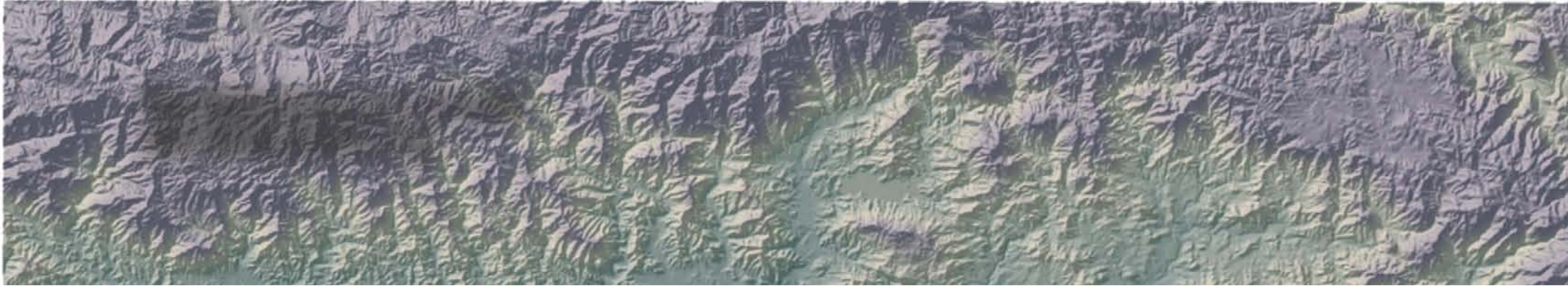

Prepared in cooperation with the
PUERTO RICO ELECTRIC POWER AUTHORITY

Stratigraphy, Structure, and Geologic and Coastal Hazards in the Peñuelas to Salinas Area, Southern Puerto Rico: A Compendium of Published Literature

Open-File Report 2007-1259

U.S. Department of the Interior
U.S. Geological Survey

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By Jesús Rodríguez-Martínez

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DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
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Conversion Factors, Datum, and Acronyms

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
feet per mile (ft/mi)	0.1905	meter per kilometer (m/km)
feet per squared second (ft/s^2)	0.3048	meter per squared second (m/s^2)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)

Datum:

Horizontal Datum - Puerto Rico Datum, 1940 Adjustment
Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) -- a geodetic datum derived from general adjustments of the first-order level nets of both the United States and Canada, formerly called “Sea Level Datum of 1929.”

Acronyms used in this report:

GNPRFZ	Great Northern Puerto Rico Fault Zone
GSPRFZ	Great Southern Puerto Rico Fault Zone
PGA	peak ground acceleration
PRDNER	Puerto Rico Department of Natural and Environmental Resources
PREPA	Puerto Rico Electric Power Authority
PREQB	Puerto Rico Environmental Quality Board
PRSN	Puerto Rico Seismic Network
USGS	U.S. Geological Survey
UPRM	University of Puerto Rico at Mayagüez

Translations

Spanish	**English**
Lago	Lake
Río	River

Stratigraphy, Structure, and Geologic and Coastal Hazards in the Peñuelas to Salinas Area, Southern Puerto Rico: A Compendium of Published Literature

By Jesús Rodríguez-Martínez

Abstract

The Puerto Rico Electrical Power Authority has proposed construction of a pipeline to convey natural gas from the municipio of Peñuelas to the Aguirre thermoelectric power plant in the municipio of Salinas in southern Puerto Rico. To ensure that the geologic conditions along the possible routes do not represent a threat to the physical integrity of the natural gas pipeline, and thus comply with State and Federal regulations, the Puerto Rico Electrical Power Authority requested the U.S. Geological Survey to provide a synthesis of published literature of the geology of the coastal plain in the Peñuelas to Salinas area.

The study area is located in part of the Southern Coastal Plain of Puerto Rico. In the area that extends from the municipio of Peñuelas eastward to the Laguna de las Salinas at Ponce, a distance of about 5 miles, the study area is underlain by middle Tertiary carbonate units. Eastward from the Laguna de las Salinas to the pipeline terminus at the Aguirre power plant in Salinas, a distance of about 30 miles, the terrain is underlain by fan-delta deposits of Quaternary age. The carbonate units and the fan-delta deposits are underlain by early Tertiary and older-age volcaniclastics with subordinate sedimentary rocks and lavas. The Great Southern Puerto Rico Fault Zone is the principal geologic structural feature in southern Puerto Rico. At present, the Great Southern Puerto Rico Fault Zone is considered largely quiescent, although it apparently is associated with minor earthquakes. There is no evidence of terrestrial, late Quaternary faulting within the Peñuelas to Salinas area. Seismic activity in this area mostly originates from extension zones of more distal shallow sources such as Mona Canyon to the northwest and the Anegada Trough northeast of the island of Puerto Rico. The magnitude of completeness of earthquakes in the study area ranges from 2.0 to 2.5. The seismic density for the southern coast including the study area is about 0.128 earthquakes per square mile, which is close to the average for southwestern Puerto Rico.

The estimated maximum peak ground acceleration most likely to occur in the study area, due to shallow depth seismicity with 2 percent probability of exceedance in 50 years, is 9 feet per second squared, as obtained by modeling results. The estimated peak ground acceleration with 2 percent probability of exceedance in 50 years, due to deep seismicity is 7 feet per second squared. In Ponce, the probability of exceedance per year is higher than 0.1 for the peak ground acceleration values less than 1 that result from shallow depth seismicity sources such as the Mona Passage extension zone.

The potential for liquefaction due to seismic activity may exist in areas near the coastline that have loosely to poorly consolidated sedimentary deposits and a water table close to or at the land surface. Slope failure susceptibility within the study area, due to rainfall and seismic activity, may be limited to the area that extends westward from Laguna de las Salinas to Peñuelas. In this area, foothills with slopes exceeding 10 degrees are close to the coastline and are underlain by clayey limestone and marls. In the remaining part of the study area, eastward from Laguna de las Salinas to Salinas, the land is either nearly flat or has a slope of less than 10 degrees; consequently, the susceptibility to landsliding (slope failure) caused by seismic activity and rainfall is considered to be minimal or nonexistent.

Based on modeling results from a previous study, the estimated maximum inland extent of tsunami-induced flooding is 2,600 feet in the Laguna de las Salinas and Boca Chica, located in Ponce and Juana Díaz, respectively. Flooding about 3,000 and 2,800 feet from the coastline are estimated for areas near Punta Cabullón and Jobos areas, respectively. According to the modeling results, the estimated maximum runup of the tsunami-induced flooding ranges from 9 to 14 feet for the Boca Chica and Punta Cabullón areas, respectively.

Introduction

The Puerto Rico Electric Power Authority (PREPA), as part of its efforts to diversify the fossil fuel sources to its thermoelectric power generation plants, has proposed the construction of a pipeline to convey natural gas from storage facilities in the municipio of Peñuelas to the Aguirre thermoelectric power plant in the municipio of Salinas in southern Puerto Rico (fig. 1 at end of report). The proposed paths for the route that eventually will be selected by the PREPA for the natural gas pipeline all lie along the fan-delta complex of the Southern Coastal Plain of Puerto Rico. The pipeline will cross the coastal plain along municipios from Peñuelas to Salinas, with the exception of portions between the municipios of Peñuelas and Ponce where the coastal plain is narrow or absent and the foothills extend to the coastline. To ensure that geologic conditions along the possible route(s) do not represent a threat to the physical integrity of the natural gas pipeline, and thus comply with State and Federal regulations, the PREPA requested the U.S. Geological Survey (USGS) to conduct a study of the geology along the proposed route(s) of the natural gas pipeline. This study was conducted to: (1) describe the surface and subsurface distribution of the main rock units existing along the path of the proposed pipeline, (2) determine the magnitude and distribution of present and historical seismic activity in the study area, (3) assess the potential for land liquefaction and landslides, and (4) assess the potential for the occurrence of tsunamis along the coastal portion of the Peñuelas to Salinas area. This study will help the PREPA assess the probable geologic threats to the proposed natural gas pipeline along the Southern Coastal Plain of Puerto Rico. This study will also help the USGS improve the delineation of the hydrogeologic framework of the Southern Coastal Aquifer System of Puerto Rico.

Purpose and Scope

The purpose of this report is to document the geology in the Peñuelas to Salinas area using available published scientific literature. The specific objectives of the report are to: (1) describe and present the surface and subsurface distribution of the main rock types in the Peñuelas to Salinas area along the coastal plain, and (2) describe the potential for seismic and other geologic risks in the study area, including land liquefaction, landslides, and tsunami-induced coastal flooding.

The objectives of the report are achieved primarily by integrating the results of previous geologic studies conducted within the study area along the Southern Coastal Plain of Puerto Rico. These studies, conducted by the USGS and other Federal agencies, as well as State and private entities, include but are not limited to, geologic maps, hydrogeologic assessments, geophysical surveys, and localized geologic assessments prepared as part of environmental impact statements. The published literature used in this report was prepared primarily by the USGS, the University of Puerto Rico at Mayagüez (UPRM), the Puerto Rico Department of Natural and Environmental Resources (PRDNER), and the Puerto Rico Environmental Quality Board (PREQB). Unpublished USGS data were also used, and include lithologic logs from water well drilling and other stratigraphic data from deep exploratory test holes drilled within the study area.

Geomorphology of the Study Area

The study area occupies the southernmost portion of the Southern Coastal Plain of Puerto Rico and includes the coastal portions of all municipios between the municipios of Peñuelas and Salinas (fig. 1). In the westernmost part of the study area, between Peñuelas and Laguna de Salinas, the Southern Coastal Plain is about 5 miles long and is either very narrow or absent and coastal plain foothills of Tertiary age carbonates are incised by alluvium-filled stream valleys along the Río Tallaboa and Río Matilde (Monroe, 1980). From Ponce to Salinas, a distance of about 30 miles, the study area lies within the **fan-delta**[1] complex of the Southern Coastal Plain (Renken and others, 2002). The topographic slope in the fan-delta complex is lowest near the coastline, ranging from 5 to 20 feet per mile (ft/mi), and steepest near the apex of each fan where it ranges from 13 to 26 ft/mi (Renken and others, 2002). A narrow coastal zone separates the Southern Coastal Plain from the Caribbean Sea, and consists mostly of mangrove swamps, salt flats, and minor wetlands and hypersaline lagoons. Bedrock hills (locally known as cerros), the result of normal faulting in the basement rocks (described later), protrude above the Southern Coastal Plain in the municipios of Santa Isabel and Salinas (Renken and others, 2002).

Caliche is a distinctive feature in soils of the study area, as well as the rest of the Southern Coastal Plain, particularly in areas underlain by carbonate rocks such as those in the highlands of Peñuelas and Ponce (Monroe, 1980; Renken and others, 2002). Unique to semiarid to arid climates such as that of the study area, Caliche is a residue created by the evaporation of water saturated in calcium bicarbonate. Caliche forms a surficial crust with a thickness that ranges from a few inches to several feet and acts as a barrier that, together with the arid climate, has substantially limited the development of karst topography along the Southern Coastal Plain of Puerto Rico (Giusti, 1978).

[1] Terms in bold format are defined in the glossary.

Trunk streams that traverse the fan-delta plain exhibit a straight to slightly sinuous channel morphology. Two such examples are the Río Nigua at Salinas, which is relatively straight and extends southwest from the apex of the Salinas fan apex, and the Río Coamo channel that drains the Coamo fan delta within the municipio of Santa Isabel.

Geology

The rocks underlying the wedge of middle Tertiary and Quaternary age rocks in the study area are early Tertiary and older in age (Monroe, 1980; Renken and others, 2002). These rocks generally are not exposed along the South Coastal Plain in the Peñuelas to Salinas area, except where exposed locally by normal faulting (Renken and others, 2002; Berryhill, 1960). The rocks are predominantly volcaniclastic, complemented by lesser amounts of sedimentary rocks and lavas, and are considered equivalent in age to rocks in the Cordillera Central north of the Southern Coastal Plain (Renken and others, 2002). The stratigraphic and structural relation of the early Tertiary age and older rocks in the Peñuelas to Salinas area and the rest of the Southern Coastal Plain, have been determined or inferred from outcrop exposures in foothills north of the study area, the Cordillera Central, and from analysis of geophysical data collected for coastal assessments of oil and seismic-hazard potential.

In contrast to the geology of early Tertiary age and older rocks, which generally are poorly understood, the geology of the middle Tertiary and Quaternary formations in the Peñuelas to Salinas area is well studied (Monroe, 1980). This discrepancy exists because the main aquifers in the Southern Coastal Plain of Puerto Rico are composed of middle Tertiary and Quaternary-age rocks, and thus all hydrogeologic studies of the Southern Coastal Plain have focused on these rocks. Carbonate and clastic strata of the Juana Díaz Formation and Ponce Limestone of middle Tertiary age underlie the western part of the study area from Peñuelas to Ponce (fig. 2 at end of report; Monroe, 1980). The eastern part of the study area, which extends from Ponce to Salinas, is underlain by fan-delta deposits consisting of gravel, sand, silt, and clay, predominantly of Quaternary age (Renken and others, 2002).

The Great Southern Puerto Rico Fault Zone (GSPRFZ) is the principal structural feature along the southern coast of Puerto Rico, and it contains a wide variety of fault structures (Renken and others, 2002; Krushensky and Monroe, 1978). The fault zone is formed by parallel to subparallel sinistral faults oriented northwest-southeast that extend diagonally across the south-central part of the island, and beneath the fan-delta plain and the Isla Caja de Muertos shelf offshore from southern Puerto Rico (Renken and others, 2002). The sedimentation pattern in the Southern Coastal Plain has largely been determined by the GSPRFZ. The structural dip of the middle Tertiary age rocks is generally southward, except where locally reversed northward by normal faulting that probably is associated with the GSPRFZ (Monroe, 1980).

Stratigraphy

The recent (post 1969) stratigraphic nomenclatures used by previous studies to represent the stratigraphy of the south coast of Puerto Rico are presented in figure 3 at end of report. The nomenclature used in this report is adopted from Renken and others (2002), because unlike previous nomenclatures, it incorporates and properly defines the Quaternary-age deposits along the Southern Coastal Plain of Puerto Rico.

As noted earlier, unconsolidated to lithified, clastic, and carbonate deposits of middle Tertiary and Quaternary age are better understood than other stratigraphic units in the study area because they have been studied more than older units within the Southern Coastal Plain of Puerto Rico. In ascending order (oldest to youngest), the middle Tertiary and Quaternary age stratigraphic units are the Juana Díaz Formation (Oligocene age), unnamed pelagic deposits (early Miocene), Ponce Limestone (middle Miocene to Pliocene (?) age), and unnamed units of gravel, sand, silt, and clay of Pleistocene and Holocene age (figs. 2 and 3). The middle Tertiary and Quaternary age rocks in the study area are underlain by undifferentiated igneous rocks (volcaniclastics, lavas, and intrusives) and minor sedimentary units of early Tertiary age and older. These older rocks are exposed or present at shallow depths locally within the study area where exposed by normal faulting, as noted earlier. The contact between the two rock sequences is highly unconformable, the result of substantial erosion prior to sea transgression and the onset of carbonate deposition.

Early Tertiary Age and Older Rocks

The volcaniclastics (sandstone, siltstone, breccia, and conglomerate) are by far the largest group among the early Tertiary age and older rocks (fig. 2), as indicated by examination of blocks upthrown by normal faulting and exposures of time-equivalent units in the foothills of the Cordillera Central to the north (Renken and others, 2002). The volcaniclastics are complemented by secondary amounts of igneous intrusives and lavas. Limestone and other non-volcaniclastic sedimentary rocks are minor constituents within this age-group of rocks.

The lithologic character and stratigraphic relations of the early Tertiary age and older rocks are not well understood in the Peñuelas to Salinas area. These rocks are hundreds to more than 1,000 feet (ft) beneath the land surface and are either exposed or present at shallow depths where upthrown by normal faulting, such as at Cerro Aguirre in the municipio of Salinas (Berryhill, 1960) (fig. 2). However, examination of cores obtained from exploratory borings as part of the site assessment for the proposed nuclear plant in Aguirre, Salinas, and examination of the upthrown blocks exposed by normal faulting indicate that the texture and mineralogical composition of the early Tertiary age and older rocks within the study area are similar to those of their time equivalents in the Cordillera Central to the north (Puerto Rico Water Resources Authority, 1972).

The early Tertiary age and older rocks generally become shallower east of Juana Díaz as the middle Tertiary basin gradually pinches out (fig. 4 at end of report). In the Salinas area, these rocks are overlain directly by Quaternary age deposits. This eastward shallowing trend is interrupted locally by normal faulting, either by downward or upward movement, as evidenced in the USGS test hole SC-2 in Salinas (fig. 4; for lithologic log of this test hole see plate 3 in Renken and others, 2002). These rocks are present about 850 ft below land surface in oil test well CPR-3, drilled near the coast in Ponce (fig. 4; detailed stratigraphy in U.S. Geological Survey, unpub. data). In agricultural wells east of the study area, these rocks are present mostly at depths of less than 100 ft below land surface (Renken and others, 2002; U.S. Geological Survey, unpub. data).

Middle Tertiary Age Rocks

In ascending order (oldest to youngest), the middle Tertiary units in the study area are the Juana Díaz Formation of Oligocene age, an unnamed pelagic unit of early Miocene age, and the Ponce Limestone of middle Miocene to presumably Pliocene age (figs. 2 and 3). Stratigraphic boundaries between these two geologic units have been revised several times as a result of macrofaunal and microfaunal studies (mainly of foraminiferal assemblages and their age ranges), recognition of mappable lithofacies, and the identification of unconformities.

Juana Díaz Formation

Within the study area, the Juana Díaz Formation is continuously exposed along the coastal parts of the municipios of Peñuelas and Ponce, except where locally covered by alluvium in the valleys of the Río Tallaboa, Río Pastillo, and Río Cañas (fig. 2). East of Ponce, the exposures of the Juana Díaz Formation within the study area are limited to outliers, such as those at Cerro de los Muertos in Santa Isabel and Cerro Aguirre in Salinas (Berryhill, 1960).

The lower or basal part of the Juana Díaz Formation consists of clastic mudstone or equivalent facies composed of conglomerates that include boulders, cobbles, sand, and mudstone of possible alluvial fan or fan-delta origin. The coarser clastic facies (cobbles and boulders) are commonly expressed as cut and fill structures that resulted from high energy events (Renken and others, 2002). Deposition of these facies was probably in response to uplift and increased erosion of the underlying early Tertiary age and older rocks during a low sea-level stand (Renken and others, 2002; Monroe, 1980). Some of the lithofacies of this basal unit apparently were deposited in a shallow sea environment, probably a shelf setting, as indicated by the marine fossils present in the rock. As observed at outcrops, an angular unconformity separates the basal clastic facies of the Juana Díaz Formation from the older underlying rocks. The basal clastic facies are well exposed north of the study area, along Highway 52 in the municipio of Juana Díaz. The basal deposits, however, are not exposed within the study area and are overlain by younger units (Monroe, 1980).

In the western part of the study area that includes the municipios of Peñuelas and Ponce, the basal part of the Juana Díaz Formation grades upward into a limestone sequence deposited in a shelf-type marine environment, as indicated by the presence of reef, fore reef, and back-reef fossils (Frost and others, 1983). Eastward from Ponce, the upward transition is from basal terrigenous to carbonate slope deposits indicative of a deeper marine environment than that of rocks in the Peñuelas to Ponce area. Generally, the limestone of the Juana Díaz Formation is highly fossiliferous, containing a diverse faunal assemblage of coral, coralline algae, large benthic foraminifers, and bivalves deposited during alternating periods of reef growth and destruction (Frost and others, 1983).

Limited lithologic data and structural dislocation in the form of tilting and complex fault relations make the estimation of thickness in the Juana Díaz Formation difficult. The Juana Díaz Formation ranges from 656 to more than 2,296 ft thick in the Peñuelas to Santa Isabel area (U.S. Geological Survey, unpub. data; Todd and Low, 1976; Monroe, 1980). The Juana Díaz Formation may be thickest in the Río Tallaboa, Peñuelas to Playa de Ponce area (fig. 2), with a thickness ranging from 1,300 to about 2,200 ft (Monroe, 1980; Renken and others, 2002). At well CPR-3, an oil exploratory well drilled near the coast in the Punta Cabullón area (fig. 4; U.S. Geological Survey, unpub. data), the top of the Juana Díaz Formation was estimated to be about 1,600 ft below land surface, with an estimated thickness of 1,200 ft (Renken and others, 2002). The Juana Díaz Formation thins eastward to less than 660 ft in the municipio of Salinas where it lies buried, except at Cerro Aguirre where it crops out (Berryhill, 1960). At outcrops, the thickness of the clastic beds of the basal part of this formation may range from 330 to about 1,400 ft, whereas the thickness of the limestone facies may range from about 500 to more than 1,950 ft (Renken and others, 2002).

Unnamed Pelagic Rocks or Deposits

An unnamed carbonate-rock sequence of early Miocene age unconformably overlies the Juana Díaz Formation and crops out locally in the north-central part of the southern middle Tertiary belt. This rock sequence includes the Angola Limestone, composed of island-slope chalk beds described by Seiglie and Bermúdez (1969), the pelagic Río Tallaboa marlstone described by Seiglie and Moussa (1974), and an upper "new formation" described and defined by Frost and others (1983). The chalk and marlstone beds crop out in a few localities within the Peñuelas to Ponce area, but these units or their time-equivalent strata presumably are buried beneath the rest of the study area (Moussa and Seiglie, 1970). Moussa and Seiglie (1970) believe an unconformity separates the Angola Limestone and Río Tallaboa units and their time equivalents, whereas Frost and others (1983) have suggested continuous deposition during the early Miocene. Renken and others (2002) referred to this unnamed carbonate sequence as the unnamed pelagic deposits.

Ponce Limestone

The Ponce Limestone of Miocene and Pliocene age unconformably overlies the unnamed carbonate unit described above, and where this unit is missing, the Ponce Limestone unconformably overlies the Juana Díaz Formation (Monroe, 1980). The Ponce Limestone consists mostly of yellowish-orange, soft to moderately hard fossiliferous limestone, and within the study area it crops out almost continuously from Peñuelas to Río Pastillo in the municipio of Ponce (Monroe, 1980). Outcropping strata of Ponce Limestone north of the study area contain abundant marine fossils, such as molds of gastropods, pelecypods, coral heads, and large foraminifera, all of which are indicative of deposition in shallow-water lagoon and back-reef environments. Samples collected from the Kewannee oil test wells (CPR1, 2, and 3 in fig. 4) indicate that shallow-water beds of the Ponce Limestone grade west to east from a shallow carbonate facies to terrigenous sand, gravel, and mudstone interbedded with some limestone, as evidenced in lithologic logs from oil test well Kewannee CPR-3. Within the study area, between Playa de Ponce and Santa Isabel, the Ponce Limestone is replaced by time-equivalent terrigenous clastics buried beneath fan-delta deposits of Quaternary age.

As with the Juana Díaz Formation, structural complexities and a limited availability of water-well lithologic data make it difficult to accurately estimate the thickness of the Ponce Limestone. Within the study area, the limestone facies and equivalent clastic strata appear to be thickest in the Juana Díaz to Santa Isabel area (1,000 to more than 1,300 ft) (Monroe, 1980; fig. 4). The Ponce Limestone in the Río Tallaboa area was estimated to be 2,788 ft by Monroe (1980). This value is considered excessive by Frost and others (1983) and Renken and others (2002), who believe the estimate is inconsistent with the regional trend east of Peñuelas. Both later studies attribute the initial overestimate by Monroe (1980) to complex fault relations and vegetative cover, each of which can result in erroneous interpretation of geologic relations.

Quaternary Age Fan-Delta and Alluvial Deposits

The middle Tertiary section is overlain by fan-delta and alluvial deposits of Quaternary age. In the municipio of Salinas, however, the Quaternary age deposits are directly underlain by early Tertiary and older-age rocks in the vicinity of Aguirre.

The part of the study area between Ponce and Salinas lies within the fan-delta plain along the southern coast of Puerto Rico. This plain was formed by the coalescence of four larger and seven smaller fan deltas along an area that extends from Ponce to the municipio of Patillas, about 16 mi (miles) east of Salinas (Renken and others, 2002). The fan-delta deposits are predominantly Quaternary in age and consist of gravelly sand (including boulders and cobbles), and silt (Renken and others, 2002). Poorly developed soil caliche is exposed in isolated areas north of the study area, and its presumed existence in the subsurface below land surface is consistent with semiarid conditions that existed during the Pleistocene (Renken and others, 2002). The strata deposited within a fan-delta environment are dominated by streamflow, sheetflow, and gravity-driven depositional processes. Alluvial deposits are restricted to areas near streams, and are dominated by streamflow features (Renken and others, 2002).

In the municipio of Peñuelas and the westernmost part of Ponce, fan-delta deposits are replaced by time-equivalent alluvial deposits that occupy the narrow coastal valleys of Río Tallaboa and Río Matilde. These alluvial deposits presumably are underlain by the Ponce Limestone or time-equivalent units. Eastward from Playa de Ponce to Salinas, the fan-delta deposits unconformably overlie unconsolidated to poorly consolidated clastic sediments, as well as minor limestone and marl deposits of shallow-marine conditions that are, at least in their lower part, time-equivalent to the Ponce Limestone (figs. 4 and 5 at end of report; Renken and others, 2002: Monroe, 1980). The clastic-sedimentary units directly beneath the fan-delta deposits are Pleistocene or Holocene in age (Renken and others, 2002). Eastward from about Salinas, the fan-delta deposits are underlain by early Tertiary and older age rocks (Renken and others, 2002; fig. 4).

The delta plain occupies the low-lying part of the Southern Coastal Plain of Puerto Rico. Most of the fan deltas between Ponce and Salinas do not exceed an altitude of 160 ft above sea level at their apex, except for the Capitanejo fan in Juana Díaz, which is up to 260 ft above sea level (fig. 1; U.S. Geologic Survey topographic quadrangles of Playa de Ponce, Santa Isabel, Salinas, and Central Aguirre). The surface of the different fans slopes coastward with a gradient that ranges from 130 ft/mi within the apex or proximal upland channels to 10.5 ft/mi near the coast. From the apex to coastline, fan radii average nearly 32,800 ft. East of Ponce, all of the fan deltas contain a well-developed, semi-radial, subaerial morphology (Renken and others, 2002). Pre-Miocene strata protrude above the delta plain at a few localities, such as Cerro Aguirre in Salinas and Cerro de los Muertos in Santa Isabel (fig. 2; Berryhill 1960; Glover, 1971).

The fan deltas within the study area and along the rest of the Southern Coastal Plain 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 of terrestrial origin (Renken and others, 2002). The most extensive area of mangroves, marshes, and tidal flats within the study area is located along the Salinas fan-delta margin. Mangrove swamps of substantial aerial extent occupy the margins of Laguna de Las Salinas in Ponce, particularly along the northern margin close to Highway 2. Beaches between El Tuque in Ponce and Río Tallaboa in Peñuelas and along the southern edge of the Playa de Salinas at Salinas are the only areas within the study area that consist partly of skeletal carbonate sand, with bioclastics derived from fringing reefs (Frost and others, 2003).

Renken and others (2002) used water-well logs and other well drilling data to estimate the thickness of fan-delta and alluvial deposits and map the configuration of the underlying contact (fig. 6 at end of report). Fan-delta deposits usually do not exceed 33 to 98 ft in thickness within both the proximal part of the fan and inland alluvial channels that extend downward from the fan apex. The thickness of the fan-delta sequence east of Ponce increases from less than 10 ft at its landward margin to between 150 and about 330 ft in most coastal areas (figs. 4 and 6). The fan-delta sequence and other associated Quaternary age deposits may locally thicken to about 490 ft where they overlie the structural basin in the Playa de Ponce to Bahía de Rincón area in the municipios of Santa Isabel and Salinas (figs. 2 and 4). The actual thickness of the Quaternary deposits within this basin, however, is poorly known because of limited control and lack of age indicators, such as faunal assemblages. The fan-delta deposits thin considerably east of Bahía de Jobos and are less than 130 ft thick.

Renken and others (2002) recognized three scales of cyclical deposition within the vertical sequences of fan-delta deposits from exposed and subsurface sections in the Southern Coastal Plain, including the study area. The small-scale pattern, from less than 3 to 70 ft thick, is characterized by a progressive-upward change in grain size within a discrete bed. The intermediate-scale pattern, from 50 to 230 ft thick, is characterized by a progressive change in bed thickness. The large-scale pattern, from 1,310 to 1,640 ft thick, is characterized by overall changes in bed thickness that occurs within the entire coarsest grained section of gravel, sand, and silt. Small-scale cyclicity is generally caused by short-term depositional events, such as stream and flood flow, that result either in a fining-upward sequence caused by aggradation or lateral accretion within channels, or in a coarsening-upward sequence caused by channel bar migration.

A lithofacies map for the fan-delta plain shown as plate 1D in Renken and others (2002) shows that sand and gravel deposits are concentrated as lobes, each separated by interlobe areas of fine-grained detritus. The percentage of gravel and sand content generally decreases with distance down the fan. As indicated in figure 7 at end of report, gravel and sand percentages are highest in proximal areas closest to the fan apex and along inland alluvial channels where flows are restricted and flow velocities are greatest. The gravel and sand content exceeds 40 percent within the proximal parts of the fan deltas of Salinas, Coamo, and Capitanejo in Juana Díaz. Within the proximal part of the Río Portugués-Bucaná fan delta the sand and gravel content exceeds 60 percent.

Structure

The GSPRFZ is the principal geologic structural feature in the southern part of Puerto Rico. The middle Tertiary section is inclined toward the south, except where faulting was reversed and as a result the rock sequence fragmented in blocks. The structural setting and associated tectonic movements controlled fan-delta and alluvial-fan deposition in the study area during pre-Quaternary and Quaternary periods. Late Quaternary faulting has only been observed in offshore areas south of the study area, and has not affected Quaternary alluvial deposits along the Southern Coastal Plain.

Great Southern Puerto Rico Fault Zone

The GSPRFZ consists of parallel to subparallel sinistral faults that strike northwest and extend diagonally across the south-central part of the island (Glover, 1971). Geophysical data indicate that the GSPRFZ extends beneath the fan-delta plain and the Isla Caja de Muertos shelf (Glover, 1971; Garrison, 1969), possibly forming the southern wall of the Whiting Basin (Western Geophysical Company of America, 1974). At least 12 northwest striking faults have been identified and mapped as part of the GSPRFZ (fig. 8 at end of report). Northwest of Ponce, the width of the fault zone between the northernmost and southernmost sinistral faults is more than 29,500 ft wide (Glover, 1971). The actual width of the GSPRFZ coastward, however, is not known because it is concealed by the fan-delta plain. The strike of this fault zone varies from N 54^{o} W to N 55^{o} W, where it crosses the Cordillera Central mountain range to the northwest and west of Ponce (Glover, 1971; Krushensky and Monroe, 1975, 1978, 1979), to N 75^{o} W where it underlies the fan-delta plain (Renken and others, 2002).

There is no consensus between previous studies concerning the age of the GSPRFZ. Glover (1971) has postulated that the first sinistral movement occurred during the early Cretaceous about 144 million years before present (Ma), with additional movements occurring during Maestrichtian (about 70 Ma) and Eocene (about 57 Ma). McIntyre (1971, 1975) has suggested that initiation of the GSPRFZ (fig. 8) occurred after the middle Eocene (about 45 Ma). Krushensky and Monroe (1975, 1978) have constrained sinistral movement to Eocene to Oligocene (55-35 Ma) with horizontal movement continuing along the Lago Garzas and Bartolomei faults (fig. 2) as late as the early Miocene (about 23 Ma). Sinistral movement along these two faults could correspond with the development of the large structural and depositional basin that underlies the fan-delta deposits between Ponce and Santa Isabel (Renken and others, 2002). Other faults of the GSPRFZ that strike east-west and have a normal slip component displace rocks of the Ponce Limestone and Juana Díaz Formation that are exposed west and north of Ponce. Renken and others (2002) have suggested that the pattern of buried bedrock highs and lows are relict features of a braided sinistral fault system. These highs and lows supposedly originated as horst and graben fault blocks, formed by movement along the GSPRFZ that were subjected to subaerial erosion and then buried and preserved as paleotopographic ridges and valleys beneath the fan-delta plain.

Late Quaternary Faulting

As of March 2005, no evidence of terrestrial, late Quaternary (since about 10,000 years ago) faulting has been found along the southern coast of Puerto Rico (Mann and others, 2005). In an aerial photography study, Geomatrix Consultants (1988) detected the presence of numerous, predominantly east-west trending lineaments on the coalesced alluvial fan complex between Río Coamo and Río Jueyes in the municipio of Santa Isabel (fig. 1). No evidence of deformation of the late Quaternary alluvial fan deposits (fan-delta deposits), however, was recognized in the field during the study by Geomatrix Consultants (1988). As of March 2007, no comprehensive study of late Quaternary faulting has been conducted along the southern coast of Puerto Rico (E. Asencio, University of Puerto Rico at Mayagüez, written commun., 2007).

A geophysical survey conducted during 2000, however, revealed evidence of late Quaternary seafloor faulting in three offshore areas along the southern coast of Puerto Rico (fig. 8; Mann and others, 2005). Late Quaternary seafloor faulting is indicated by a recent scarp with about 66 ft of relief on the seafloor of the offshore Ponce Basin that bounds the ridge where the island of Caja de Muertos is located. Late Quaternary seafloor faulting also was observed along the offshore extensions of the Esmeralda and Río Jueyes faults, both of which are strands of the GSPRFZ. This late Quaternary seafloor faulting apparently pinches out landward in a scissor-like manner and does not displace terrestrial fan-delta deposits.

Geologic Risks

The GSPRFZ is considered to be largely quiescent and is associated only with small earthquakes (McCann, 1985). The **magnitude of completeness** for earthquakes in the study area is less than the average for the island, although seismic density in the study area is close to the highest regional average for the island (Clinton and others, 2006). Mueller and others (2003) determined that the highest **peak ground acceleration** (PGA), due to **shallow seismicity** that may occur in the study area, with a 2 percent **probability of exceedance** in 50 years, is about 9 feet per squared second (ft/s^{2}). The highest peak ground acceleration, due to **deep seismicity** that may occur in the study area, with a 2 percent probability of exceedance in 50 years, is about 7 ft/s^{2} (Muller and others, 2003). The occurrence of at least one earthquake-related tsunami has been documented in the study area, and affected the municipio of Ponce during the second half of the 19th century (Neumann, 1913). Modeling results by Mercado and Justiniano (2007) indicate that the inland extent of flooding induced by a tsunami within the study area can range from about 2,600 to 3,000 ft. A study of the susceptibility of the study area to liquefaction due to seismic activity has not been done. However, the potential for liquefaction due to seismic activity may exist at localities within the study area having loose to moderately indurated sediments and a water table close to or at the land surface; these localities are generally near the coastline. The potential for rainfall-induced landslides within the study area is none to minimum, except in the area west of Laguna de las Salinas in Ponce (fig. 1), which has a moderate to high susceptibility of landsliding due to rainfall (Larsen and others, 2004).

Spatial and Temporal Distribution of Seismic Activity

The island of Puerto Rico has a long history of damaging seismic activity and associated tsunamis. The island is bounded on all sides by major tectonic faults (fig. 9 at end of report). Historical earthquakes with damaging effects on Puerto Rico have occurred in 1615, 1670, 1751, 1776, 1787 (an approximate magnitude 8.0 event that originated in the Puerto Rico Trench), 1867 (an approximate magnitude 7.3 event that originated in the Anegada Trough), and 1918 (an approximate magnitude 7.3 event that originated in the Mona Canyon). [The Richter scale used to measure the magnitude of earthquakes was invented in 1934.] The earthquakes of 1943 (approximate magnitude 7.5) and 1946 (approximate magnitude 7.8) also caused substantial damage in the Dominican Republic (Shepherd and Lynch, 1992). The 1867 and 1918 earthquakes were followed by tsunamis that affected the southern and western coasts, respectively.

Puerto Rico lies on a microplate located between the obliquely subducting North American and Caribbean plates. The main sources of seismic activity in Puerto Rico are at the defined boundaries of the microplate: the subduction zones to the north (Puerto Rico Trench) and south (Muertos Trough), and zones of extension at the Anegada Trough to the east and in Mona Canyon to the west (fig. 9). All of these regions have produced earthquakes with magnitudes above 7.0 throughout the history of the island (Asencio, 1980; Moya and McCann, 1992).

In addition to these offshore sources, Prentice (2000) recently found evidence of two surface-rupturing events, each with a component of strike-slip motion, that occurred within the last 5,000 years along the South Lajas Fault—an inland, normal fault in southwestern Puerto Rico (fig. 9). According to La Forge and McCann (2005), this 31.3-mile-long fault segment can produce magnitude 7.0 seismic events and potentially could be the western extension of a fault zone that extends eastward toward the municipio of Peñuelas. The Great Northern (GNPRFZ) and Southern Puerto Rico fault zones, considered active from the early Cretaceous to early Tertiary, are now considered largely quiescent and apparently are associated with small earthquakes that may represent inherent zones of weakness (McCann, 1985). These two fault zones have an unknown potential for large magnitude events; however, no evidence of terrestrial Holocene (late Quaternary) rupturing has been identified along these fault systems (McCann, 1985).

The average magnitude of completeness for the earthquake database of the Puerto Rico Seismic Network (PRSN) for the January 1986 to March 2006 interval is 3.5 (Clinton and others, 2006). The majority of the seismic events in Puerto Rico occur at depths of less than 82,000 ft (Clinton and others, 2006). This relatively shallow seismicity is concentrated in areas along Mona Canyon, the region between the Puerto Rico Trench and the 19° Fault zone, the Sombrero Fault zone, and across the southern part of Puerto Rico (including the study area) (Clinton and others, 2006). The deep seismicity, greater than 82,000 ft below land surface, occurs mainly in the Dominican Republic and in the northern part of Puerto Rico (Clinton and others, 2006). This seismicity is caused by the oblique subduction of the North American plate beneath the Puerto Rico microplate (Clinton and others, 2006). The magnitude of completeness in the southern part of Puerto Rico, including the study area, ranges from 2 to 2.5 for the January 1986 to March 2006 period (fig. 10 at end of report, Clinton and others, 2006).

The areas of highest seismic density in and near Puerto Rico for the January 1986 to March 2006 period are: (1) southwestern Puerto Rico between the GSPRFZ and the coast, (2) the region between the Puerto Rico Trench and the 19° fault zone, and (3) the Sombrero seismic zone (Clinton and others, 2006; fig. 11 at end of report). As noted earlier, seismic density in the Peñuelas to Salinas area averages about 0.128 earthquakes per square mile, which is close to the average for the southwestern part of Puerto Rico (Clinton and others, 2006). The seismic density parameter is based on detected earthquakes of all magnitudes and depths.

The USGS recently conducted a probabilistic seismic hazard assessment for Puerto Rico and the U.S. Virgin Islands (Mueller and others, 2003) for use in earthquake-damage mitigation, response planning, and for the adoption of stricter building codes and structural design standards. The methodology used for the study, as described by Frankel and others (1996, 2002), is based primarily on (1) gridded and smooth historical seismicity generalized using exponential magnitude distributions, and (2) specific fault sources with published slip-rate or recurrence information. These sources include the main subduction interface south of the Puerto

Rico Trench, the Mona Canyon and Anegada Trough extensional zones, the Septentrional Fault (the major plate boundary structure in the Dominican Republic), and the South Lajas Fault (fig. 9). Where information on seismicity or fault components was incomplete, the seismic hazard assessment was supplemented with sources based on geodetic or other deformation data. For this methodology, earthquakes were assumed to occur randomly in time so that probabilistic ground motions represent time-independent seismic hazards. The results of this seismic hazard assessment by Mueller and others (2003) were published in a series of maps of probabilistic ground motion for three measures: peak ground acceleration, 1.0-second **spectral acceleration**, and 0.2-second spectral acceleration. Each measure was published for 2 percent and 10 percent probabilities of exceedance in 50 years, which correspond to return times of 2,500 and 500 years, respectively.

Mueller and others (2003) excluded the Muertos Trough and related structures offshore from southern Puerto Rico in their assessment because their rates of activity are poorly known. In their assessment model, LaForge and McCann (2003) considered the activity rates of these structures low compared to those of the other structures in and near Puerto Rico and the U.S. Virgin Islands. They agreed, however, with Mueller and others (2003) that the proximity of these structures to the southern coast of Puerto Rico makes them important subjects for future research.

For simplicity, only the probabilistic PGA estimates obtained from the study by Mueller and others (2003) are presented and discussed in this report. Probabilistic PGA is considered by Mueller and others (2003) to be a parameter that, by itself, may indicate the seismic hazard potential for a given area. The highest PGA most likely to occur in the study area, with 2 percent probability of recurrence, is due to shallow depth seismicity (table 1). In Ponce, the probability of exceedance per year is greater than 0.1 only for PGA values below 1 ft/s^2 caused by shallow seismic activity (less than 31.3 miles deep) from the Mona Passage extension zone. In general, PGA values in the Ponce area have a higher probability of exceedance per year for seismic activity that originates from shallow sources, such as the Mona Passage extension zone, than from other sources.

Potential for Liquefaction, Landslides and Tsunamis

Seismic activity is itself a driving force for the occurrence of other hazards. Along a coastal zone, such as the Peñuelas to Salinas area, these earthquake-induced hazards can produce liquefaction, landslides (slope failure), and tsunamis; slope failure can result from liquefaction as well as seismic activity. As of 2006, an assessment of the liquefaction potential of the Peñuelas to Salinas area has not been conducted. No evidence has

Table 1. Estimated peak ground acceleration (PGA) in the study area from selected sources.

[ft/s^2, feet per second squared]

Estimated PGA in the study area (ft/s^2)	Source of seismicity
2 percent probability of exceedance in 50 years	
9	Shallow (less than 31.3 miles below ground surface)
7	Deep (greater than 31.3 miles below ground surface)
7	Deep subduction, predominantly from south of the Puerto Rico Trench
3	Subduction beneath Hispaniola
5-7	Active extensional zones in the Anegada and Mona Passages
13	Combination of all sources
10 percent probability of exceedance in 50 years	
5-7	Combination of all sources

been found that indicates liquefaction has occurred in historical times within the study area. It is reasonable to assume, however, that seismically-induced liquefaction may be a potential hazard at locations within the study area that have loose and poorly consolidated sedimentary deposits and a shallow water table—such areas are generally near the coast

As of 2006, landslides (slope failure) due to seismic activity have not been documented within the study area. The possibility of landslides in the study area may be limited to areas west of Laguna de las Salinas, based on the presence of foothills near the coastline in that area. It is assumed that chances of landslides due to seismic activity east of Laguna de las Salinas are probably minimal or none.

A recent landslide assessment of the municipio of Ponce indicates that the coastal area between Laguna de las Salinas and Peñuelas has a moderately high susceptibility to landslides triggered by rainfall (Larsen and others, 2004). This area is underlain by the Juana Díaz Formation and the Ponce Limestone. Locally, both of these geologic units have similar lithologies; each consisting predominantly of highly clayey limestone that grades to marl. The topographic slope in this area exceeds 12 degrees, which was determined to be the approximate threshold value for rainfall-induced landslides (Larsen and others, 2004). Between Laguna de las Salinas and Peñuelas, the coastal plain is either narrow or non-existent, except in the lower valleys of Río Tallaboa and Río Matilde. The coastal area of Ponce east of Laguna de las Salinas is not susceptible to landslides caused by rainfall because the area has low topographic relief characterized by slopes generally less than 10 degrees (Larsen and others, 2004). It is reasonable to assume that eastward from Ponce to Salinas, the landslide susceptibility along the coastal plain due to rainfall is also minimal or nonexistent, because slopes in this area are generally less than 10 degrees.

One of the primary sources of tsunamis is offshore seismic activity. For example, the 7+ magnitude 1918 earthquake, caused by a rupture in the Mona Passage extension zone, resulted in a tsunami that caused a substantial loss of property and human lives in the western part of Puerto Rico, particularly the municipios of Mayagüez and Aguadilla (Clinton and others, 2006). A tsunami caused by an earthquake on November 18, 1867, affected the municipio of Ponce (Neumann, 1913).

The approximate maximum inland extent of the tsunami flood caused by the largest probable seismic event in the Peñuelas to Salinas area was determined from a modeling study by Mercado and Justiniano (2007) and is presented on figures 12 through 15 at end of report. The maximum inland extent of tsunami-induced coastal flooding within the study area, according to Mercado and Justiniano (2007), is shown in table 2. The expected runup, or maximum vertical height onshore above sea level of tsunamis, ranges from 9 ft in the Boca Chica area (USGS Santa Isabel quadrangle) to 14 ft in the Punta Cabullón area (USGS Playa de Ponce quadrangle) (Mercado and Justiniano, 2007).

Table 2. Maximum inland extent of tsunami-induced coastal flooding within the study area.

[Data from Mercado and Justiniano modeling results are based on seismic activity produced within the immediate vicinity of Puerto Rico and assume that uniformed displacement occurs along the entire length of the fault where the seismic activity originates. A worst-case scenario is considered by assuming a maximum displacement along the fault.]

Location	Maximum inland extent (feet)	USGS quadrangle	Figure in this report
Laguna de las Salinas	2,600	Punta Cuchara	12
Boca Chica	2,600	Santa Isabel	14
Juana Díaz	2,600	Santa Isabel	14
Punta Cabullón	3,000	Playa de Ponce	13
Jobos National Estuarine Research Reserve near Aguirre	2,800	Salinas	15

Summary

The Puerto Rico Electrical Power Authority has proposed the construction of a pipeline to convey natural gas from storage facilities in the municipio of Peñuelas to the Aguirre thermoelectric power plant in the municipio of Salinas. In order to ensure that the geologic conditions along the probable routes do not represent a threat to the physical integrity of the pipeline and thus comply with State and Federal regulations, the Puerto Rico Electrical Power Authority requested the U.S. Geological Survey to evaluate and synthesize the geology of the coastal plain in the Peñuelas to Salinas area.

The proposed pipeline route traverses the fan-delta complex of the Southern Coastal Plain of Puerto Rico with the exception of areas between Peñuelas and Ponce where the coastal plain is narrow or absent and the foothills extend to the coastline. A narrow coastal zone that consists of mangrove swamps, salt flats, wetlands, and hypersaline lagoons, separates the Southern Coastal Plain from the Caribbean Sea. The study area is underlain in its western part, from Peñuelas to Ponce, by the carbonate and clastic strata of the Juana Díaz Formation and Ponce Limestone of middle Tertiary age. The eastern part of the study area, which extends from Ponce to Salinas, is underlain by fan-delta deposits, mostly consisting of gravel, sand, silt, and clay, that are mostly Quaternary in age. The rocks underlying the middle Tertiary and Quaternary age rocks are early Tertiary and older in age. The underlying rocks are predominantly volcaniclastic, with lesser amounts of sedimentary rocks and lavas. The underlying rocks are assumed to be equivalent in age to the rocks in the Cordillera Central that lies to the north of the Southern Coastal Plain.

The Great Southern Puerto Rico Fault Zone is the main geologic structure on the southern coast of the island of Puerto Rico. Geophysical data indicate that the Great Southern Puerto Rico Fault Zone extends beneath the fan-delta plain and the Isla Caja de Muertos shelf. This system of faults predominantly displaces early Tertiary and older age rocks, but some of its components that strike east-west may displace rocks of the Juana Díaz Formation and Ponce Limestone exposed west and north of Ponce. As of 2006, no evidence of terrestrial, late Quaternary faulting in the southern coast has been documented in the literature. Geophysical evidence, however, indicates the occurrence of late Quaternary seafloor faulting at three offshore localities along the southern coast. This late Quaternary seafloor faulting apparently pinches out landward in a scissor-like manner and does not displace terrestrial fan-delta deposits.

Puerto Rico lies on a microplate located between the obliquely subducting North American and Caribbean plates. The main sources of seismic activity in Puerto Rico are at the defined boundaries of the microplate: the subduction zones to the north (Puerto Rico Trench) and south (Muertos Trough), and zones of extension at the Anegada Trough to the east and in Mona Canyon to the west. The Great Northern Puerto Rico Fault zone and the Great Southern Puerto Rico Fault Zone are now considered to be largely quiescent and only seemingly associated with small earthquakes. The magnitude of completeness for earthquakes in the south coast of Puerto Rico that includes the study area ranges from 2 to 2.5, as determined by the Puerto Rico Seismic Network database. The seismic density of the study area is about 0.128 earthquakes per square mile, which is about the same as that of southwestern Puerto Rico. The estimated peak ground acceleration, a measure of seismic intensity, with 2 percent probability of exceedance in 50 years, most likely to occur along the southern coast (including the Peñuelas to Salinas area) due to shallow depth seismicity is 9 ft/s^2. The estimated peak ground acceleration, with 2 percent probability of exceedance in 50 years, most likely to occur along the southern coast due to deep seismicity (deeper 31.3 miles) is about 7 ft/s^2. In Ponce, the probability of exceedance per year is higher than 0.1 only for those peak ground acceleration values less than 1 ft/s^2 that result from shallow seismicity in Mona Canyon. In general, peak ground acceleration values in the municipio of Ponce have a higher probability of exceedance per year when caused by seismic activity from shallow sources such as the Mona Passage extension zone.

An assessment of the liquefaction potential in the study area has not been conducted as of 2006. Likewise, no evidence of the occurrence of liquefaction in historical times has been documented in the study area. However, areas near the coastline that are characterized by loosely to poorly consolidated sediments and a water table close to or at land surface may be susceptible to liquefaction caused by seismic activity.

As of 2006, no evidence of slope failure due to seismic activity has been documented within the study area. The possibility of slope failure due to seismic activity in the study area is limited to the area westward from Laguna de las Salinas, based on the presence foothills close to coastline. Eastward from Laguna de las Salinas, the possible routes for the proposed natural gas pipeline are either over land that is either nearly flat or has a minimal slope, consequently, it is reasonable to assume that eastward from Ponce to Salinas, the probability of landslides along the coastal plain is minimal to nonexistent.

The area extending westward from Laguna de las Salinas to Peñuelas is considered to have a moderate to high susceptibility to rainfall-induced landslides. This area has topographic slopes that exceed 10 degrees and is underlain by clayey limestone to marl within the foothills. Eastward from Laguna de las Salinas, the coastal area is either flat or with a topographic slope less than 10 degrees, consequently, the susceptibility to rainfall-induced landslides is considered minimal to nonexistant.

The occurrence of at least one tsunami caused by an earthquake has been documented for the second half of the 19th century, and occurred in the municipio of Ponce. Modeling results indicate that the maximum inland extents of tsunami-induced coastal flooding within the study area may be about 2,600 ft at Laguna de las Salinas in Ponce and Boca Chica in Juana Díaz, 3,000 ft in Punta Cabullón in Ponce, and about 2,800 ft in the vicinity of the Jobos National Estuarine Research Reserve in the Aguirre locality of Salinas. Runup ranges from 9 ft in the Boca Chica area to 14 ft in the Punta Cabullón area.

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Glossary

deep seismicity—is seismicity that originates at a depth greater than 31.3 miles. This type of seismicity generally originates from activity in the lower zone of the crust such as the deeper interaction of the Caribbean and North American plates.

fan delta—is an alluvial fan that progrades into a standing body of water from an adjacent highland. Fan deltas are characterized by their semi-radial or fan-like shape, concave-upward radial and convex-upward cross-sectional profiles, and the relatively narrow space they occupy between a highland mountain front and a nearby water body (Wescott and Ethridge, 1980; McPherson and Moiola, 1987).

magnitude of completeness—is the lowest magnitude at which 100 percent of the seismic events in a spaced-time volume are detected (Clinton and others, 2006). Magnitude of completeness can be considered as a quality-control parameter that assesses the spatial and temporal uncertainties of the earthquakes database. These spatial and temporal uncertainties in the database arise from such factors as limitations of networks in detecting certain signals, use of diverse equipment to detect and record signals, and processing of acquired signals with a variety of software and assumptions.

peak ground acceleration (PGA)—is the maximum acceleration (velocity rate of change with time) experienced by a particle in the ground during the course of the earthquake motion. It is a measure of earthquake ground motion and is expressed in percent of the gravity (G) force value of 32.1 feet per second per second.

probability of exceedance (PE)—is the probability that a specific ground motion (peak acceleration) is exceeded in a determined number of years. A peak ground acceleration with a PE of 2 percent in 50 years is that acceleration with a return time of approximately 2,500 years. A peak ground acceleration with a PE of 10 percent in 50 years is that acceleration with a return time of approximately 500 years. All ground motions (peak ground accelerations) from all sites and all magnitudes corresponding to a particular probability of exceedance are contoured and presented in a map.

shallow seismicity—is seismicity that originates at depths less than 31.3 miles in the Caribbean area, shallow seismicity caused mainly by extensional activity in the Mona and Anegada Troughs, and by stress at shallow depths that result from the interaction of the Caribbean and North American plates (subduction) in the vicinity of the Puerto Rico Trench. Shallow seismicity is mostly limited to the mid and upper crust regions.

spectral acceleration—is the approximated acceleration experienced by a building during the course of the earthquake motion. Likewise, it is expressed in percent of gravity (G). This acceleration is only due to those components of the ground motion that have the same or close natural periods as those of the building.

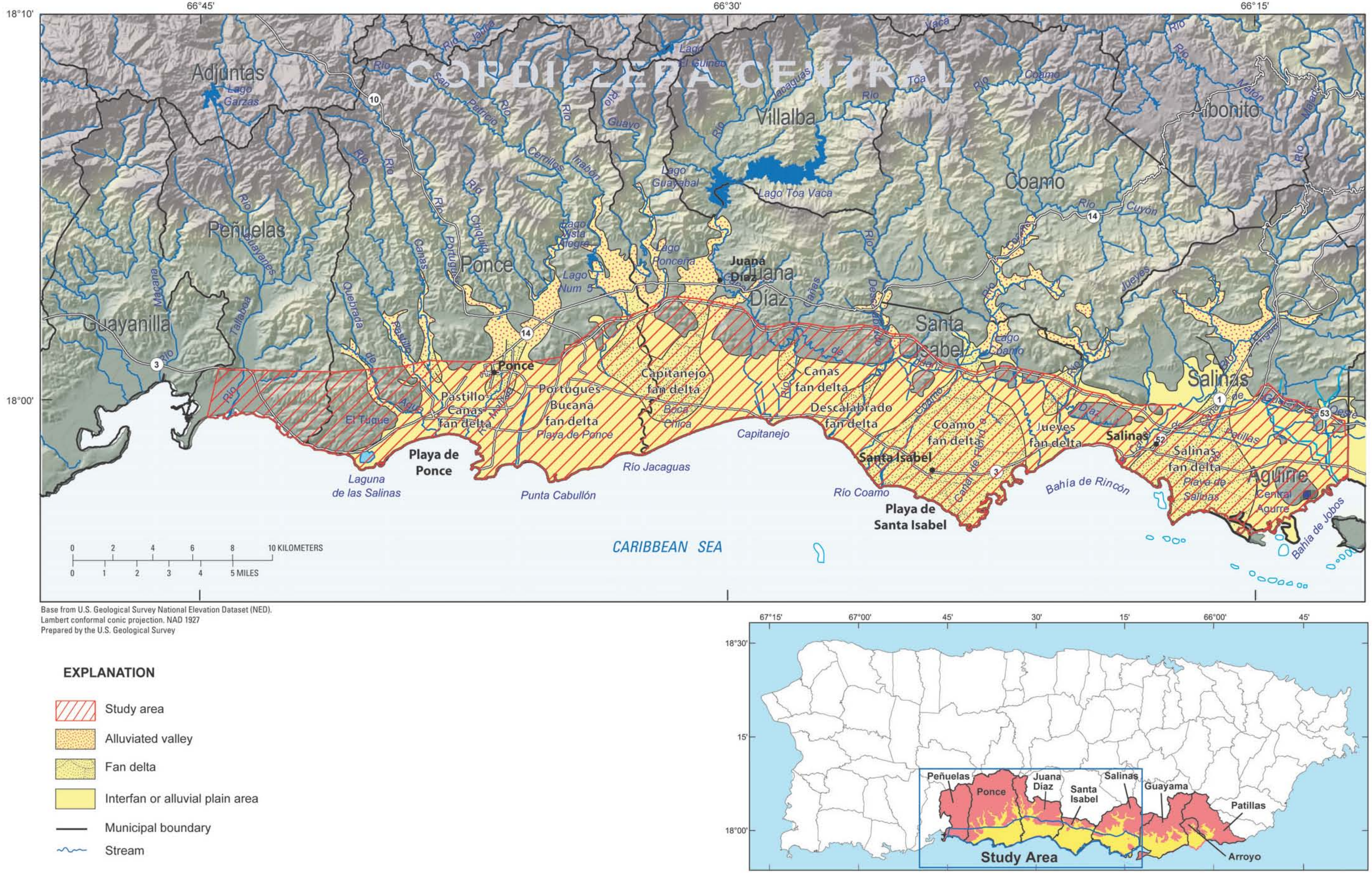
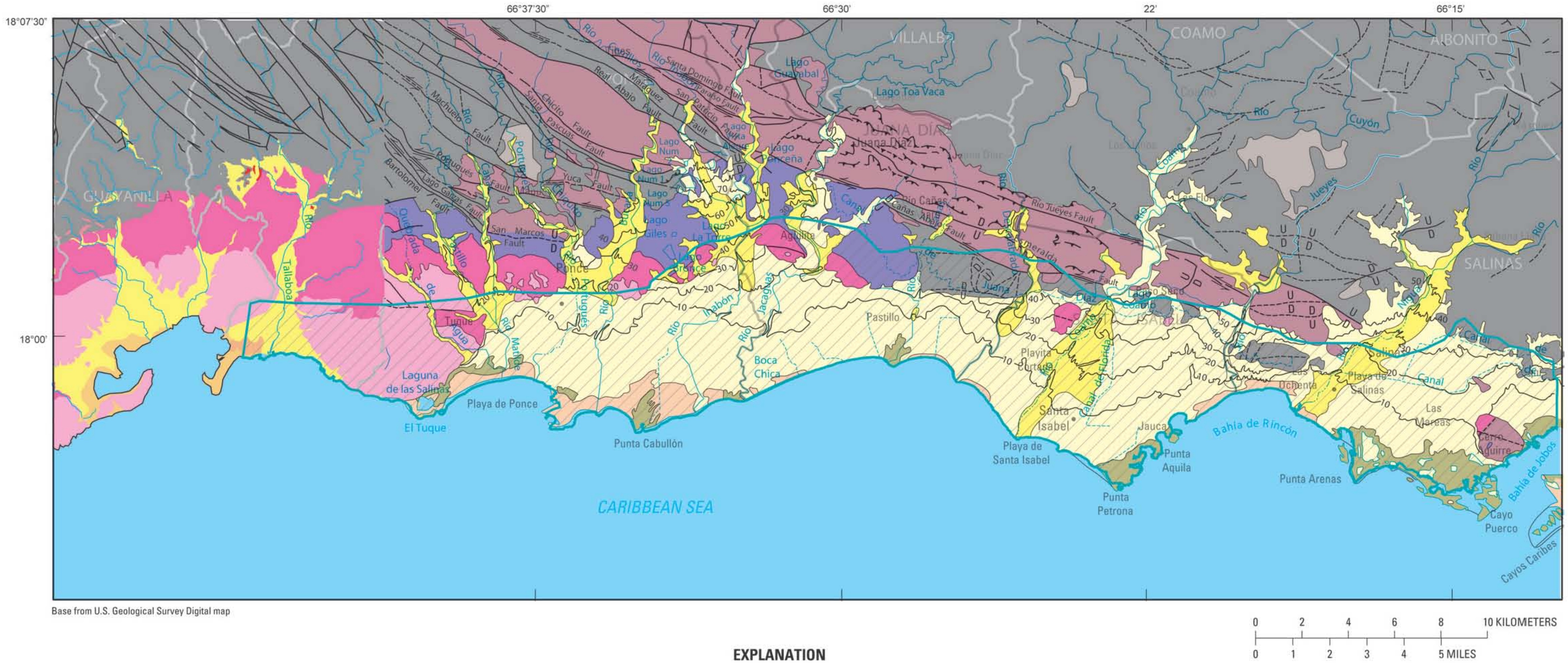


Figure 1. Location of the Peñuelas to Salinas study area. Insert shows extent of the Southern Coastal Plain of Puerto Rico (adapted from Renken and others, 2002).



EXPLANATION

DEPOSITS OF QUATERNARY AGE

Subaerial zone

- Fan-delta plain
- Alluvium
- Marsh or swamp
- Beach
- Study area

MIDDLE TERTIARY AGE ROCKS

- Ponce Limestone
- Juana Díaz Formation (limestone and chalk)
- Juana Díaz Formation (clastic sediments)

EARLY TERTIARY AND OLDER AGE ROCKS

- Tuffaceous sandstone, siltstone, lava and limestone
- Igneous intrusive rocks
- Lava, lava breccia, bedded volcaniclastic rocks, minor limestone

- 20 Contour—Shows altitude of fan-delta plain, in meters above sea level. Contour interval is variable
- D/U Fault—U, upthrown side; D, downthrown side. Dashed where approximately located
- Fault—Shows direction of horizontal movement. Dashed where approximately located
- Fault—Sawteeth on upper plate. Dashed where approximately located
- Contact—Dashed where approximately located

Figure 2. Surficial geology of the Peñuelas to Salinas study area (modified from Monroe, 1980).

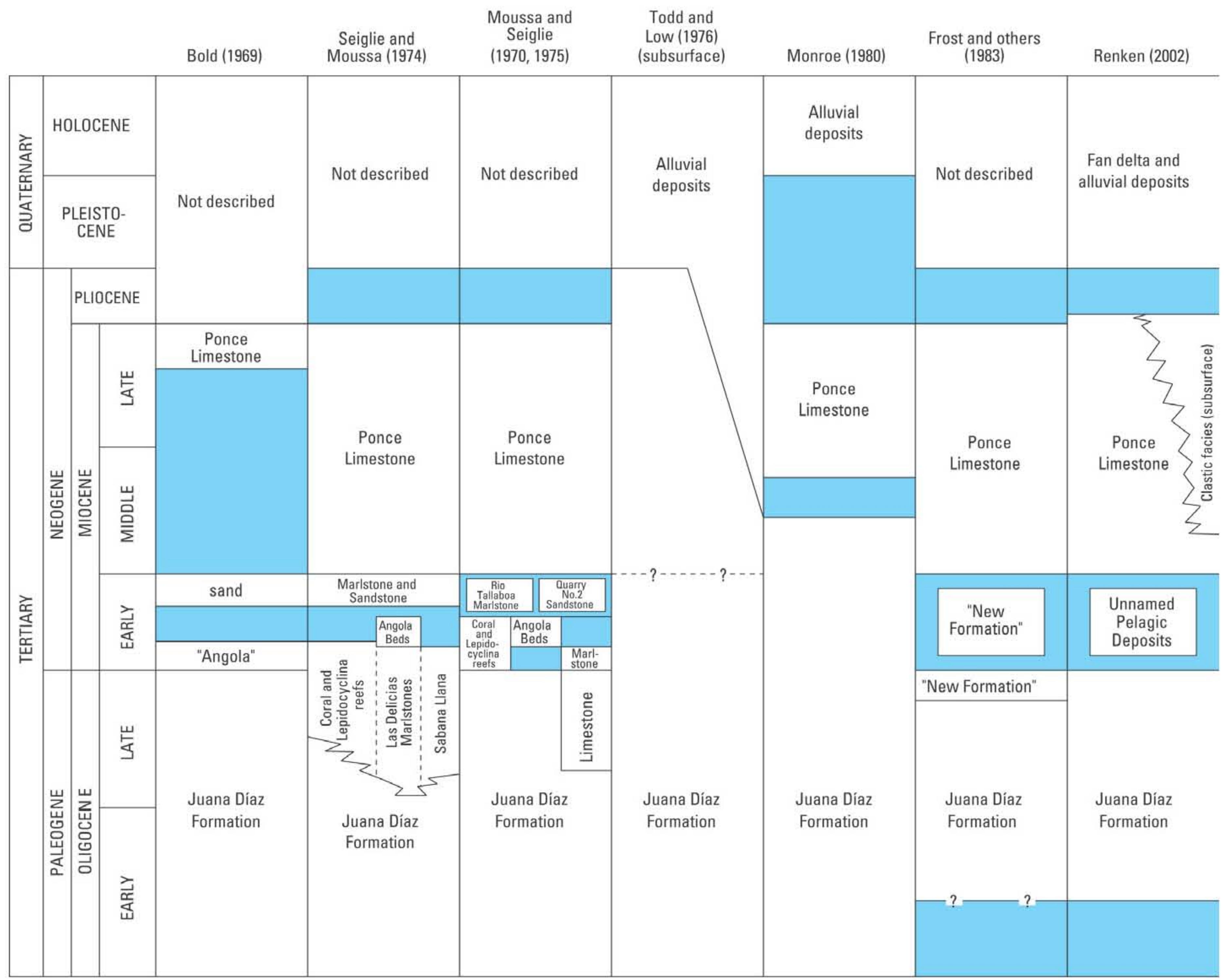


Figure 3. Recent stratigraphic nomenclatures used in the study area (modified from Renken and others, 2002).

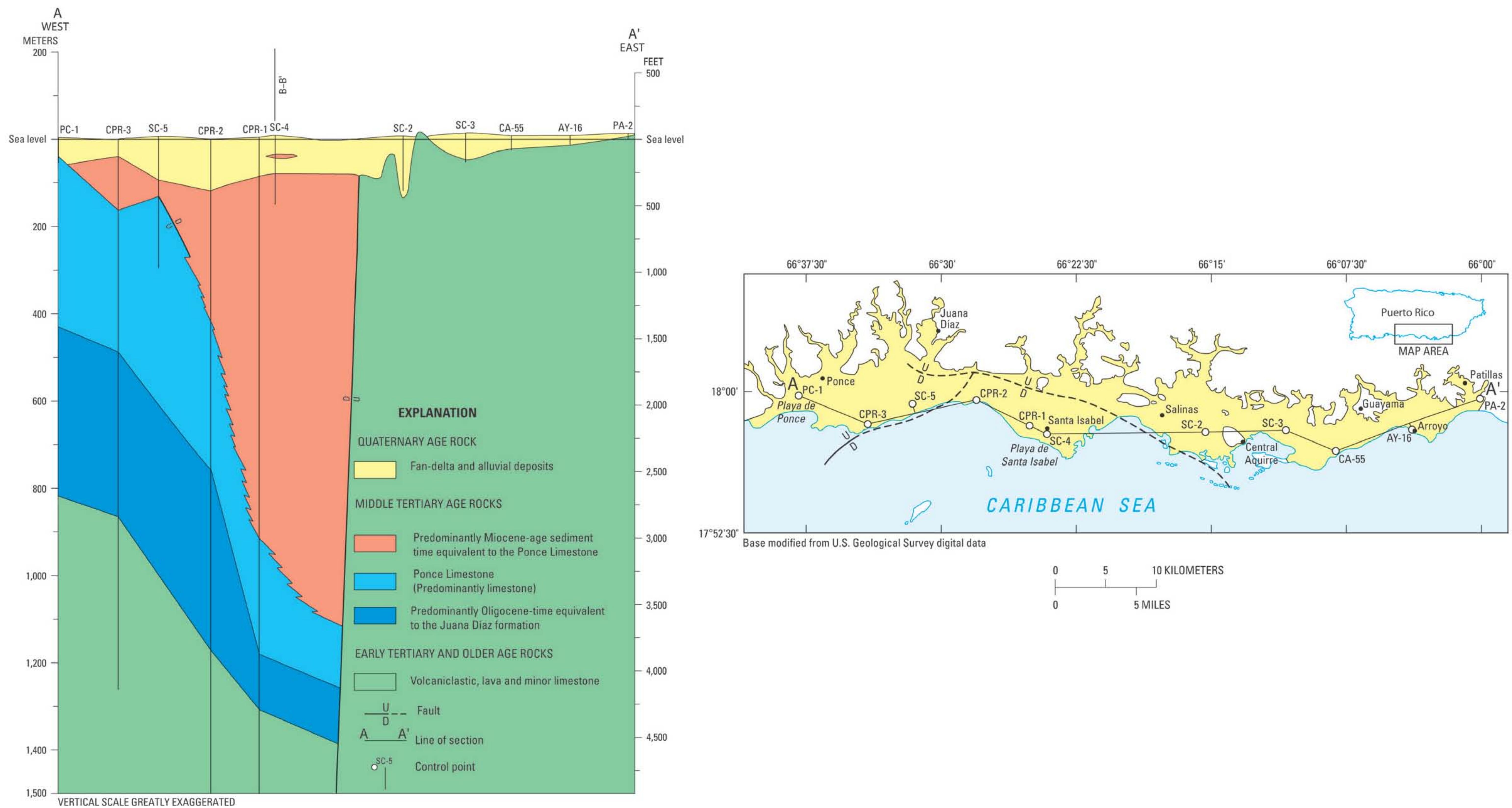


Figure 4. Geologic section across southern Puerto Rico fan-delta plain (adapted from Renken and others, 2002).

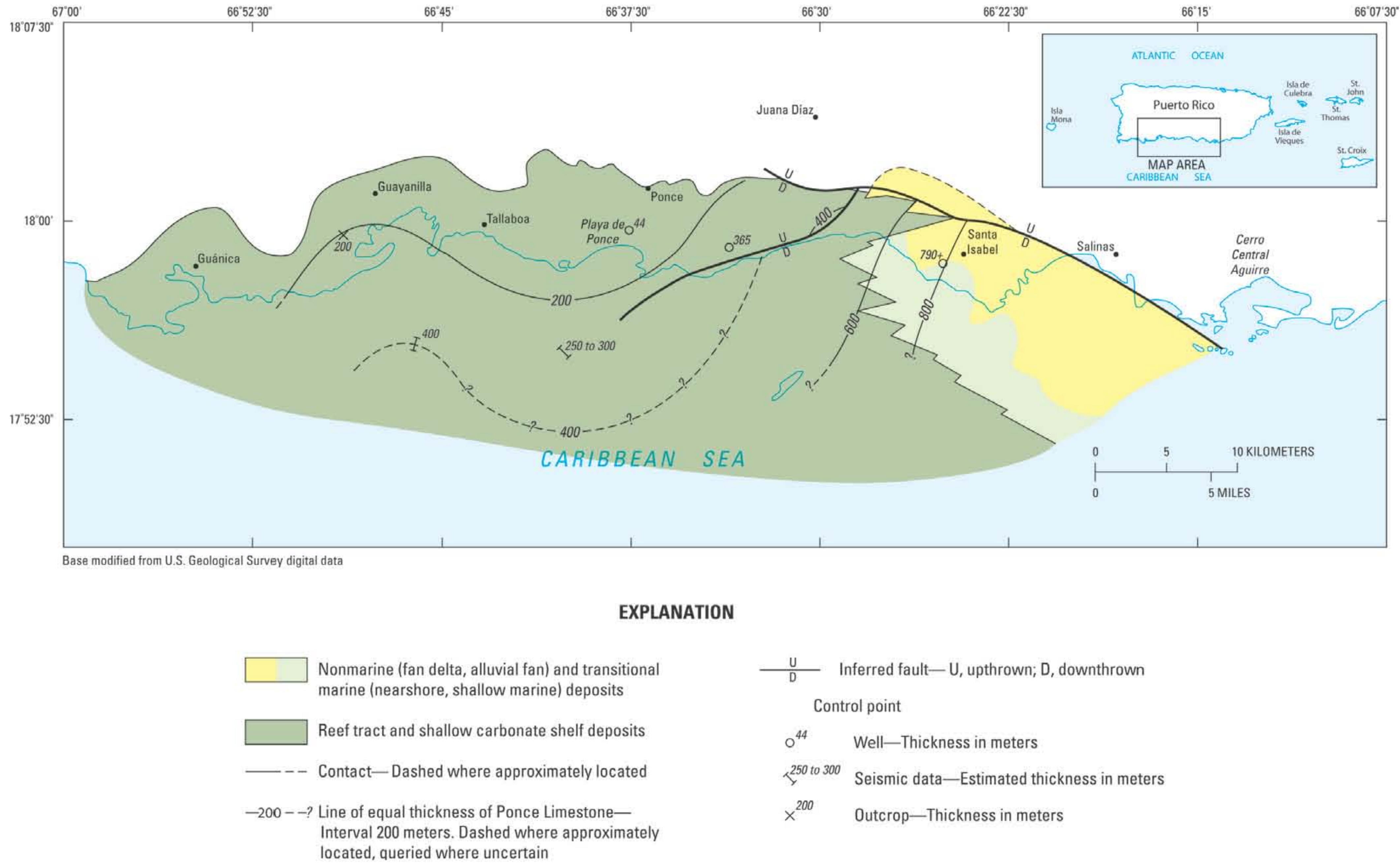


Figure 5. Major facies of the Ponce Limestone and equivalent beds (adapted from Renken and others, 2002).

Figure 6. Thickness of the fan-delta and alluvial deposits (adapted from Renken and others, 2002).

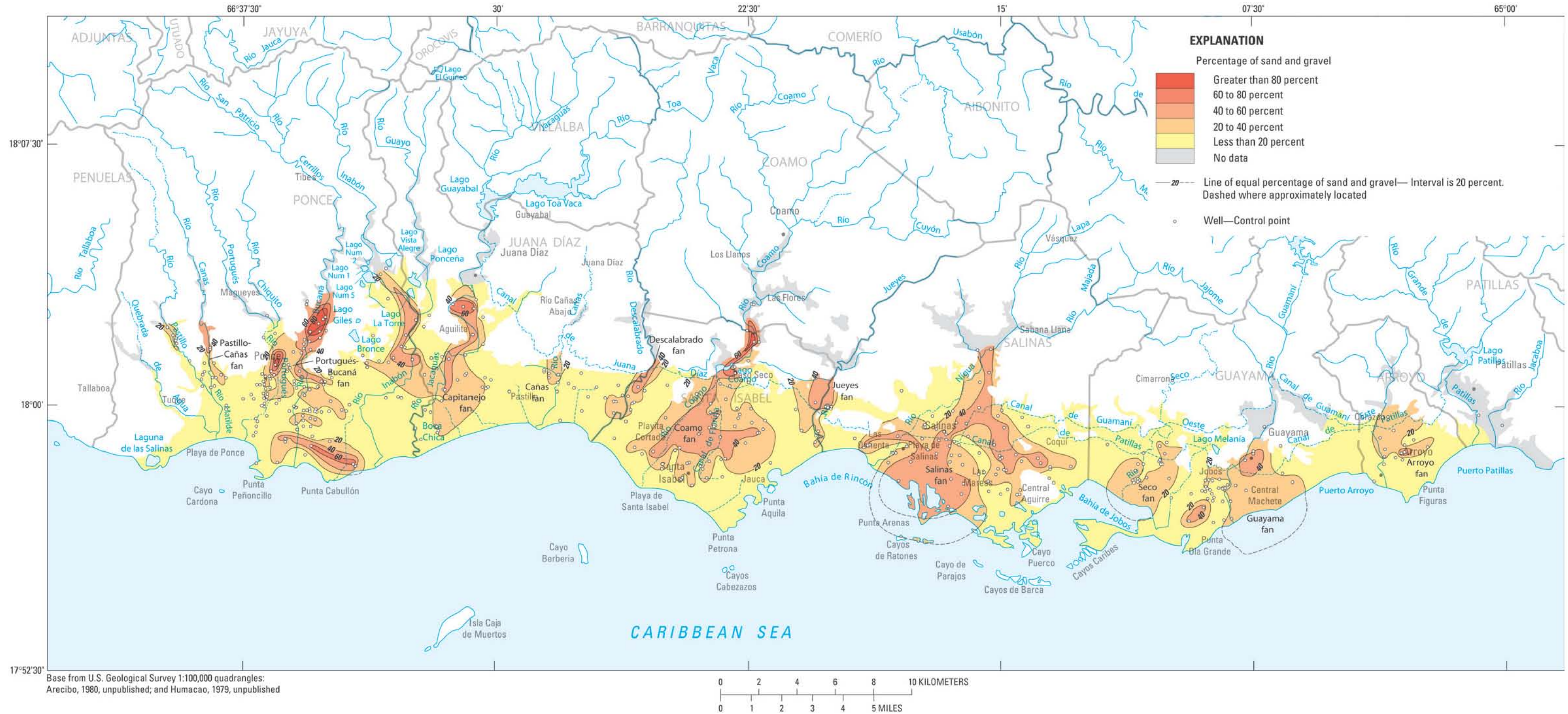
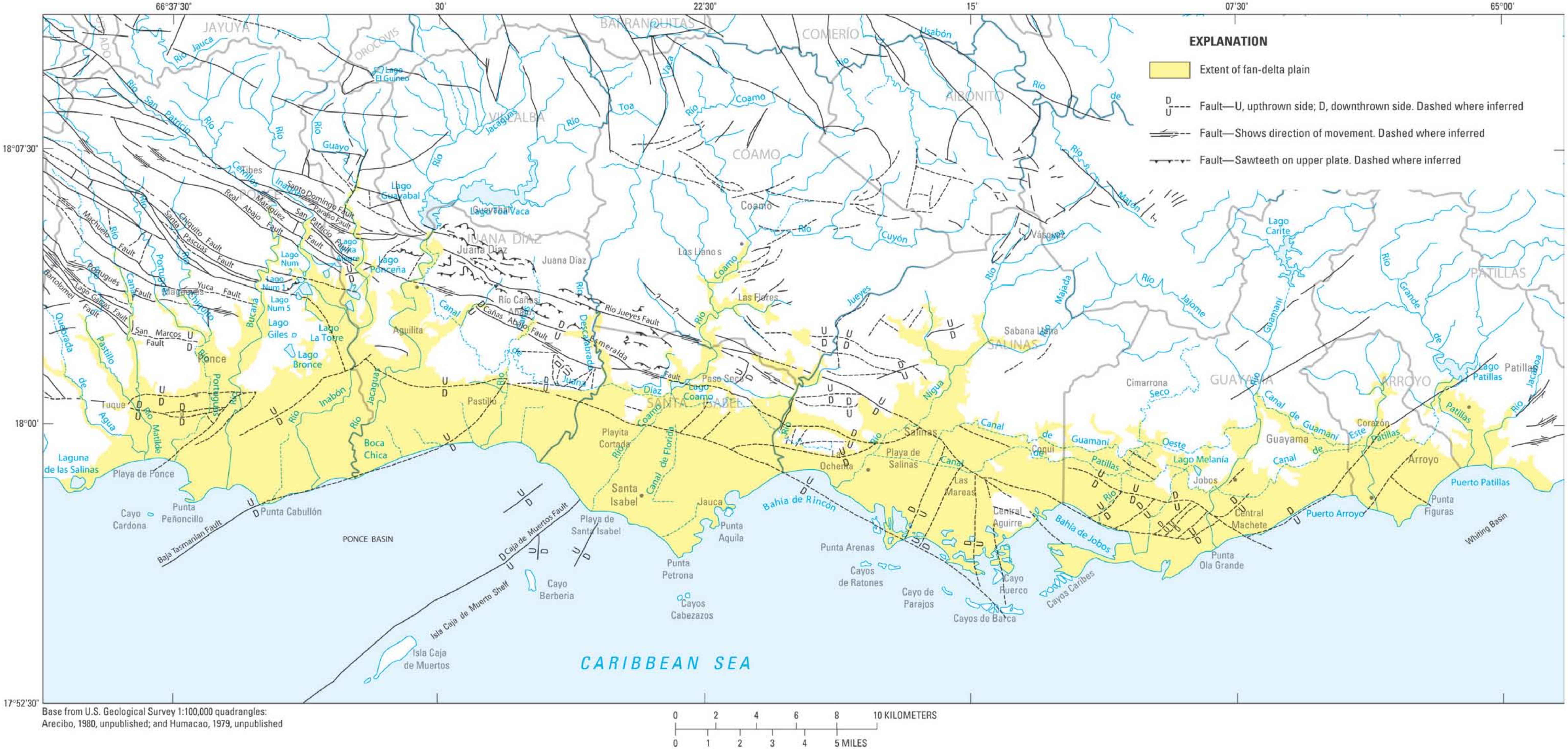


Figure 7. Percentage of sand and gravel in the fan-delta plain deposits (adapted from Renken and others, 2002).



Base from U.S. Geological Survey 1:100,000 quadrangles:
Arecibo, 1980, unpublished; and Humacao, 1979, unpublished

Figure 8. Location and orientation of the Great Southern Puerto Rico Fault zone in the study area (modified from Renken and others, 2002).

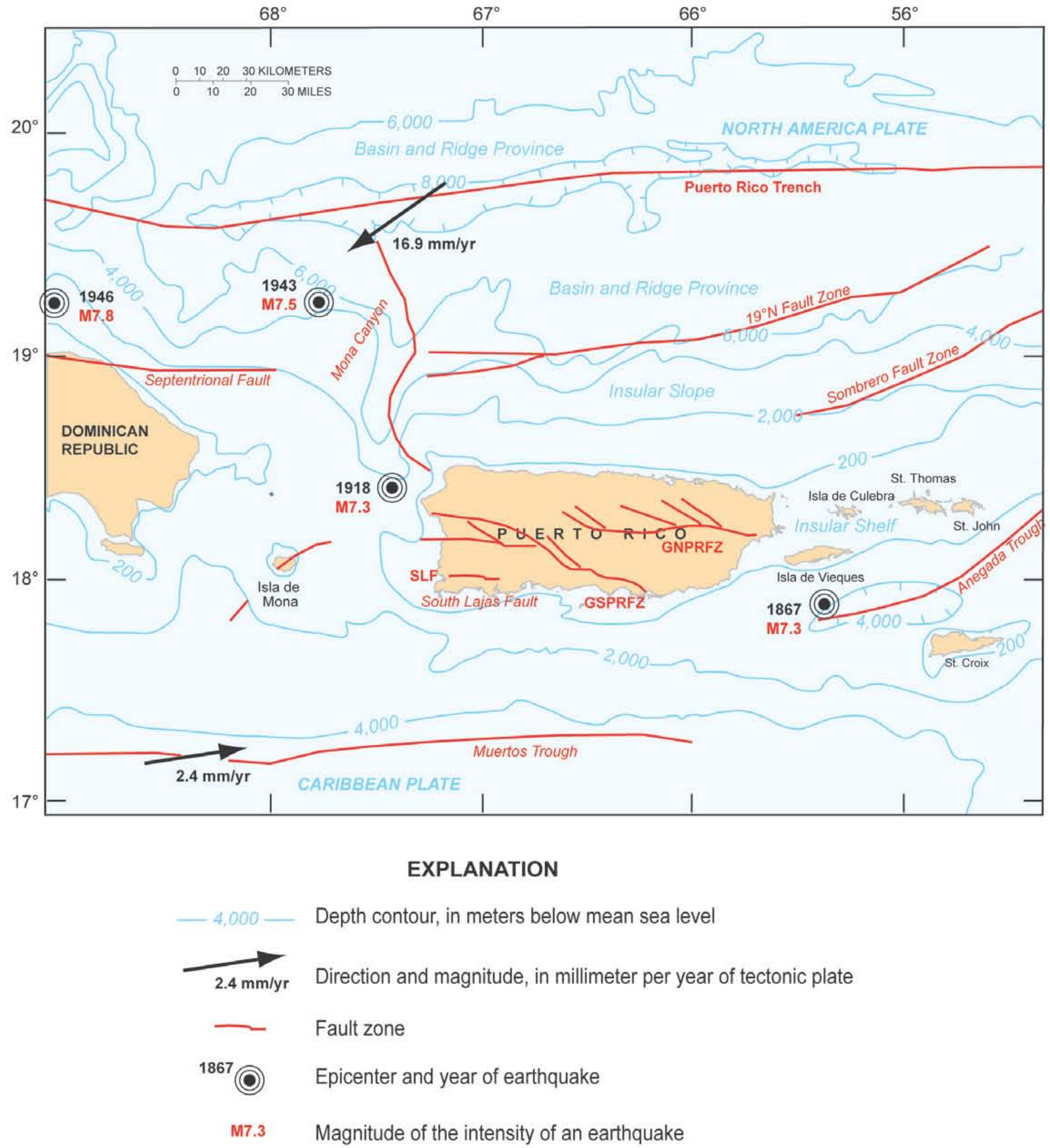


Figure 9. Major tectonic faults and historic earthquakes in Puerto Rico and its vicinity (adapted from Clinton and others, 2006).

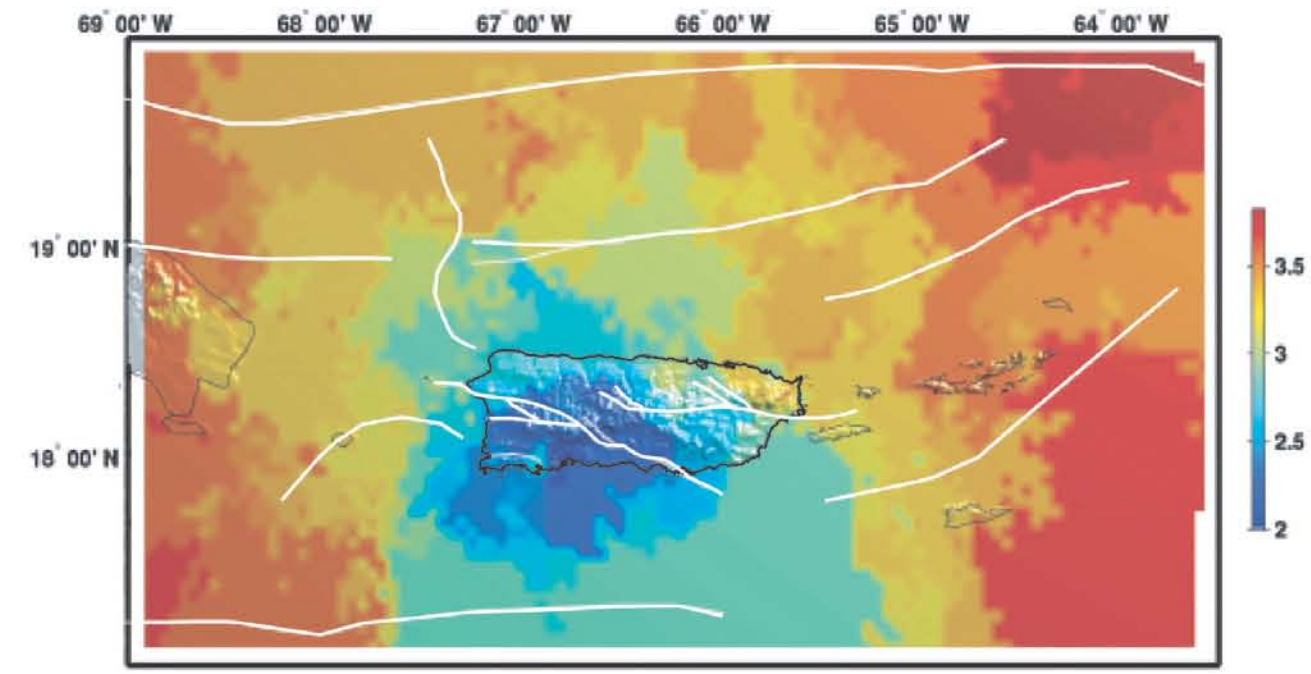


Figure 10. Geographical distribution of the magnitude of completeness values in Puerto Rico and its vicinity as determined from the Puerto Rico Seismic Network Catalog for the interval January 1986-March 2006 (adapted from Clinton and others 2006).
http://redsismica.uprm.edu/spanish/tsunami/media/PRMonitoring.pdf

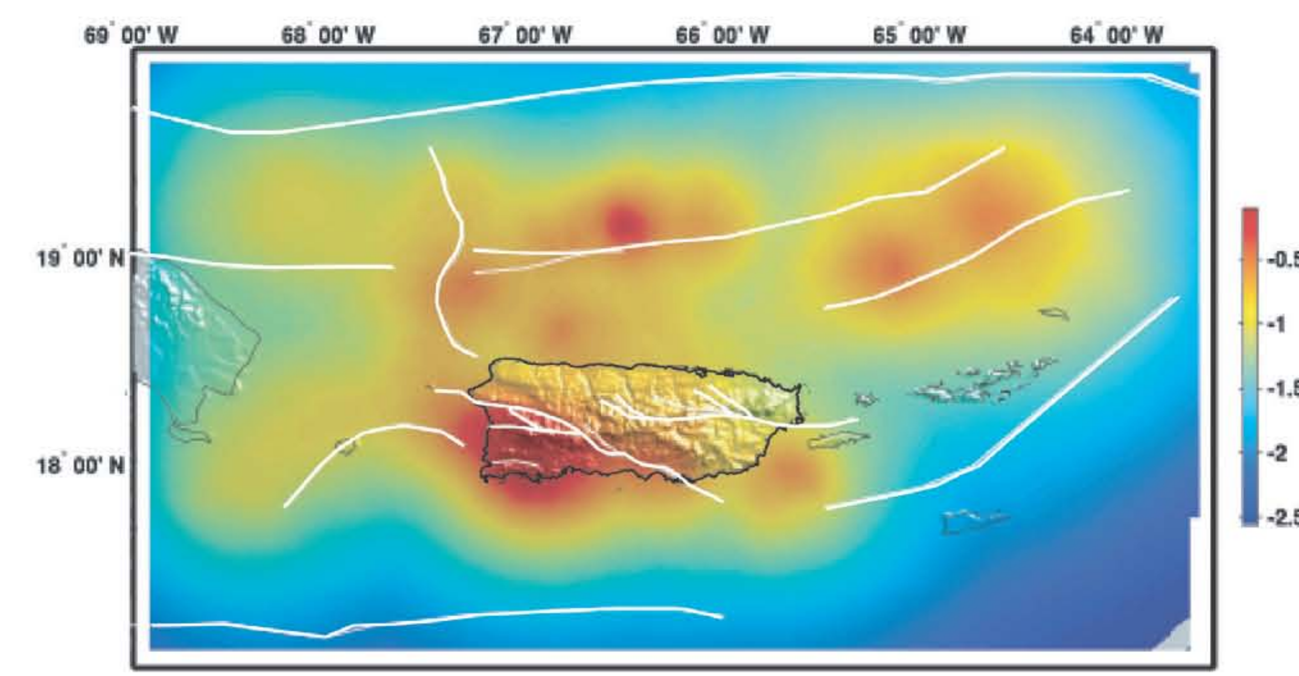


Figure 11. Seismicity density in Puerto Rico and its vicinity (adapted from Clinton and others, 2006).
http://redsismica.uprm.edu/spanish/tsunami/media/PRMonitoring.pdf

Figure 12. Inland extent of tsunami-induced flooding in the Punta Verraco and Punta Cuchara quadrangles (adapted from Mercado and Justiniano, 2007). http://coastalhazards.uprm.edu/index.html

Figure 13. Inland extent of tsunami-induced flooding in the Playa de Ponce quadrangle (adapted from Mercado and Justiniano, 2007). http://coastalhazards.uprm.edu/index.html

Figure 14. Inland extent of tsunami-induced flooding in the Santa Isabel quadrangle (adapted from Mercado and Justiniano, 2007). http://coastalhazards.uprm.edu/index.html

Figure 15. Inland extent of tsunami-induced flooding in the Salinas quadrangle (adapted from Mercado and Justiniano, 2007). http://coastalhazards.uprm.edu/index.html