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Introduction

Among natural hazards earthquakes are one of the most devastating catastrophic events. When an earthquake occurs near a populated area, widespread destruction of life and property takes place. The island of Puerto Rico is situated in a tectonically active zone and has experienced the effects of large earthquakes in the past. The 1918 and 1867 earthquakes had an estimated magnitude of 7.5 and 7.75 and were accompanied by destructive tsunamis. These events caused hundreds of deaths and millions of dollars in losses. In 1787 an earthquake with an estimated magnitude of 8-8.25 severely shocked the northern coast of Puerto Rico. Similar events are likely to occur in the future.

Fortunately, a large earthquake has not affected the island in the past 62 years. During this period the population has tripled and urban areas have expanded proportionally. Presently, a significant portion of the residential, commercial, industrial, and transportation infrastructure is located on geologic materials that are vulnerable to earthquake induced geologic hazards. Thus, the potential damage created by future earthquake events is greater today than ever before.

This study examines the seismic vulnerability of the San Juan metropolitan area by mapping the spatial distribution of geologic hazards and estimating the likely damage in these zones. Three important geologic hazards are considered: ground shaking, liquefaction, and landsliding. Evaluation of the tsunami hazard is beyond the scope of this study.

Each geologic hazard is mapped according to three levels of susceptibility determined by the geologic, hydrologic, and geomorphic characteristics of each zone. Damage is estimated by adapting the procedures recommended by the Rice Center (1983) for the application of earthquake risk analysis techniques to land use planning. The tasks of the earthquake vulnerability analysis are to

1) define tectonic setting and regional seismicity
2) identify sources of seismicity
3) define regional attenuation
4) select an earthquake hazard level for the analysis
5) define the geology of the study area
6) define and map ground shaking hazard
7) define and map liquefaction hazard
8) define and map landslide hazard
9) estimate damage ratio for each of the hazard zones

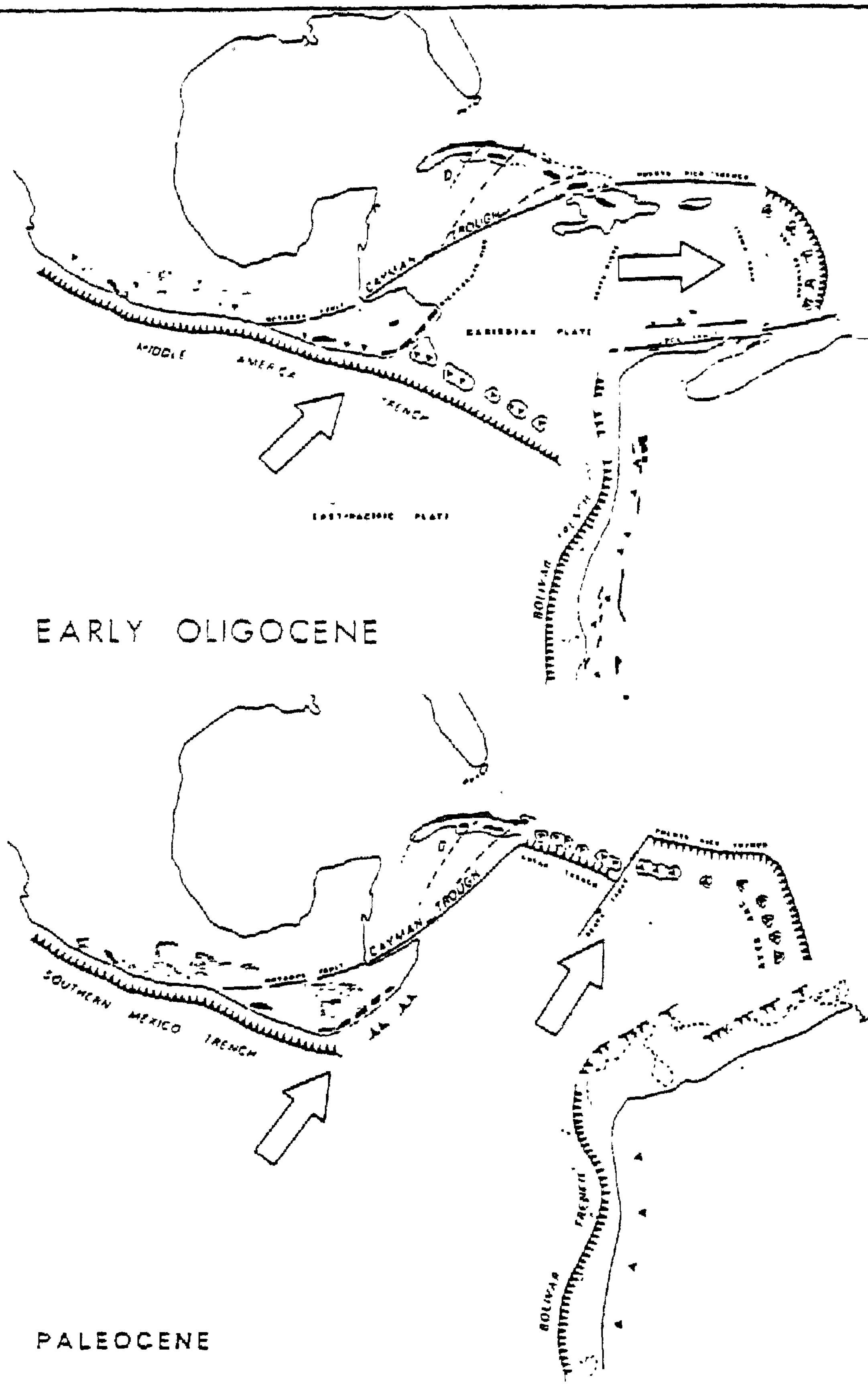
Identification of risk situations is necessary for local disaster preparedness, land use planning, estimation of economic losses, identification of measures for reducing expected economic loss, and for the selection and implementation of mitigation strategies.

Tectonic Setting and Regional Seismicity

The present tectonic regime of the Caribbean region differs markedly from that of the past. Malfait and Dinkelman (1972) proposed that the Caribbean and East Pacific Plates formed a single unit that separated during the Eocene (fig.1). Most of the northern boundary of the northeastern Caribbean Plate changed from a convergent to a transcurrent type of boundary (fig.2). The present seismicity results from the North American Plate moving 3.7 cm./year WSW with respect to the Caribbean Plate. (Sykes et al., 1982).

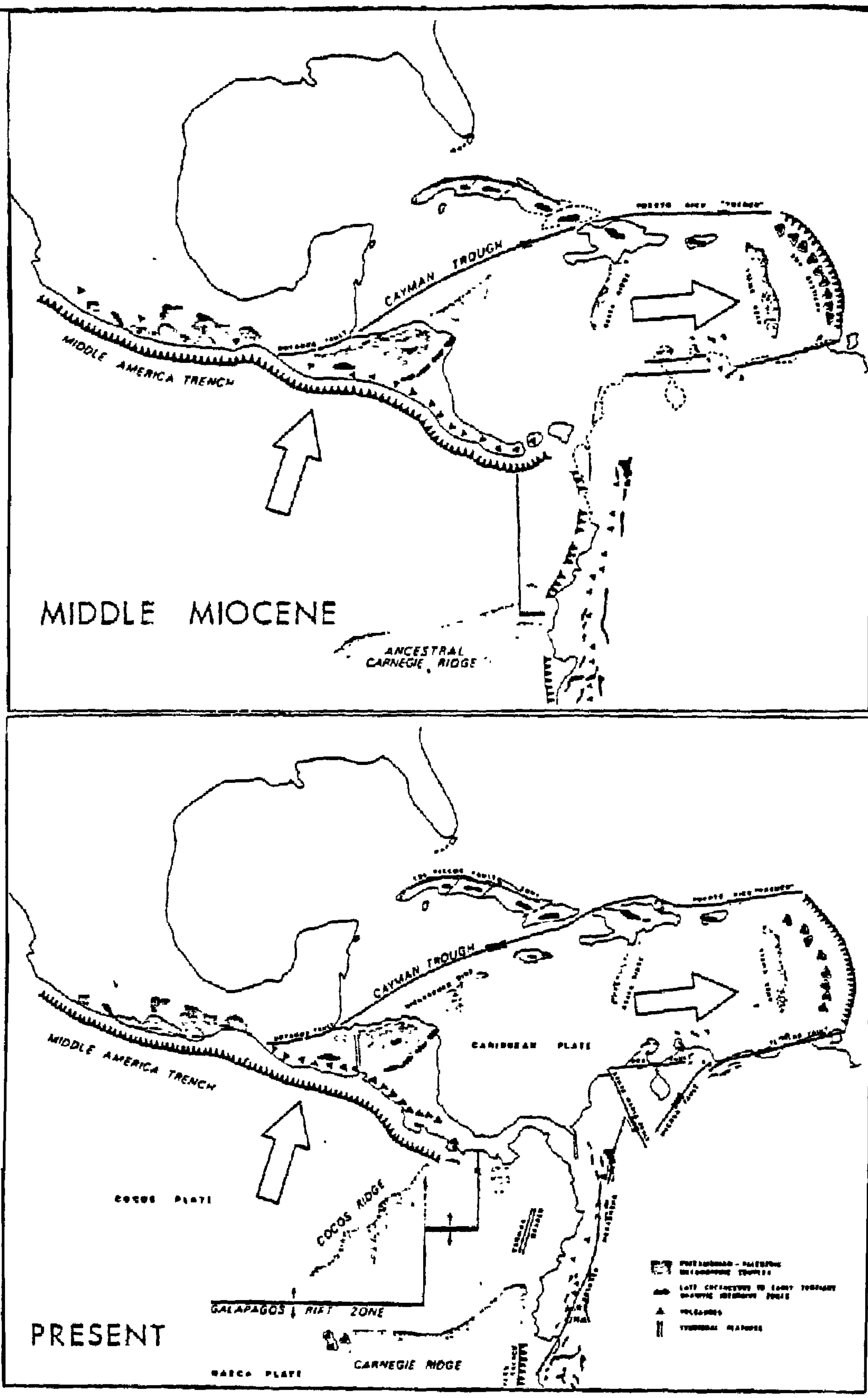
Seismic activity in the Caribbean Region extends northward from South America through the Atlantic side of the Lesser Antilles and Puerto Rico,then streaks westward through Hispaniola, the Cayman Trough, and Middle America. This belt of high seismicity corresponds to the boundary of the Caribbean Plate, which is nearly aseismic below the Caribbean Sea.

Earthquake epicenters along the Caribbean Plate margin coincide with convergent and transcurrent plate boundaries. The Cayman Trough is characterized by relatively narrow belts of seismicity caused by left lateral strike-slip motion along steeply dipping fault planes. Right lateral strike slip motion characterizes the southern boundary of the Caribbean Plate north of Venezuela. Wider belts of seismicity are present in zones where convergence processes have occurred or are occurring. Plate convergence is presently active along the entire eastern portion from Anguilla to Trinidad, its section northeast of la Hispaniola, and its western boundary along Central America. The Puerto Rico Trench is believed to be an older zone of underthrusting which is presently behaving as a "transform" trench (Case and Holcombe, 1980).



tribution of plate boundaries and Movement during the Paleocene and Early Oligocene

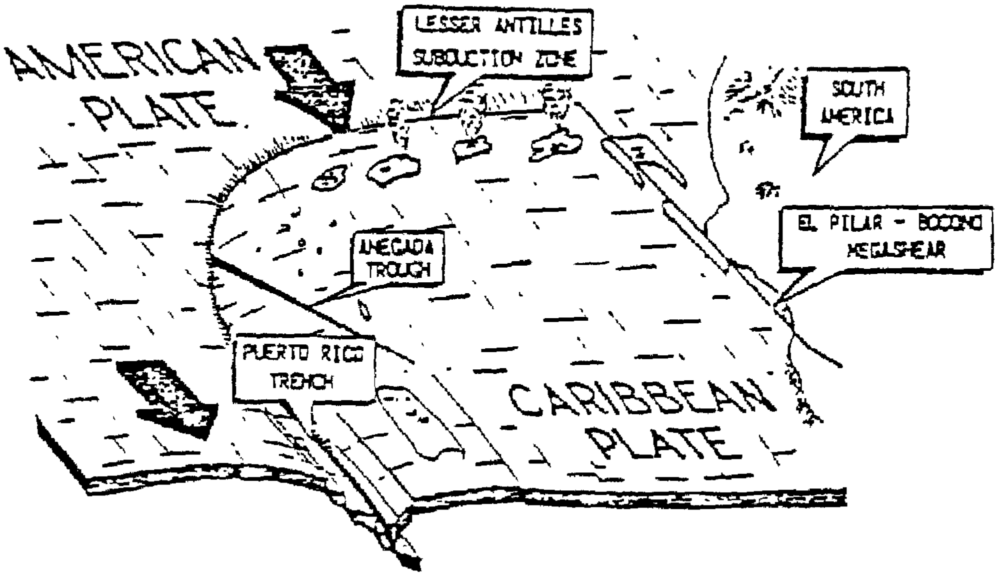
. 1 From Malfeit and Dinkelman 1972



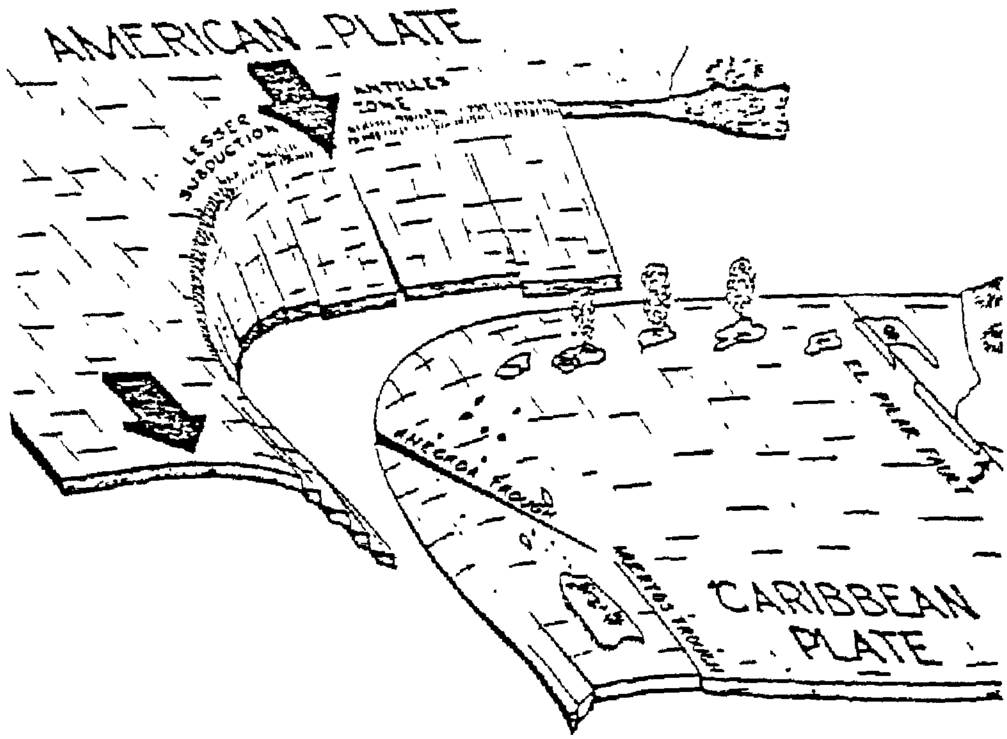
Distribution of plate boundaries and Movement during the Middle Miocene and Holocene

Fig. 2 From Malfait and Dinkelman 1972

Hypocentral distribution of seismicity in the Caribbean indicates a dip of seismic activity from the Atlantic Plate margin toward the Caribbean Sea. The foci of these earthquakes are distributed on well-defined planes that dip into the mantle. Dipping planes of seismicity define the position of the North American Plate which is plunging into the Earth's mantle beneath the Caribbean Plate (fig.3). The results from data collected by the Puerto Rico Seismic Network firmly establish the existence and configuration of the North American lithospheric plate below the Puerto Rico-Island block. Intermediate-depth earthquakes located by the Puerto Rico Seismic Network form a prominently inclined seismic zone dipping about 45-60 degrees from the Puerto Rico Trench to a depth of about 150 km.under the island (fig. 4).



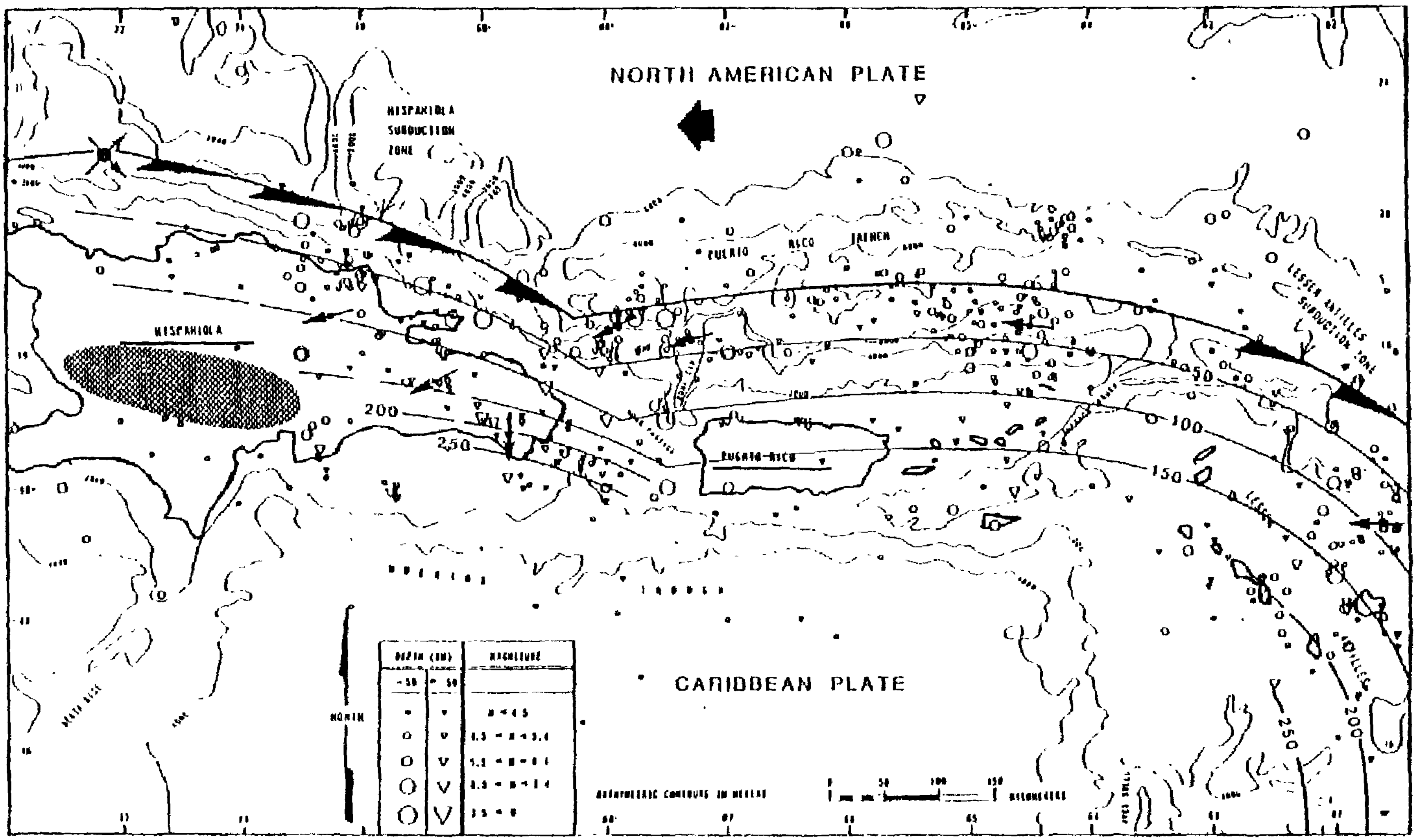
A. View is toward the southeast with American and Caribbean plates intact.



B. Plates pulled apart to allow visualization of subsurface configuration.

Boundary configuration of the North-American and Caribbean plates

Fig. 3 From Schell and Tarr 1978



Major plate-tectonic features and seismicity in the northeastern Caribbean Sea region

Fig. 4

From Schell and Tarr

The Sources of Seismicity

The on-site seismicity of Puerto Rico is characterized by the general absence of large and shallow events on the island itself. Small magnitude events of generally less than magnitude 3 typify its seismicity (Dart et. al. 1980). The largest shallow earthquakes on the island were located west of Guajataca in the northwest and near La Parguera in the southwest (NORCO-NP-1-ER, 1972).

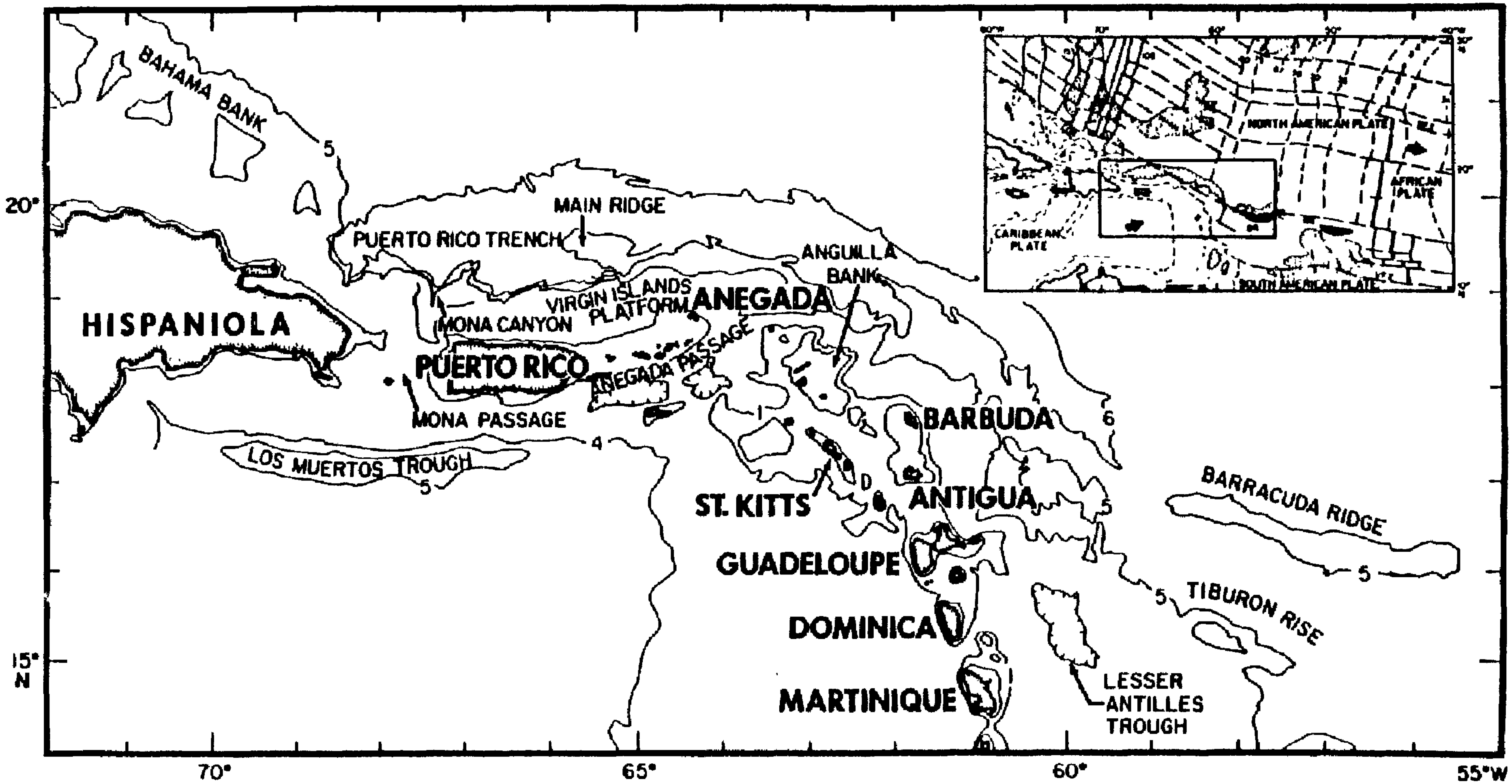
Seismic events with epicenters in Puerto Rico are not likely to cause significant damage. The essentially undeformed nature of Middle Terciary limestones and the absence of evidence of faulting indicate a long period of tectonic stability with respect to surface faulting. Thus, the probabilities of ground rupture due to faulting in San Juan are very low.

The off-site seismicity is the product of seismically active offshore zones where large magnitude events have occurred in the past. The most significant, seismically active, tectonic features capable of generating large earthquakes are the Puerto Rico Trench, the Mona Canyon-Mona Passage area, the Anegada Passage, and the northern portion of the Muertos Trough along the southern slope of the Puerto Rico insular shelf (fig.5).

The Puerto Rico Trench forms an arc that extends about 100 km north of the eastern cape of Hispaniola to approximately 200 km east of Barbuda. It parallels the north-eastern Caribbean arc system. The Trench axis lies at a depth of 8 km north of the Puerto Rico-Virgin Islands platform. The Puerto Rico Trench is bounded by high angle faults with a structural configuration suggestive of a downdropped block. Most seismic events are of shallow focus and occur in clusters where the Mona Canyon meets the Puerto Rico Trench northwest of Puerto Rico and in the area immediately northwest of Anegada. Fault zones just south of the Trench are likely to produce earthquakes with magnitudes as large as 8 to 8.25 (McCann, 1984). Puerto Rico is aproximately 60 km from the southern wall of the Trench. The closest fault zone south of the Trench that extends to the sea floor is about 35 km north (NORCO-NP-1-ER pag 9.c-15) of the north central coast.

The Mona Canyon-Mona Passage area is located between Puerto Rico and the Dominican Republic. Seismic activity is largely concentrated on the western side of the Mona Passage. The most prominent features of the passage are the north and north-westerly striking gravens extending from the Muertos Trough in the South to the Puerto Rico Trench in the north. The Mona Canyon graven seems to be the source of the 1918 earthquake (M=7.5) which, in conjunction with a tsunami that flooded the coastline, caused widespread destruction in the north-western region of Puerto Rico. The earthquake was probably caused by vertical displacements of the faults bounding the Canyon (Reid and Taber, 1918).

The seismicity along the Muertos Trough is low compared to that of the Puerto Rico Trench. The Muertos Trough is located approximately 75 km south of Puerto Rico. It extends from south of the Dominican Republic to near the St. Croix Ridge. This structure is likely to be a subduction zone where the northern margin of the Venezuelan Basin moves underneath Puerto Rico. This may indicate that Puerto Rico is a smaller plate or block separating the larger plates (McCann, 1984). Major quakes with a long repeat time are likely to occur on the slope south of Puerto Rico. Contrary to the eastern region where any fault rupturing during an event is of limited length (McCann, 1984), the western and central parts of the insular shelf's



Place Names and general bathymetry of northeastern Caribbean

Fig. 5

From McCann 1984

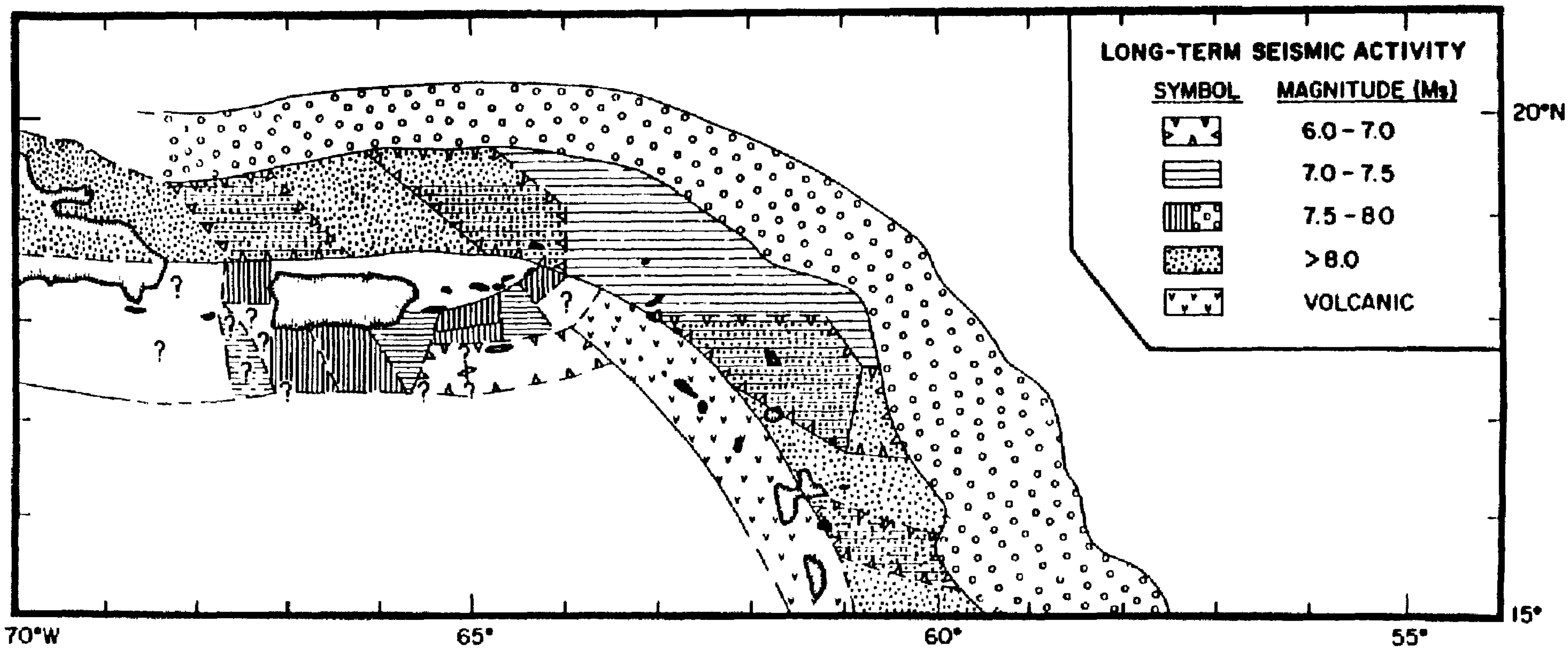
southern slope are likely to generate mayor earthquakes (M-7-8) because the tectonic blocks are bounded by long faults.

The Anegada Passage, lying 50 km east of Puerto Rico, consists of several basins and ridges that separate St. Croix from the Puerto Rico-Virgin Islands platform. Complex geologic features are present around the Virgin Islands and St. Croix basins. Faults in the northern wall of the Virgin Islands Basin are a likely source of strong shocks (M=7-8). The large earthquake of 1867 presumably originated along the northern flank of the Virgin Islands Basin (Reid and Taber, 1919). Although McCann's (1984) work concludes that the major earthquake hazard comes, not from great earthquakes to the north, but from major ones occurring closer to the land, this author concludes that the major earthquake hazard to the Metropolitan Area of San Juan comes from the Puerto Rico Trench to the north for the following reasons:

a) The San Juan metropolitan area is closer to the Puerto Rico Trench (approx. 60 km.) than to the Anegada Passage (approx. 100 km.) or the Mona Canyon (approx. 120 km.)

b) Following McCann, the frequency of great seismic events in the Puerto Rico Trench may not be different from that of major events originating from faults closer to the land. Thus, closer epicentral distance and great events with the same frequency of major ones closer to the island expose the metropolitan area of San Juan to a higher hazard from this zone.

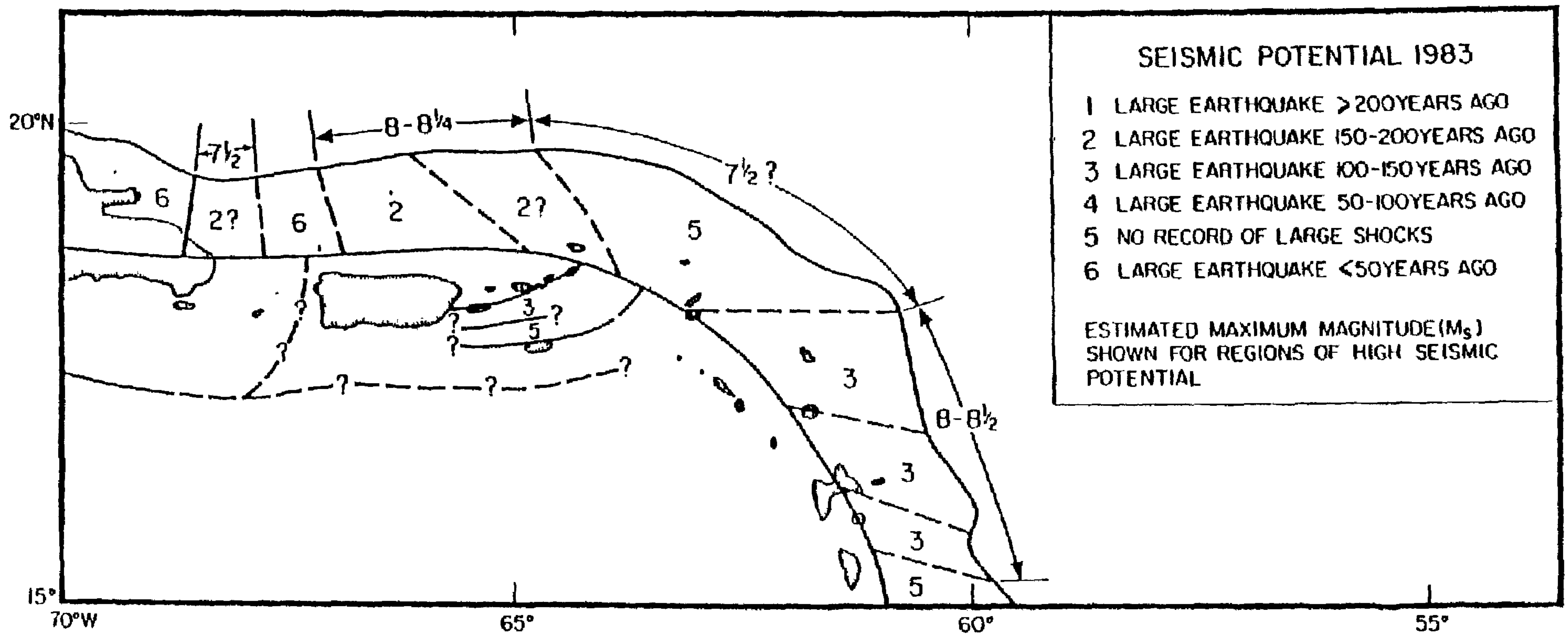
c) The portion of the Puerto Rico Trench north of San Juan is a zone of little seismicity likely to experience maximun magnitudes about 8.8.25 perhaps every 200 years (minimun value) (McCann 1984 Fig 6).



Estimate of long-term activity of shallow focus along the Caribbean - North American plate boundary

Fig. 6

From McCann and Sykes, 1984



Estimate of Seismic Potential for the northeastern Caribbean

Fig. 7

From McCann 1984

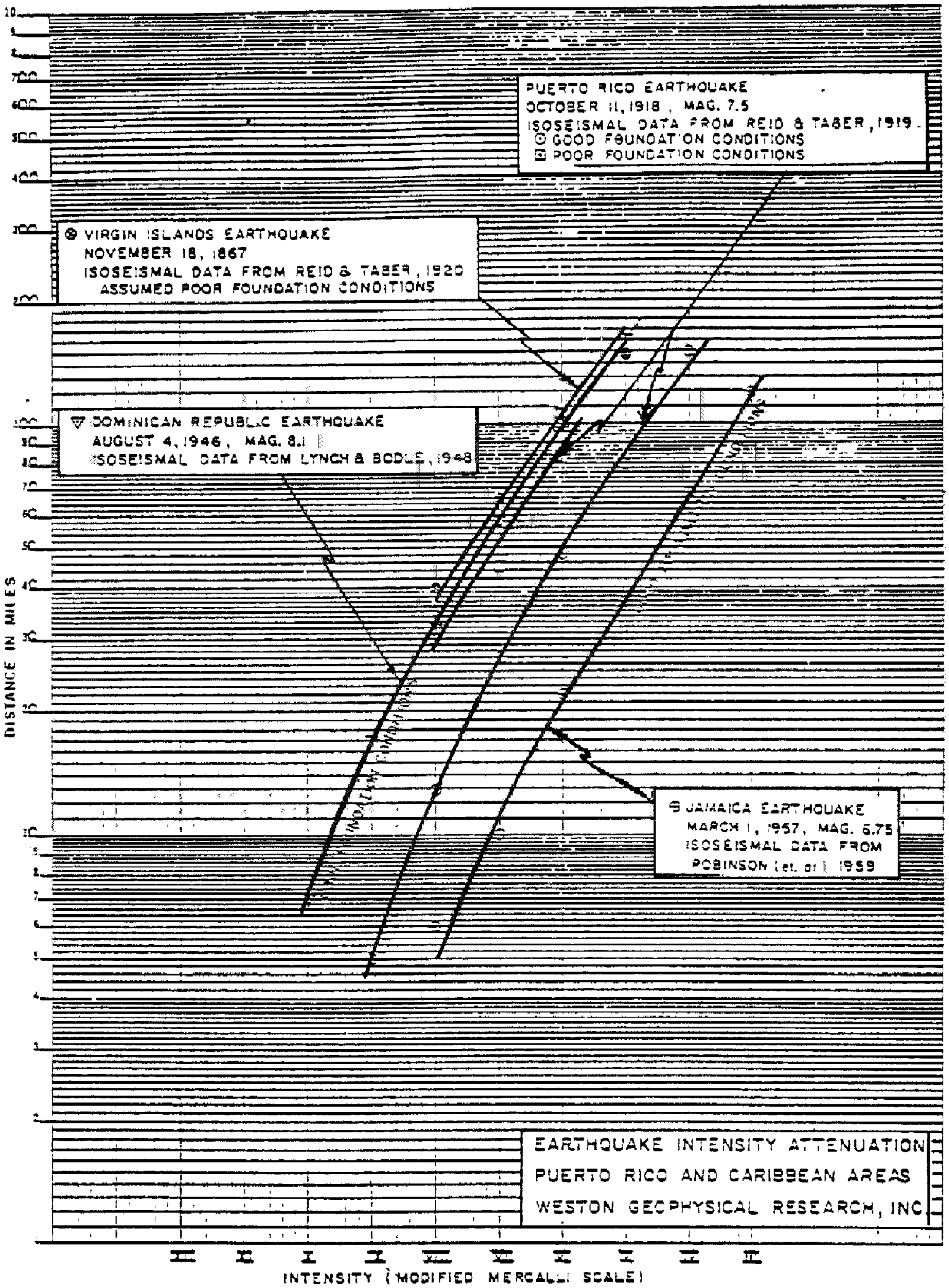
Attenuation

The appropiate estimation of earthquake energy attenuation is a fundamental part of the seismic vulnerability analysis because energy attenuation, as determined by path parameters, determines ground motion intensity on a regional scale. The lack of strong ground motion records and the limited usefulness of attenuation rates from other geographical areas require the use of isoseismal maps from past earthquake events in the area. The critical data contained in an isoseismal map are the values of maximun intensities reported at various locations either in Modified Mercalli or Rossi-Forel intensity scales. These values are plotted on an iso-intensity contour map. The isoseismal map for the earthquake of October 11, 1918 and November 18, 1867 are shown in fig.8 and 9 respectively. The contours can be deceiving because isoseismal maps typically represent intensity values reported at sites underlaid by alluvium or unconsolidated materials. Because these sites undergo more intense ground motion than sites underlaid by rock, attenuation functions derived from an isoseismal map without regard for the local site geology may overestimate ground motion at the site of interest (Hays, 1980).

The regional earthquake intensity attenuation used in this study is presented in fig 10 . Differences of up to 1 on the Modified Mercalli intensity scale occurred between sites located in good and poor foundation conditions during the October 11, 1918 earthquake. This shows the effect of local ground conditions on earthquake ground motions. These intensity attenuation relations are equivalent to a reduction of 2 orders of magnitude at an epicentral distance of 120 kilometers. This relation is consistant with that shown for the July 7, 1970 earthquake in Figure 11 (Capacete, 1972).

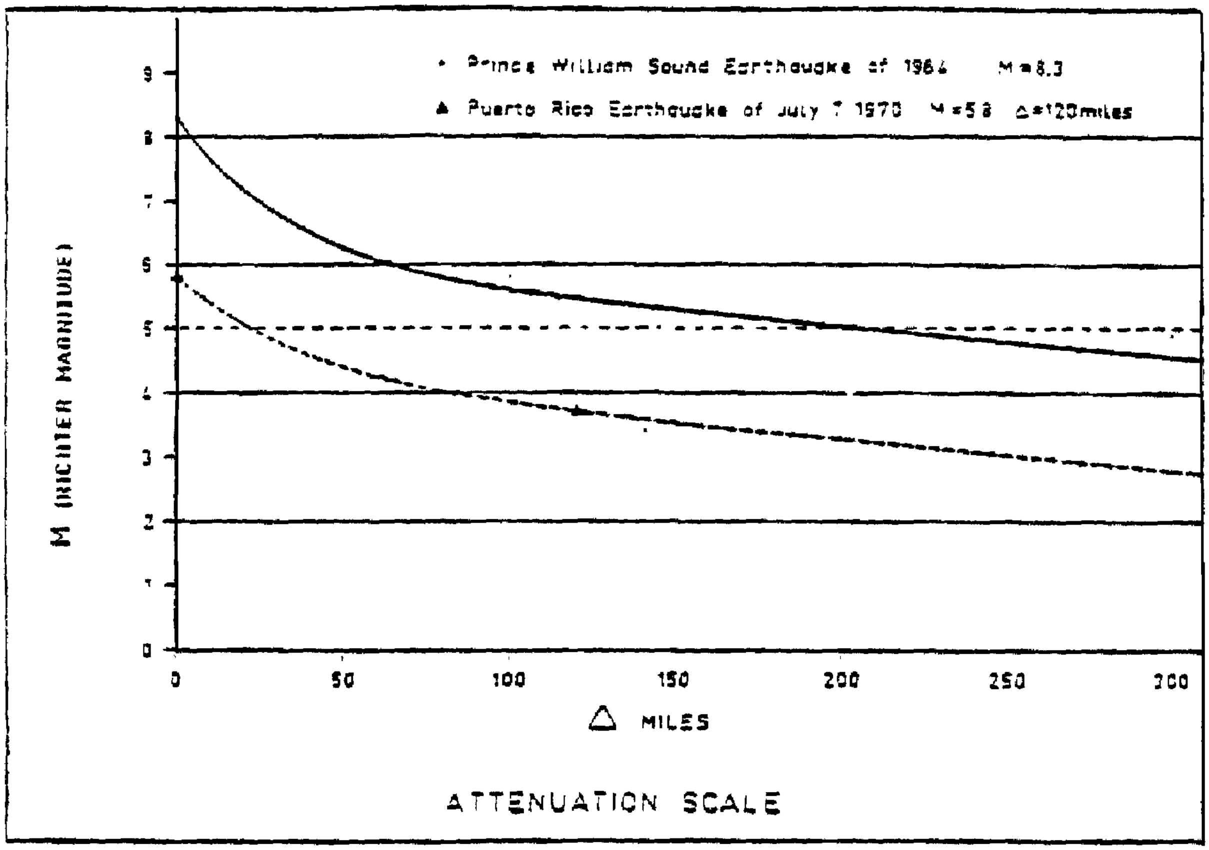
Observación:

Las páginas 20 y 21 no se encuentran disponibles ya que en el documento original no las tiene.



Regional earthquake intensity attenuation

Fig. 10



Earthquake attenuation curve for the July 7, 1970 earthquake

From Capacete, 1971

Fig. 11