Formation and lowermost beds that are part of the unnamed upper member of the Cibao Formation. In the eastern and western sections of the study area, the lithologic character of the lower aquifer is more heterogeneous as the Lares Limestone and Montebello Limestone Member grade by facies changes to increasingly terrigenous, but chronostratigraphically equivalent, rock units. In the San Juan, Cataño, and Guaynabo area, the salinity of water within the lower aquifer varies from fresh to brackish. Well data indicate that the lower aquifer pinches out near Río Piedras and Carolina.
KEY WORDS: Northern Coastal Province; Karst; Aquifer; Hydrogeologic framework; Puerto Rico.

INTRODUCTION

The Northern Coastal Province aquifer system is an important source of water in Puerto Rico. It consists of a highly karstified carbonate platform sequence of middle Tertiary age that extends eastward about 100 mi (miles) from Aguadilla to Loíza (fig. 1). As part of a cooperative effort of the U.S. Geological Survey and the Puerto Rico Department of Natural Resources, 15 wells were drilled to study the character and extent of water-bearing units of the Northern Coastal Province aquifer system.

Purpose and Scope

This paper outlines the hydrogeologic framework of the Northern Coastal Province aquifer system. The regional hydrogeologic units were defined and delineated on the basis of relative permeability, hydraulic continuity, and mappable extent. This hydrogeologic framework served as the basis of a regional ground-water flow model (Torres-González and Wolanski, 1984).

Location and Geographic Setting

The Northern Coastal Province (fig. 1) encompasses approximately 700 mi^2 (square miles) and is part of a coastward thickening carbonate platform sequence of Oligocene to Miocene age. The Northern Coastal Province aquifer system is bordered to the north by the Atlantic Ocean and flanks Cretaceous and lower Tertiary igneous and

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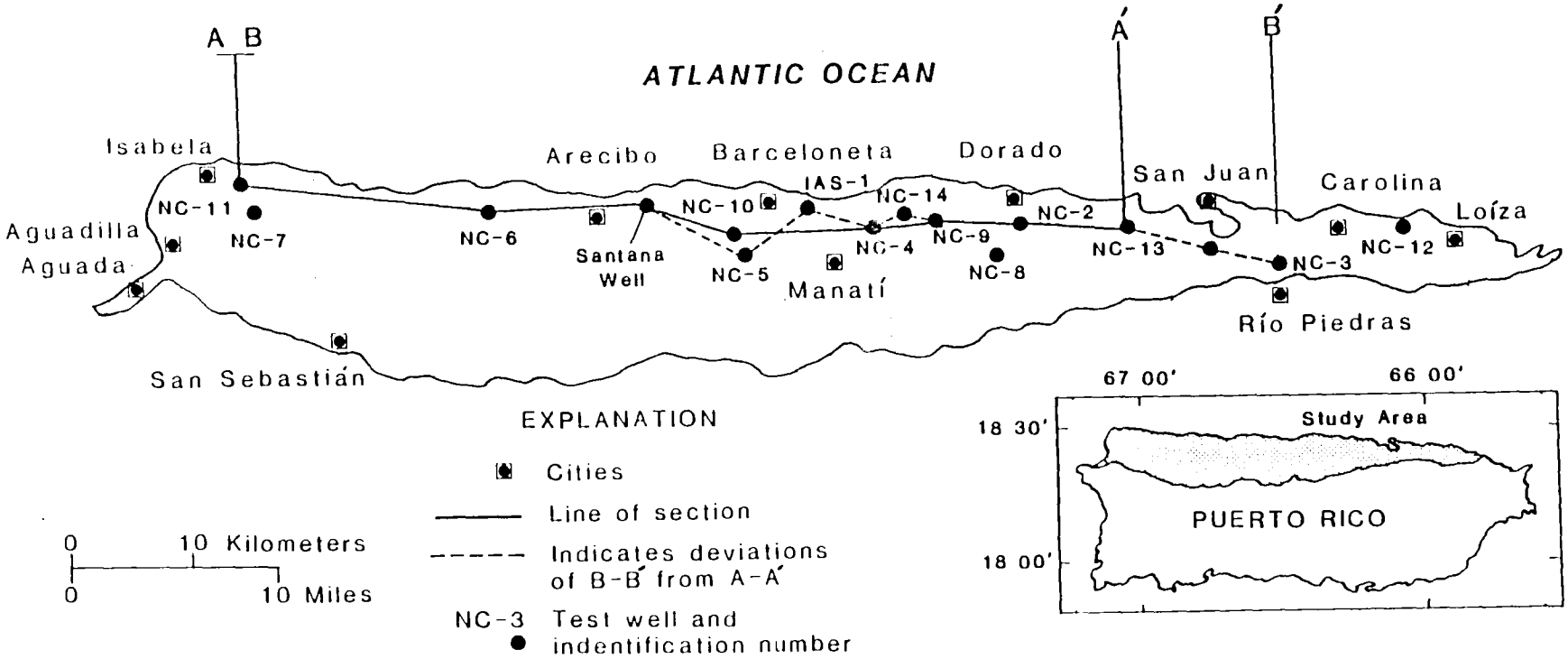


Figure 1.--Areal extent of the Northern Coastal Province of Puerto Rico and location of cities and test wells.

sedimentary rocks on the south. The maximum width of the limestone outcrop belt is approximately 6 mi near Arecibo. The limestone belt is thinnest (3.1 mi) in the Río Piedras to Loíza area.

PREVIOUS HYDROGEOLOGIC STUDIES

Giusti (1978) summarized hydrogeologic studies of the north coast prior to 1973. However, discovery of a regional confined artesian aquifer had occurred only several years earlier in 1968, and the flow system was poorly understood. A number of other studies have been completed subsequently for various areas of the north coast; however, none of these studies have examined the hydrogeologic framework of the artesian part of the flow system (Quiñones-Aponte, 1986; Gómez-Gómez, 1987).

METHOD OF STUDY

The hydrogeologic framework of the Northern Coastal Province aquifer system is based on data obtained during the deep-well drilling phase of the U.S. Geological Survey investigation that began in 1985 (Torres-González and Wolansky, 1984). Fifteen deep test wells (fig. 1) were drilled ranging in depth from 365 to 2,574 ft (feet). Lithologic, geophysical, and hydraulic data available from other wells were also used to define the framework.

The hydrogeologic framework described herein is based on the stratigraphic framework presented by Ward and others (1991), Hartley (1989), and Scharlach (1990). Two hydrogeologic sections were assembled and are presented here. These show the physical extent of the principal water-bearing units.

The configuration of the base of freshwater was also mapped and incorporated as an important element of the basic hydrogeologic framework. A concentration of 250 mg/L (milligrams per liter) of chloride was used to define the saline-freshwater boundary. Although water with higher concentrations of chloride is suitable for some uses, the U.S. Environmental Protection Agency established 250 mg/L as the upper limit of the standard for drinking water (U.S. Environmental Protection Agency, 1976). Because of the absence of chloride analyses of ground water in certain areas of the Northern Coastal Province, both surface resistivity and borehole geophysical data were used to define the position of the interface.

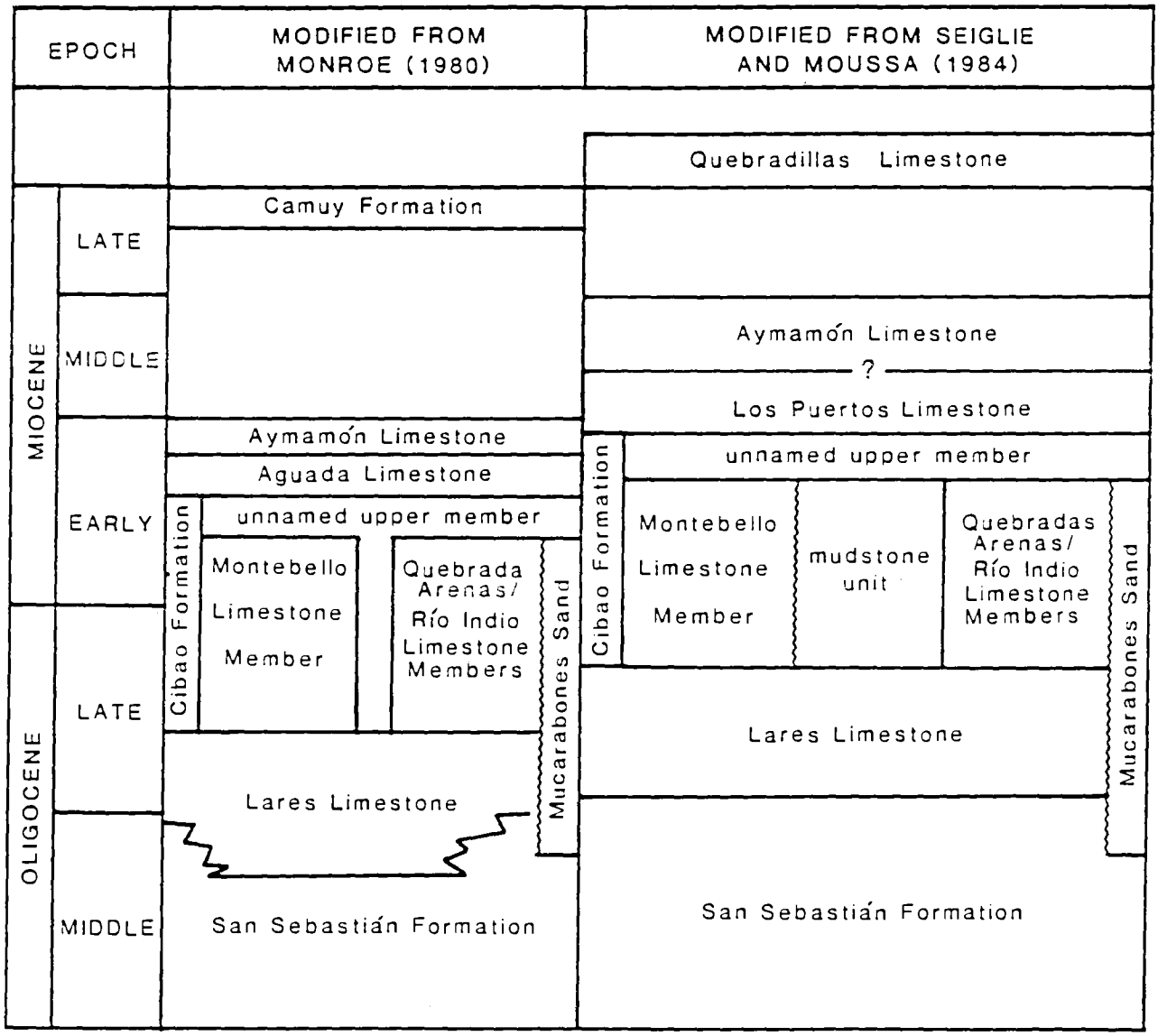
GEOLOGIC SETTING

Platform carbonate and minor clastic rocks of Oligocene to early Pliocene age constitute a homoclinal sequence that dips gently northward at an average of three to four degrees. Dips near the coast average about two degrees whereas steeper gradients of six to seven degrees are found at the southern limit of the Northern Coastal Province. A series of uplifts and structural "lows" within and underlying the rocks that underlie the Northern Coastal Province may have compartmentalized the middle Tertiary basin of the Northern Coastal Province (fig. 2) (Meyerhoff and others, 1983). Underlying basement rocks consist of Late Cretaceous and Early Tertiary volcaniclastic rocks and intrusives that have been displaced by faults that strike northwest (Monroe, 1980; Meyerhoff and others, 1983).

The entire middle Tertiary sedimentary section is separated into seven formations whose outcrop areas are characterized by tropical karst topography. In coastal areas the middle Tertiary beds are overlain by surficial deposits (assorted mixtures of sand, silt, and clay) of late Pliocene to Holocene age (fig. 3). For the most part, the stratigraphic nomenclature of the Northern Coastal Province has been based on outcropping rock characteristics that may differ from equivalent strata found in the subsurface. This paper follows the formational division of Seiglie and Moussa (1984), which differs from Monroe (1980) because it is, in part, based on both the outcrop and subsurface facies (table 1).

The seven formational units found in an east-west stratigraphic section of the Northern Coastal Province are shown in figure 4. In ascending order they are: the San Sebastián Formation (coastal and fluvial terrigenous clastics, marginal marine clay and limestone); the Lares Limestone (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 (marginal marine clays and minor fluvial clastics); the Cibao Formation (claystone, marl, and limestone containing terrigenous material) and its members, the Montebello Limestone (mid-platform limestone), and the unnamed "mudstone unit"; the Quebrada Arenas and Río Indio Limestone (inner platform terrigenous limestones); Los Puertos Limestone (Aguada Limestone) (inner platform carbonates); the Aymamón Limestone (mid-platform coral-rich limestone). The Quebradillas Limestone (outer platform chalk limestone) does not occur in this section (table 1).

Table 1.--Stratigraphic nomenclatures of the Middle Tertiary basin of the Northern Coastal Province, Puerto Rico (modified from Ward and others, 1991)



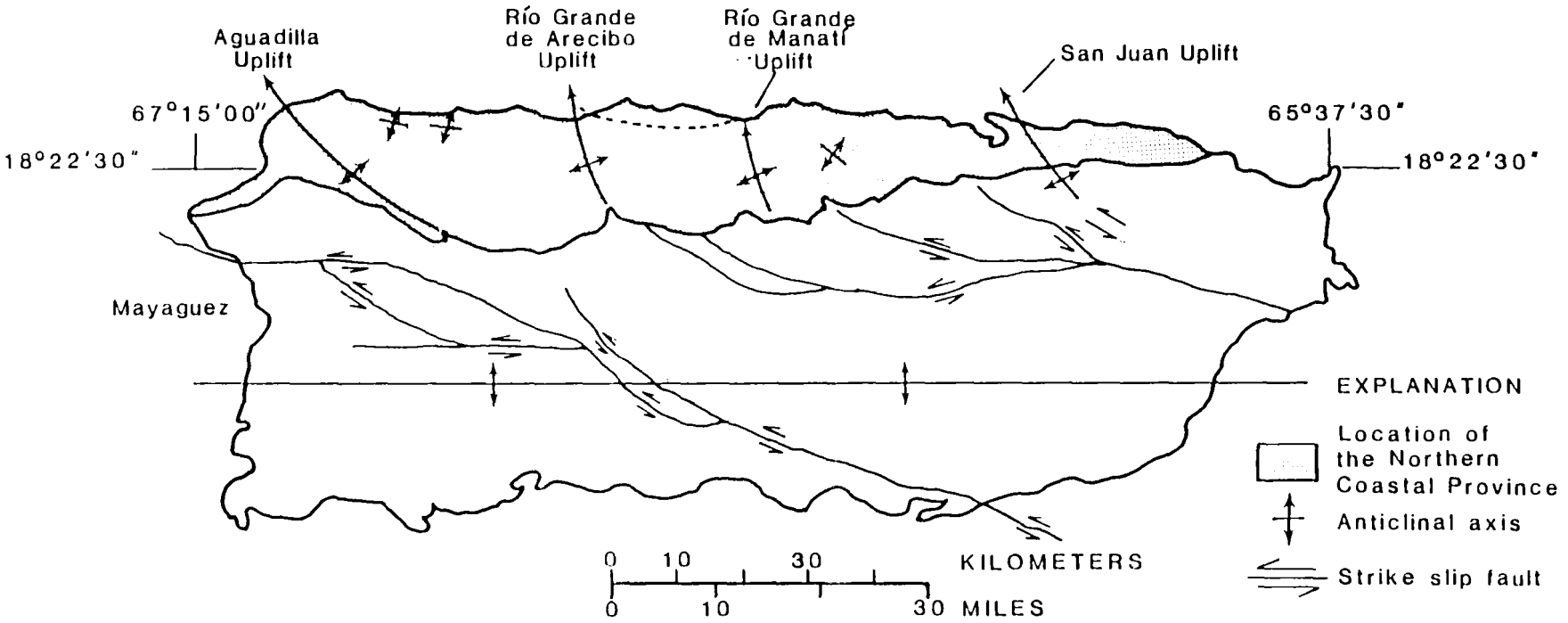


Figure 2.--Major structural features of Puerto Rico (modified after Meyerhoff and others, 1983).

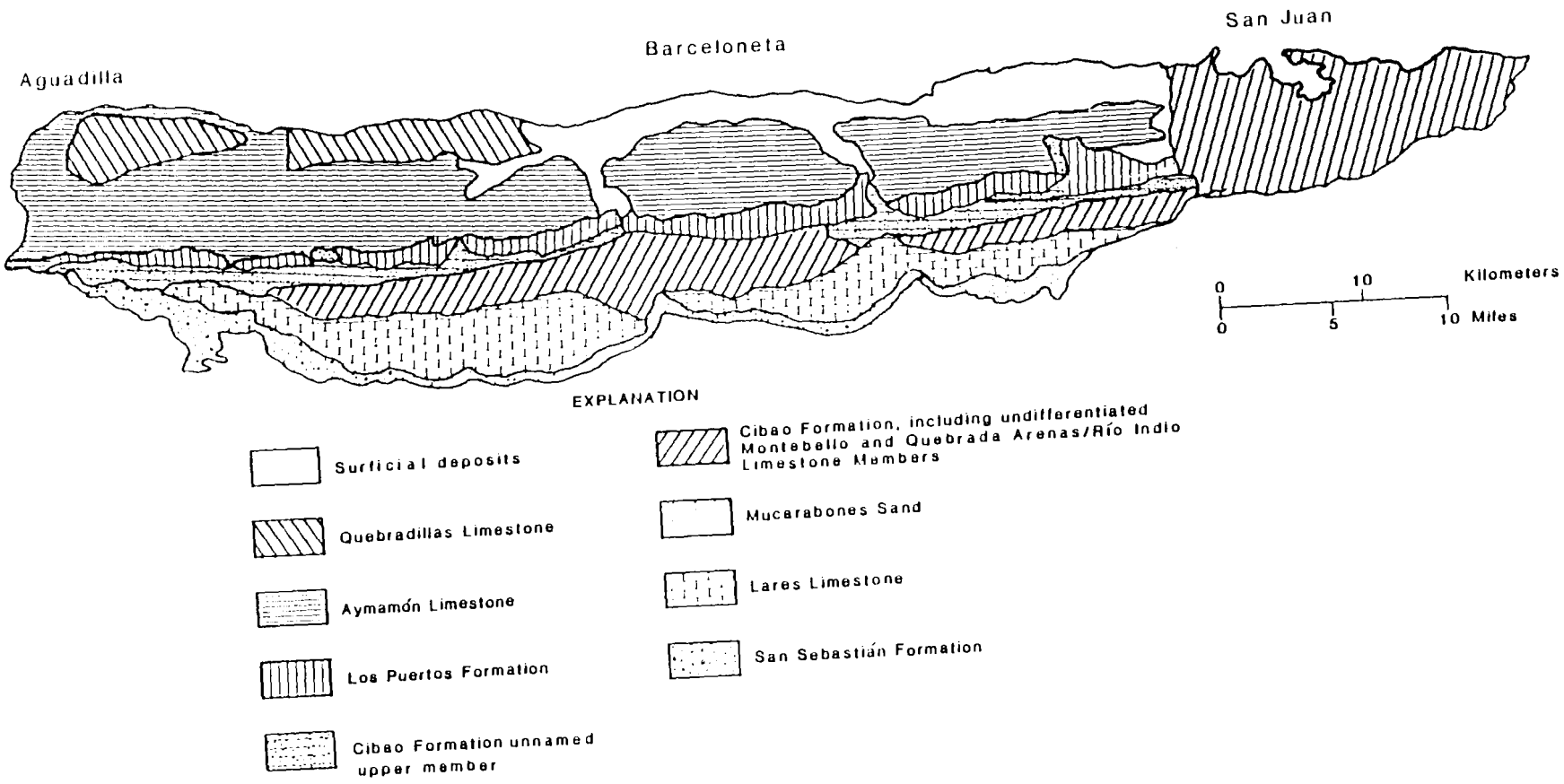


Figure 3.--Surface geology of the Northern Coastal Province of Puerto Rico as described by Seiglie and Moussa (1984).

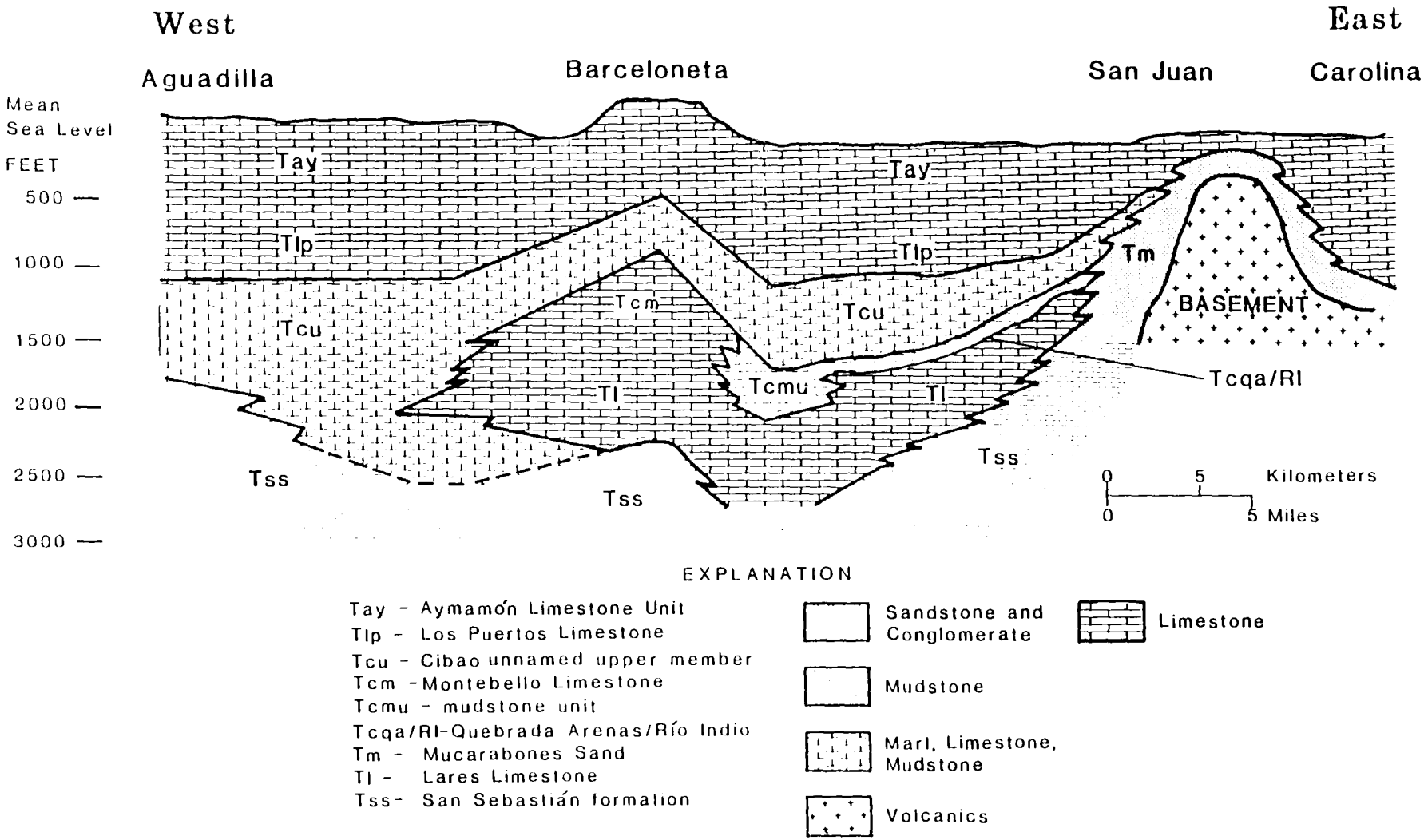


Figure 4.--Generalized east-west stratigraphic section of the Mid-Tertiary sequence of the Northern Coastal Province of Puerto Rico (from Ward and others, 1991).

HYDROGEOLOGIC FRAMEWORK

The Northern Coastal Province aquifer system can be divided into three principal hydrogeologic units: an upper aquifer containing a basal saline-water zone in the coastal regions, an intervening confining unit, and an underlying confined aquifer. A local artesian zone also has been identified within the middle confining unit.

Upper Aquifer

The upper aquifer consists of the Aymamón Limestone and underlying Los Puertos Limestone; however, in several localities along the Northern Coastal Province the upper aquifer also includes the uppermost rocks of the unnamed upper member of the Cibao Formation (fig. 5). The upper aquifer contains water under unconfined conditions except in coastal areas where it is confined by overlying surficial deposits. In these coastal areas, this aquifer contains a basal saline-water zone.

The freshwater part of the upper aquifer is thinner east of Manatí than in the north-central area (Manatí to Arecibo). In the north-central area, the thickness of this zone ranges from 130 to 240 ft. However, the thickness changes little between Manatí and Dorado (fig. 5). East of Dorado the saline and fresh water parts of this aquifer are both reduced in thickness. The aquifer pinches out east of test well NC-13, near Toa Baja. West of Arecibo the thickness of the freshwater zone gradually decreases to 25 ft in Isabela, in the northwest of Puerto Rico.

The upper aquifer is largely absent in the San Juan metropolitan area. Where locally present, it is very thin, and usually contains brackish water. The Aymamón and Los Puertos Limestones have been extensively eroded by karstification in this area, and the erosional remnants have very little hydrologic importance.

Confining Unit

The confining unit is composed largely of the unnamed upper member of the Cibao Formation, a calcareous and marl unit. Recent test drilling shows that the confining unit is thickest in the area between Manatí (test well IAS-1) and Vega Baja (test well NC-14). The confining unit underlies the upper aquifer in much of the area west of Toa Baja (fig. 6).

Although the Cibao Formation's unnamed upper member is the principal rock-stratigraphic unit that makes up the middle confining unit, the upper boundary of the confining unit does not coincide everywhere with the top of the Cibao Formation. In some localities, the facies within the lower part of the Los Puertos Limestone has low permeability and the rocks function as a confining unit. For example, core data for test well NC-6 in Hatillo show that the top of the confining unit is contained within rocks that are within the upper part of the Los Puertos Limestone. Conversely, the uppermost part of the Cibao Formation is reef limestone (wackestone-packstone) in several locations and is considered part of the upper aquifer. In these areas, the middle part of the Cibao Formation's unnamed upper member is the confining unit.

The base of the middle confining unit is particularly difficult to define in the Hatillo to Isabela area; the underlying lower aquifer contains multiple confining and water-bearing zones. For the purposes of this paper, the lower boundary of the confining unit is defined as the lowermost strata of low permeability beneath which artesian conditions are first encountered. Deep low-permeability strata act as local confining units but are contained within the lower aquifer.

The confining unit gradually thickens east of Barceloneta (fig. 6). Between test well IAS-1 near Manatí and Vega Baja (test well NC-14), the confining unit is composed of the lowermost part of the upper member of the Cibao Formation and the underlying Quebrada Arenas and Río Indio Limestone Members, and the unnamed mudstone unit. In this area it ranges in thickness from 75 ft immediatly east of Barceloneta to 825 ft at well IAS-1. Between Vega Baja and Dorado (test well NC-2), the confining unit lies within the Cibao Formation and its average thickness (600 ft) is less than that in the Manatí to Vega Baja area. East of Dorado, which includes Toa Baja, Guaynabo, and Río Piedras (test wells NC-13, NC-1, and NC-3), the confining unit thins considerably (500 to 75 ft) and is within the uppermost part of the Cibao Formation.

A water-bearing zone of local extent is found within the middle confining unit between Arecibo (Santana Well) and south of Manatí (test well NC-4). This local water-bearing zone consists mostly of coral-bearing wackestones and packstones, representative of deposition in a patch-reef environment of the inner part of the middle carbonate platform.

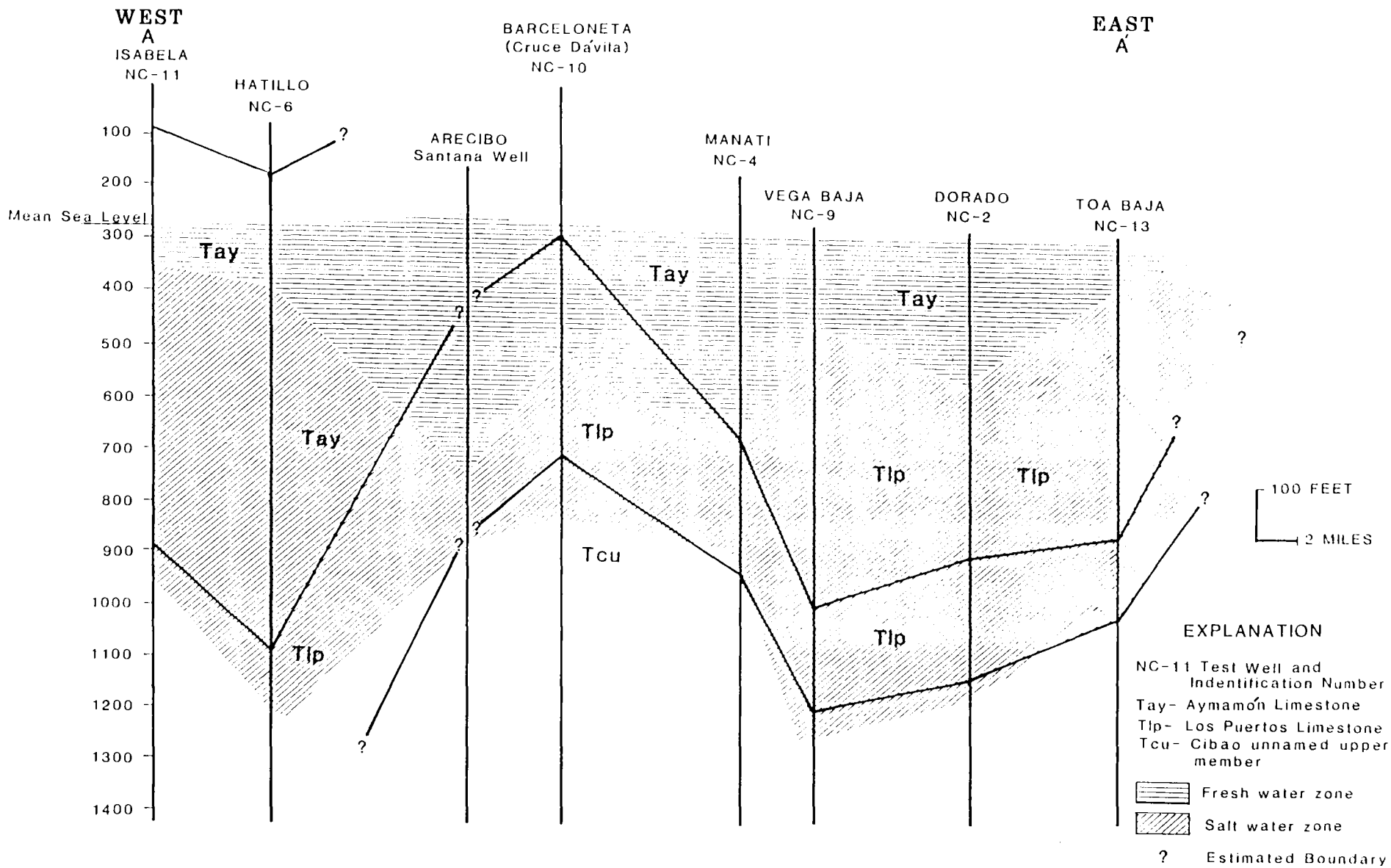


Figure 5.--Section A-A' from Isabela to Toa Baja showing the extent of the upper aquifer in the Northern Coastal Province aquifer system of Puerto Rico.

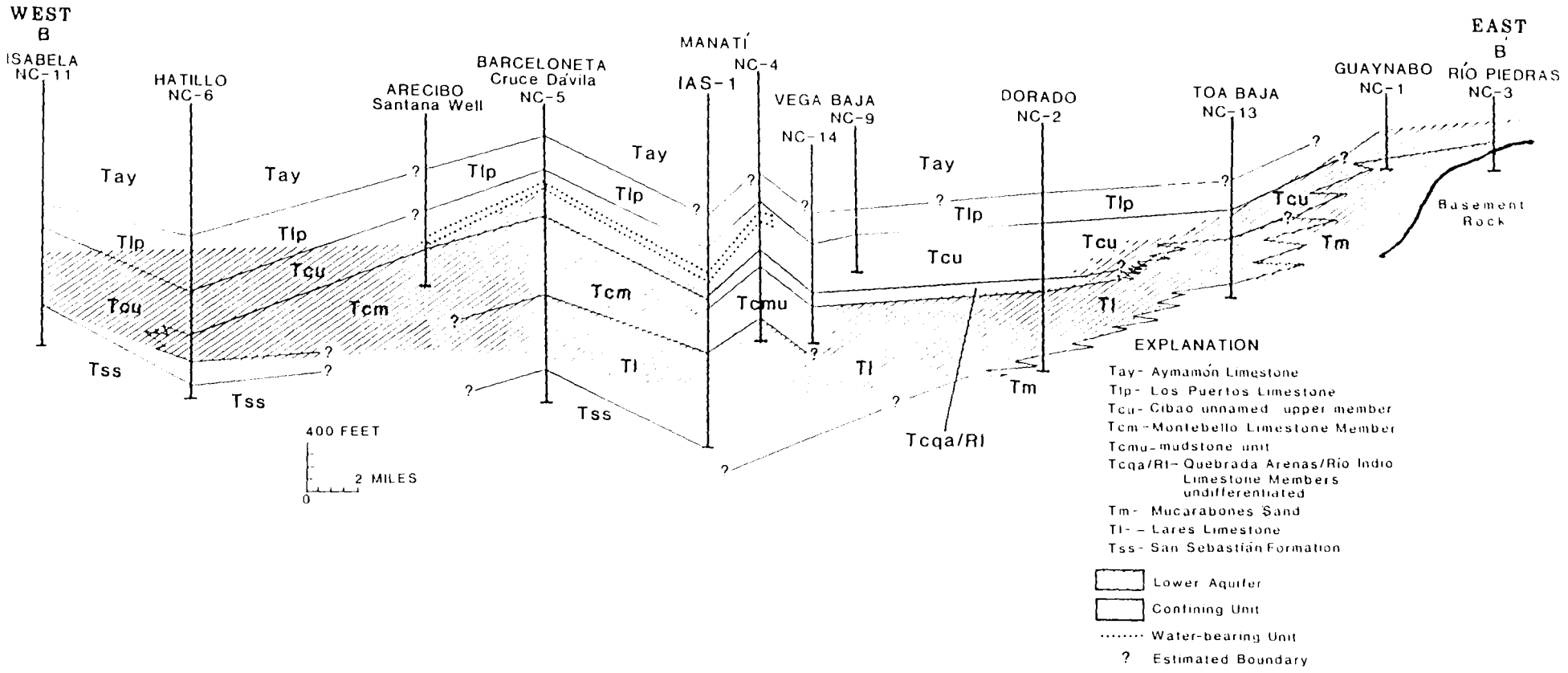


Figure 6.--Section B-B' from Isabela to Río Piedras showing configuration of the lower aquifer in the Northern Coastal Province aquifer system of Puerto Rico.

Lower Aquifer

The drilling of two disposal wells in 1968 in the Cruce Dávila area of Barceloneta, first revealed the presence of artesian conditions in the Northern Coastal Province (Guisti, 1978). Prior to more recent drilling activities, these disposal wells provided the only information regarding the extent and thickness of the lower aquifer.

The lower aquifer attains its maximum transmissivity and homogeneity in the area between Arecibo and Manatí. Here, the lower aquifer consists of the Lares Limestone, the Cibao Formation's Montebello Limestone Member and lowermost strata of the unnamed upper member (fig. 6). Core specimens from test well NC-5 show the aquifer consists of skeletal wackestone-packstone and packstone-grainstone deposited in a middle carbonate platform environment. However, the Lares Limestone is generally much finer-grained than the Montebello Limestone. It is in this area that the greatest permeability within the lower aquifer occurs, particularly in the Montebello Limestone. No hydraulic separation was observed between the limestone units in this area.

West of Arecibo, the Montebello Limestone Member becomes progressively finer grained and chalky, and its upper part grades into typical Cibao Formation calcareous wackestone, siliciclastic mudstone and marl. These facies changes appear as an intertonguing of different geologic units in the outcrop and in the subsurface (Hartley, 1989).

The Lares Limestone is lithologically more uniform than the Montebello in the area between Arecibo and Hatillo (Monroe, 1980; Hartley, 1989); however, beds of marl and chalky limestone, and small lenses of sand and clay can be observed in outcrop. In the vicinity of Isabela, the Lares Limestone is lithologically indistinguishable from the Cibao Formation (typical lithology is marl, claystone, wackestone) (Hartley, 1989). Further west, near San Sebastián, the exposed Lares Limestone is mostly a terrigenous unit and, in part, chronostratigraphically equivalent to the San Sebastián Formation (Monroe, 1980).

A result of the increasing stratigraphic complexity west of Arecibo is that the lower aquifer is fragmented, heterogeneous, and composed of multiple confining and water-bearing strata of limited extent. Local permeable zones known to exist in the westernmost part of the middle Tertiary sedimentary section are found within small lenses of volcanic conglomerates and sandstones of the San Sebastián Formation.

In the area between Vega Baja and east of Dorado, the lower artesian aquifer is composed solely of the Lares Limestone (fig. 6). The Lares Limestone in this area is a moderately to highly terrigenous and mostly fine-grained wackestone-packstone, predominantly argillaceous at its base (Scharlach, 1990). The Montebello Limestone Member grades by facies change to time-equivalent calcareous mudstone-marl and highly argillaceous wackestone in the area between Manatí and Vega Baja. The Quebrada Arenas and Río Indio Limestone Members here are more argillaceous and silty than their outcrop facies (Scharlach, 1990). The Quebrada Arenas and Río Indio Limestone Members are, in part, chronostratigraphically equivalent to the Montebello Limestone Member found to the west. Where mapped at outcrop, they are separated by an "interbiohermal area" (Monroe, 1980). East of Dorado, the members grade by facies change to the Mucarabones Sand. In an area that extends east from Toa Baja, the lower aquifer includes rocks that are part of the Mucarabones Sand and Cibao Formations (fig. 6). 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).

In the area of San Juan, Guaynabo (test well NC-1), and Río Piedras (test well NC-3), the lower aquifer is composed mostly of the Mucarabones Sand and locally includes minor strata of the Cibao Formation (fig. 6). The Mucarabones Sand has completely replaced the Quebrada Arenas and Río Indio Limestone Members, as well as the Lares Limestone. Here, the lower aquifer consists of sandstone and gravel of terrestrial origin. Minor limestone lenses within the Cibao Formation make up part of the lower aquifer. In San Juan and to the east, the quality of water within the lower aquifer varies from fresh to brackish. The lower aquifer probably does not extend eastward beyond Río Piedras.

SUMMARY

Three hydrogeologic units -- two aquifers and one confining unit -- constitute the Northern Coastal Province aquifer system. The upper aquifer is composed mainly of the Aymamón and Los Puertos Limestones, and locally includes rocks in the unnamed upper member of the Cibao Formation. This hydrogeologic unit extends along much of the northern coast of Puerto Rico, but is largely absent east of Toa Baja. A saline-water zone underlies the freshwater zone of the upper aquifer in the coastal regions. The regional configuration of this saline-water zone, in terms of its position, density stratification, and thickness, is not only a function of the hydraulic anisotropy of the rock units, but also of the degree of development of the overlying freshwater aquifer.

A confining unit consists of the unnamed upper member of the Cibao Formation, the Quebrada Arenas and Río Indio Limestone Members of the Cibao Formation, the mudstone unit, and the lower part of the Los Puertos Limestone.

The middle confining unit contains a local water-bearing zone that contains water under artesian conditions in an area that extends between Manatí and Arecibo.

The lower aquifer is the principal artesian aquifer of the Northern Coastal Province and attains its maximum thickness and productivity between Arecibo and Manatí where it is composed of the Lares Limestone, the Montebello Limestone, and lowermost rocks of the Cibao Formation. The aquifer is increasingly heterogeneous where the Lares and Montebello Formations extend westward and grade to the San Sebastián and Cibao Formations. 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 is comprised of the Mucarabones Sand and the Cibao Formation and contains water that ranges from fresh to brackish.

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