Selection of Earthquake Hazard Level

A probabilistic approach that incorporates judgement of the researcher is used in the selection of the earthquake hazard level for this study. An earthquake recurrence analysis prepared by the Department of Natural Resources (personal communication: Anselmo De Portu) using a catalogue of all instrumentally located earthquakes within 330 kms. of San Juan between 1915 and 1983 shows the one hundred year earthquake to be of an order of magnitude 8 on the Richter Scale (Appendix I). This is approximately the same order of magnitude as the largest earthquake in the historic record (8.0-8.25) (table 1). While great earthquakes ($M \leq 7.75$) will occasionally occur in the Puerto Rico Trench 50 to 100 kms to the north of the Island, the historic record and regional tectonic framework suggest that major shocks (M-7-7.5) occur on intraplate faults close to the Island just as frequently (McCann, 1984). These events (1867, 1918) did not cause serious damage in San Juan, but on the east and northwest coasts. The 1867 and 1918 earthquakes generated intensities equivalent to VI and V to VI at San Juan and Río Piedras. The historic record indicates that San Juan has experienced an intensity VIII to IX only once-- the 1787 earthquake. On the other hand, the Island as a whole, over a period of 450 years, had been subjected to one earthquake of intensity VIII or IX and to intensities VII to VIII five times (der Kiureghian and Ang, 1975). Thus, in terms of intensity, the island of Puerto Rico experiences on the average an MM intensity of VIII once every hundred years. Return periods in terms of intensity are presented below.

Return period in years	MMI	Estimated maximum acceleration
50	VII	.15
90	VII-VIII	.18
100	VII-VIII	.19
200	VIII	.25
450	VIII-IX	.33
500	IX	.35

(der Kiureghian and Ang, 1975)

Different criteria can be used to select a particular earthquake hazard level. Return periods of 500 years (maximum credible earthquake), of 100 years (widely used in flood plain management), and 50 years (approximate structure life in some areas) have been suggested for use in earthquake risk analysis (Rice, 1983). The maximum credible earthquake focuses on lower probability events with return periods of 300 years or more. The most probable earthquake considers a shorter return period of 100 years. Introducing conservatism in the selection of the maximum possible earthquake that can damage San Juan requires the selection of the maximum historical earthquake (Slemmons, 1982) (8-8.25) and moving it the closest credible epicentral distance to the study area (approx. 60 kms.). Such earthquakes will produce maximum intensities of X to XI, causing very severe to total damage in the San Juan metropolitan area. Its return period greatly exceeds the useful life of most building structures. A more realistic estimate is obtained by selecting a smaller but more frequent earthquake capable of causing significant damage. In addition, the damage pattern of the selected hazard level should exceed the threshold for most secondary geologic hazards. In this way, damages produced by higher levels of ground motion will change proportionally but not areally, permitting the estimation of likely damages for different hazard levels.

The 100 year earthquake, capable of producing an estimated MM intensity of VIII, fits the above requisites. Such intensity is felt in Puerto Rico (on the average) once every 100 years. Although San Juan experienced a similar intensity only once, conservatism dictates the use of the maximun intensity felt in Puerto Rico every 100 years.

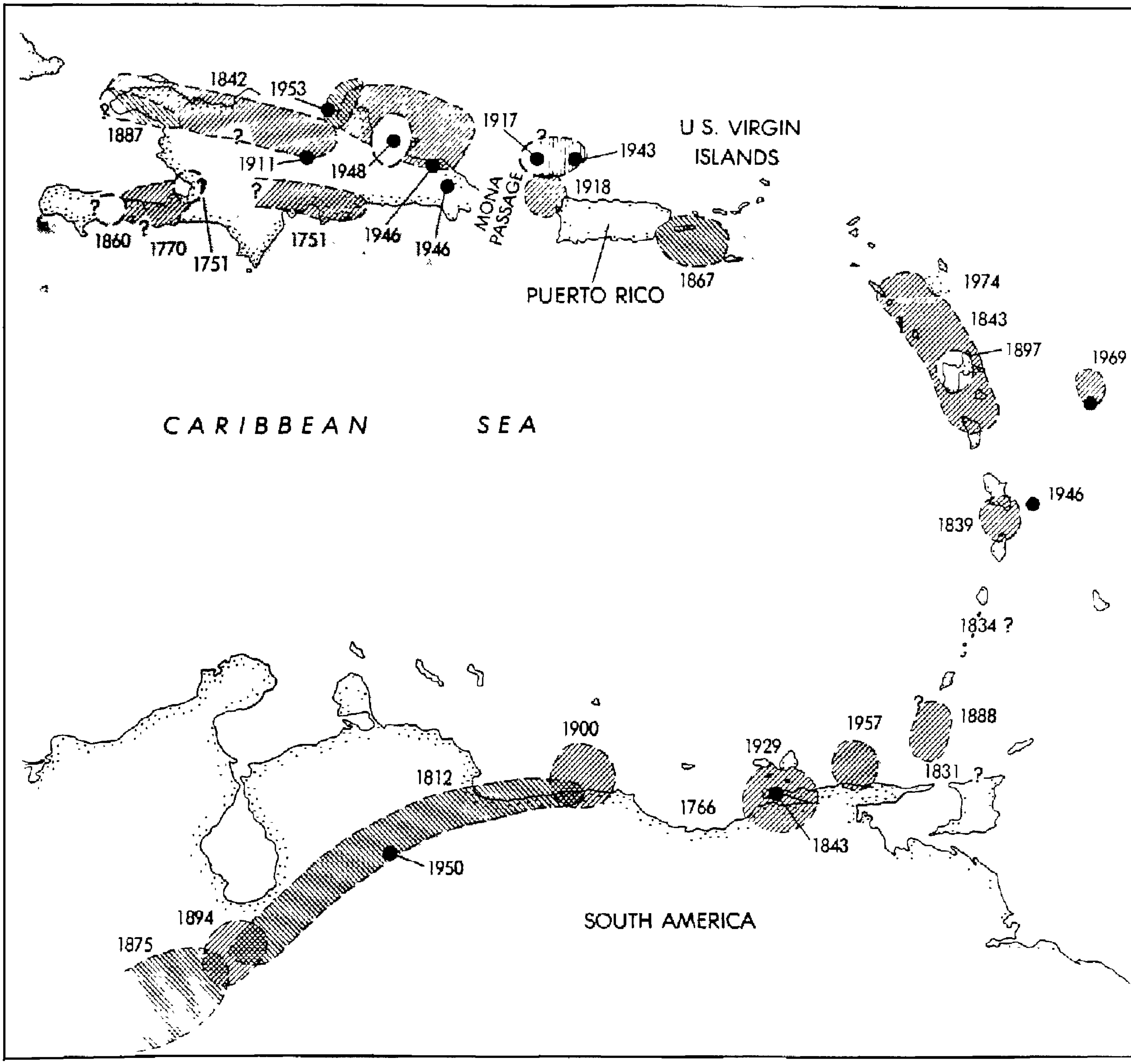
Thus the selected hazard level is MM intensity VIII. Such intensity can be caused by an earthquake Richter magnitude 8 with epicenter 120 km north of San Juan.

TABLE I

Most destructive earthquakes felt on Puerto Rico

Date	Estimated Maximun Intensity	Description
1524-1528	VI	The Añasco house of Juan Ponce de León and other strong buildings were destroyed. The shock was felt strongest in the north, from Mayaguez to Añasco
1615 Sept. 8	VI	The earthquake and hurricane did much damage and caused great suffering in Puerto Rico. Epicenter probably in or near Santo Domingo. Many aftershocks during the next 40 days.
1717	VII	Very strong and damaging earthquake. The San Felipe Church in Arecibo was completely ruined. The 100 year old parish house in San German was destroyed.
1740	VI	The earthquake totally destroyed the Guadalupe Church in Ponce.
1787	VIII-IX	A violent earthquake felt over the entire Island. Many churches and chapels destroyed. In San Juan great damage was done to the forts of el Morro and San Cristobal as well as to the docks and the Cathedral.
1844	VI	Severe earthquake of 30 seconds duration. The origin may have been north of Puerto Rico. Several houses and some public buildings were demolished or cracked. In San Juan nearly all stone houses were cracked.

Date		Estimated Maximun Intensity	Description
1846	November 28	VI	Felt throughout the Island, Epicenter probably in the Mona Passage. More intense in the northwestern part of Puerto Rico.
1867	November 18	VII-VIII	This was the great Virgin Islands earthquake that caused very great damage, specially in the eastern part of Puerto Rico. The shock was followed by a severe tsunami
1875	December 8	VI	Strong earthquake knocked down some chimneys at sugar mills and damage was reported in Arecibo and Ponce.
1906	September 27	V-VI	Heavy double shock with epicenter north of Puerto Rico. In San Juan objects were overturned and people were frightened and confused, but material damage was not done.
1918	October 11	VIII	Disastrous earthquake accompanied by tsunami. Very great damage to the west coast of Puerto Rico. Epicenter in the Mona Canyon northwest of Mayaguez.
1946	August 4	VI	Strong earthquake with epicenter in the Dominican Republic caused general alarm and fear. No loss of life or serious property damage.
1946	August 8	VI	Strong earthquake of short duration accompanied by tsunami affected mostly the west coast. People terribly frightened, but no significant damage was done.



Estimated rapture zones of Caribbean shocks since 1800 are shown; three great shocks of the 18th century are included also. Areas with highest seismic potential for events of magnitude 7 during the next few decades (regions where great earthquakes occured 100 or more year ago) are shaded.

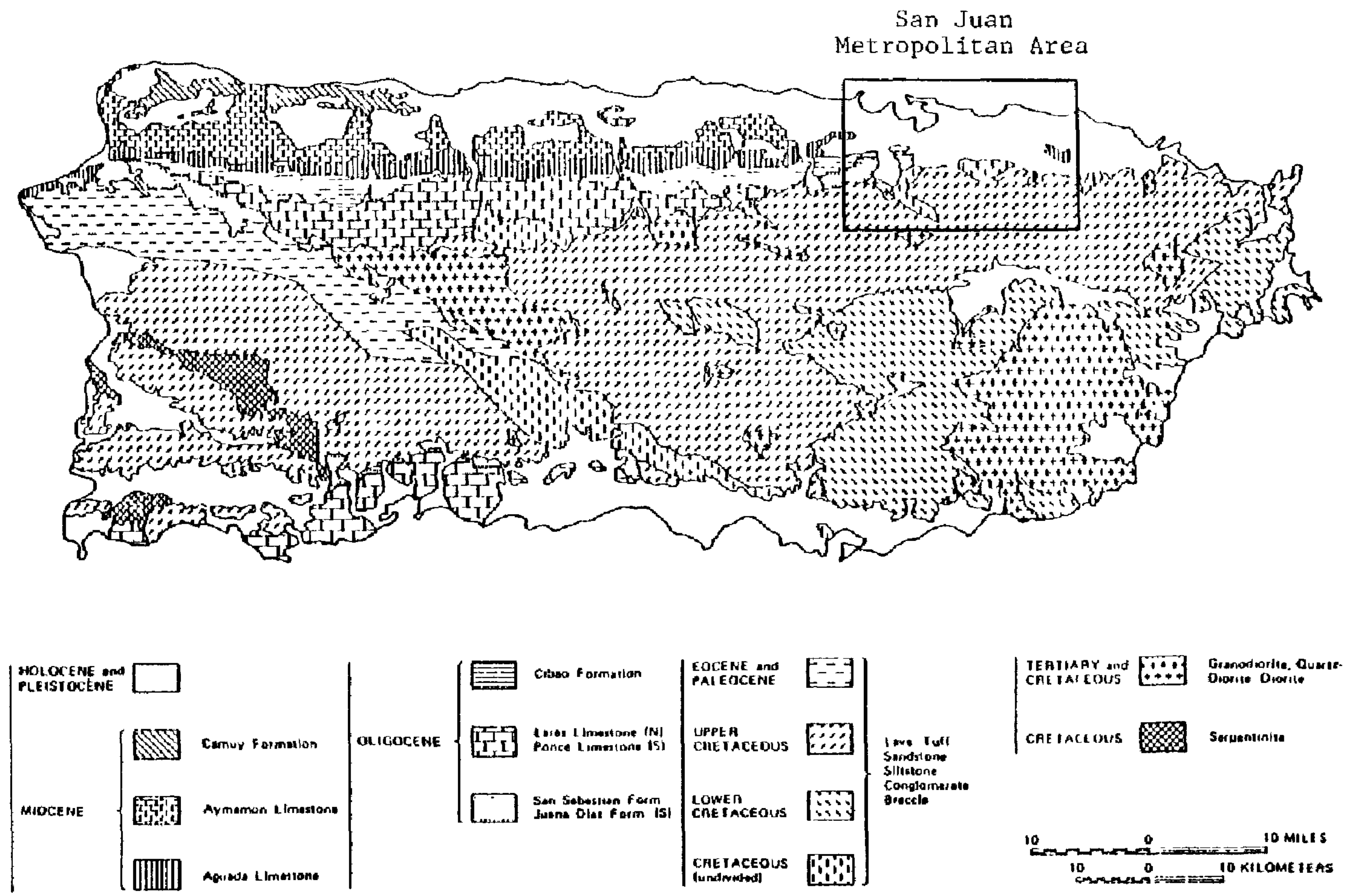
Source: "National Earthquake Hazards Reduction Program: Overview" Geologic Survey Circular 1918 - United States Geological Survey.

Geology

The San Juan metropolitan area lies on the northern flank of a thick sequence of highly deformed and faulted early Cretaceus to Early Terciary volcanic and sedimentary rock. Mid-Terciary epiclastic and limestone sequences rest over the deformed volcanic core. Late Terciary and Quaternary unconsolidated to semiconsolidated terrigenous materials overlie most of the Mid-Terciary formations and portions of the volcanic core (fig.12). The geology and the stratigraphic summary of the metropolitan area of San Juan appear in fig 13 .

Three physiographic regions are present in the study area: the interior volcanic upland province, the northern Karst province, and the Coastal Plain province (fig. 14). These provinces are characterized by a unique combination of relief, landforms, and geology.

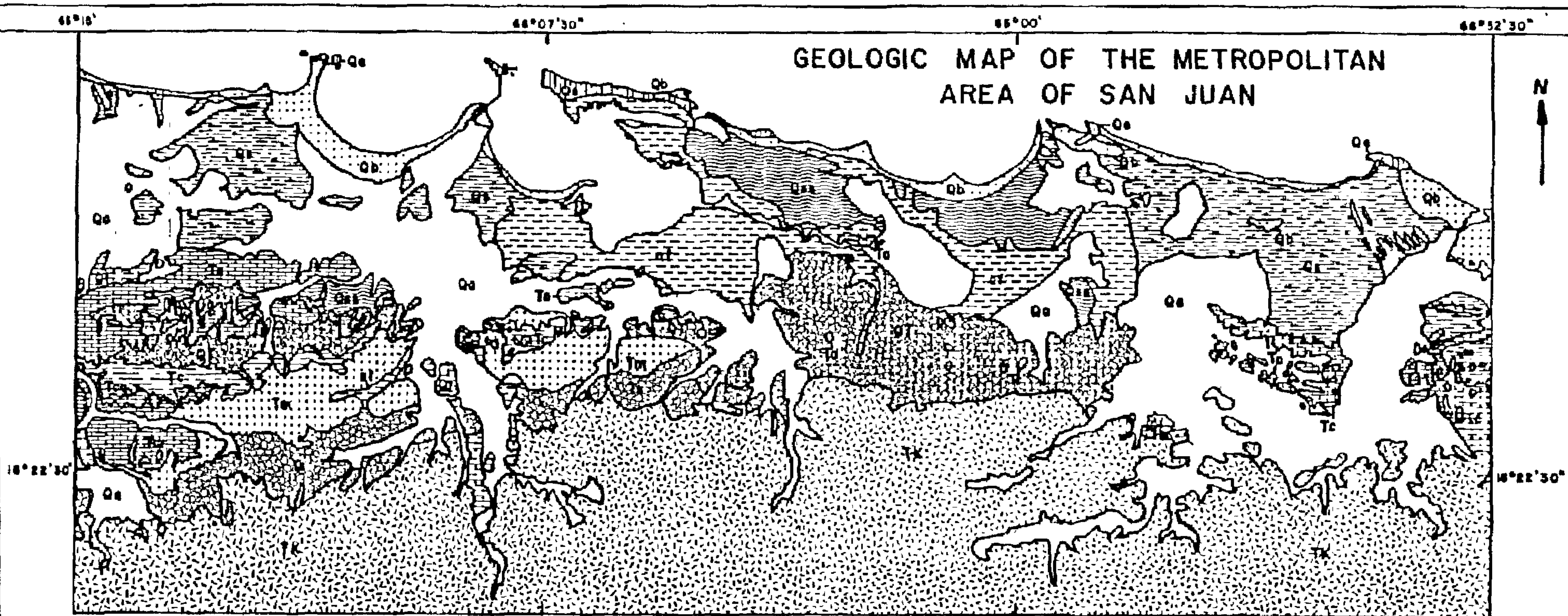
The interior upland shows the effects of fluvial erosion over a complex sequence of volcanic and sedimentary deposits of Cretaceous and Early Terciary age. The Cretaceous rocks were formed during a period when volcanism and sedimentation were dominant geological processes. The lower Cretaceous rocks consist primarily of lava, lava breccia, tuff and tuffaceous breccia with some thin bedded sandstone, siltstone, and limestone. When exposed they are thickly weathered. Upper Cretaceous rocks consist of tuffaceous sandstone, siltstone, breccia, conglomerate, lava, tuff, and some pure and impure limestone lenses. When exposed they, too, are deeply weathered (Briggs and Akers, 1965; Briggs, 1964). The collision of the Caribbean Plate with the North American Plate by the end of the Mesozoic gave rise to the "Caribbean Orogeny" (Malfait et al., 1972). At the end of orogeny (Middle Eocene), most Cretaceous



Simplified geologic map of Puerto Rico

Fig. 12

From Beinroth (1969)



Adapted from GEOLOGIC MAP AND SECTION IN NORTHERN PUERTO RICO, U.S.G.S., 1979

Prepared for José Molinelli by Thalia Vera
April 1985

DESCRIPTION OF MAP UNITS

ARTIFICIAL FILL (HOLOCENE) - Sand, limestone, and volcanic rock

ALLUVIUM (HOLOCENE) - Sand, clay, gravel, and cobbles

LANDSLIDE DEPOSITS (HOLOCENE) - Masses of soil, calcareous clay, and limestone rubble

BEACH DEPOSITS (HOLOCENE) - Sand composed of rounded grains of quartz, volcanic rock, and shell

SWAMP DEPOSITS (HOLOCENE) - Sandy muds and clayey sand

EOLIANITE (PLEISTOCENE) - Friable to consolidated calcareous eolian sandstone composed of fine to coarse grains of shell fragments and quartz

SILICA SAND DEPOSITS (PLEISTOCENE) - Very pure fine to very fine quartz sand

TERRACE DEPOSITS (PLEISTOCENE) - Clay, sand, and gravel deposits

UNDIFFERENTIATED SURFICIAL DEPOSITS (QUATERNARY AND TERTIARY?) - Clay, sandy clay, and sand deposits

AYMAMÓN LIMESTONE (MIOCENE) - White to very pale orange, locally pale-yellow and grayish-pink, very pure fossiliferous limestone and AGUADA LIMESTONE (MIOCENE) - Thick layers of very pale orange to pink hard calcarenite alternating with chalky and rubbly limestone

CIBAO FORMATION (MIOCENE AND OLIGOCENE) - Typical beds of calcareous clay, earthy limestone, and marl, very pale orange to pale yellowish-orange and moderate-orange-pink

Quebrada Arenas Limestone Member - Very finely crystalline to dense, very pale orange to pale-grayish-orange limestone

Río Indio Limestone Member - Compact, but chalky, fragmental limestone, mostly pale-yellowish-orange

MUCARABONES SAND (MIOCENE AND OLIGOCENE) - Grayish-orange to yellowish-brown highly crossbedded medium to coarse calcareous sand

SAN SEBASTIÁN FORMATION (OLIGOCENE) - Reddish-brown and gray sandy carbonaceous clay

UNDIFFERENTIATED LOWER TERTIARY AND CRETACEOUS FORMATIONS - Limestone, tuffaceous sandstone and siltstone, tuff breccia, lava, granodiorite and quartz diorite

SCALE

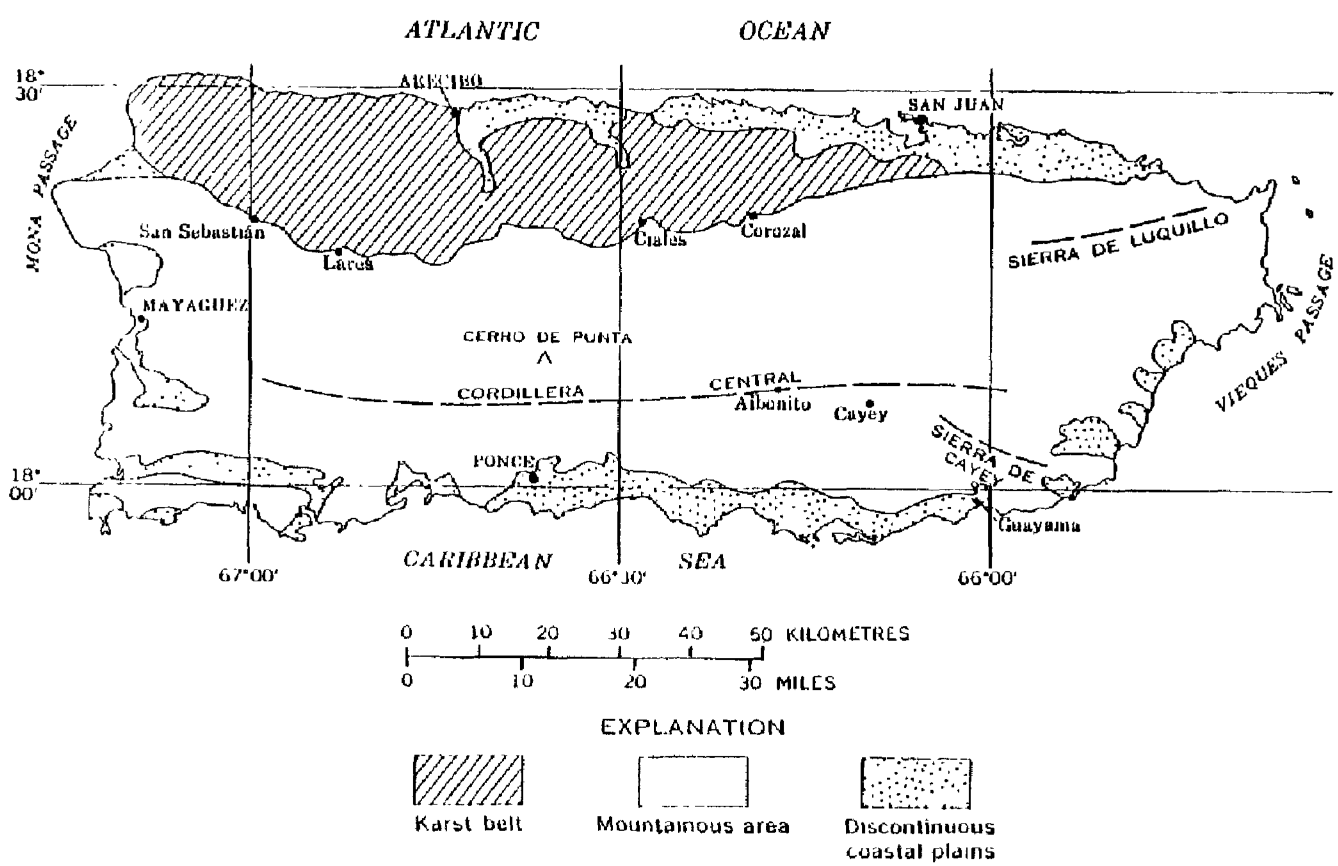
0 5 10 KILOMETERS

0 2.5 5 MILES

General designation	Stratigraphic unit	Brief description	Approx. thickness (feet)	Age
	Made ground and fill.			
	Beachrock pavement	Carbonate-cemented beach sand. Some iron-oxide cementation		Recent
	Recent littoral deposits	Beach sand and associated sand aprons; foredunes		
	Floodplain alluvium	Mostly silt and clay		
	Bay mud	Soft black mucky silt and clay		
	Pleistocene littoral deposits	Reef rock, eolianite, and paleosols		Pleistocene
	Santurce sand	Quartz sand and white clayey sand		Pleistocene and Pliocene (?)
	Older alluvium	Red silty to sandy clay		
	—— Unconformity ——			
Middle Tertiary sequence.	Aymamón limestone	Thick bedded, light-colored, dense limestone	960+	early Miocene
	Aguada formation	Friable sandstone, clay, and concretionary limestone	378	
	—— Unconformity ——			
	Intrusive igneous rocks	Diabase, granodiorite porphyry, and augite andesite porphyry		early Eocene (?) or late Paleocene (?).
	Fajardo formation	Light-colored ashy siltstone, siliceous siltstone and chert, interfingering graywacke, conglomerate, and impure limestone	3,000+	
	Figuera volcanics	Hornblende andesite breccia, minor flow, limestone member at base	>3,000	
	——Local unconformity——			
Older complex	Trujillo Alto limestone	Fossiliferous medium-bedded to massive limestone	900−	Late Cretaceous
	Monacillo formation	Graywacke and conglomerate; commonly red or purple	920	
	Frailes formation (Leprocomio limestone member and La Muda limestone member).	Massive lapilli tuff with some stratified shale, siltstone, and graywacke. Leprocomio limestone member at top and La Muda limestone member near base.	2,800	
	Tortugas andesite	Augite andesite breccia and flows	1,300	
	Guaynabo formation	Graywacke, conglomerate, and shale	4,600	Late Cretaceous (?)
	Hato Puerco tuff	Massive volcanics and metavolcanics and some stratified ash	(?)	

Stratigraphic summary of the metropolitan area of San Juan

Fig. 13



Map from Puerto Rico showing principal physiographic divisions

From Monroe (1976)

Fig. 14

and Early Terciary rocks had been faulted, folded and intruded. Early Terciary rocks were formed during a mountain building period. Both intrusive and extrusive igneous activity were the dominant geologic processes.

Intrusive rocks emplaced during the orogeny are mainly granodiorite, quartz-diorite, diorite and some minor quartz porphyry, gabbro, and amphibolite. Associated with the intrusives are zones of hydrothermal alteration and contact methamorphism (Hildebrand, F.A., 1961).

Paleocene and Eocene deposits consist of siltstone, sandstone, conglomerate, lava, and tuff. They are locally deeply weathered.

The northern Karst province in the study area consists essentially of the following formations; San Sebastian, Cibao, Aguada, and Aymamon (Monroe, 1973, 1976, 1977, 1980, Pease and Monroe 1977). The San Sebastian formation is at the base of the Mid-Terciary sequence, lying unconformably over Cretaceous volcanics and sedimentaries. The formation is heterogeneous and contains clayey sand, lenses of sandy clay, pebbles, and cobbles. South of San Juan it grades upward into thin bedded, fine sand and mottled clay. The thickness is greater than 40 meters. The Cibao formation consists of an argillaceous marl, chalky limestone, and thin beds of sand and clay. Outcropping members are Miranda sand, upper member, and Quebrada Arenas and Rio Indio limestone. The Aguada formation consists of alternating beds of indurated calcarenite and clayey to chalky limestone. Its thickness ranges from 70 to 35 meters. Conformably overlying the Aguada is the Aymamon limestone formation consisting of massive to thickly bedded, very pure fossiliferous limestone (Monroe, 1980, 1973). Sinkhole formation is a potential hazard in the Aymamon and Aguada limestones formations.

The Coastal plain province consists of Late Terciary and Quaternary deposits. Late Terciary sequences include older alluvial deposits, high terrace deposits, alluvial fans (Hato Rey Formation), alluvium and river terrace deposits, silica sands, beach deposits, swamps, eolianite, and artificial fill.

Older alluvial deposits, high terrace deposits, and alluvial fans consist of varying proportions of clay, silt, and sand, mainly red or mottled red. The material is deeply weathered, stiff, and hard. Most of the non-quartz components are altered into clays. They are unrelated to present stream alluviation.

Holocene alluvium and river terrace deposits of Pleistocene age consist of sand, clay, and sandy clay. Beds of sand containing gravel are present at the sides of the Río Grande de Loíza, Río Grande de Bayamón, and Río La Plata. Thickness is variable, but as much as 20 meters has been penetrated in the Bayamón and San Juan quadrangle areas, possibly as great as 100 meters at the sides of the Río Grande de Loíza .

Silica sands of Holocene to Pleistocene age consist of very pure quartz sand 99% silica but locally containing organic matter.

The deposits grade downward into compact, ferruginous sand,mapped as blanket deposits,having a thickness ranging from 1 to 4 meters. In Santurce it was named Santurce sand (Kaye 1959). The outcrop of the Santurce sand is generally a loose, very well-sorted, medium grain, almost pure sand. It grades downward into the Older Alluvium where the cohesive nature of the clay binder imparts a great,dry strength. Erratic variations in the density of sand occurs with depth.

Beach deposits consist of sand composed largely of fine quartz mixed with minor quantities of shell and volcanic rock fragments on beaches and abandoned beach ridges in the Carolina quadrangle area. Deposits are generally medium to course sand in other zones. Thickness varies from 1 to 5 meters but may reach more than 13 meters in the Luis Muñoz Marín Airport area (Kaye, 1959). Beach rock is commonly present in the intertidal zone due to sand cementation.

Eolianites are cemented dunes consisting of sand and clayey sand, friable to consolidated, crossbedded, calcareous, eolian sandstone composed of fine to course grains of shell fragments and quartz. The maximum thickness ranges from 20 to 30 meters.

Together with beach and eolianite deposits of Holocene age, swamp deposits dominate the northern portions of the study area. They consist of sandy muck and clayey sand generally underlaid by peat formed in mangrove swamps. The peat is very compressible, generally 10 meters thick. Peat is the weakest foundation soil in the area.

Artificial fill has been placed over swamps, sections of the San Juan Bay, and in valleys to provide foundation for housing and industrial development. Fill material generally consists of sand, limestone, and volcanic rock. More than one third of the bay shoreline has been filled or dredged, mostly after 1940.