APPENDIX A

SEISMIC HAZARD STUDY REPORT, RIO VALENCIANO RESERVOIR
-BLACK AND VEATCH-

Seismic Hazard Study
Rio Valenciano Reservoir

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Executive Summary

The island of Puerto Rico is situated on a fault block between the North American and Caribbean tectonic plates. Active tectonics occurring along the margin between these two plates requires that the Rio Valenciano dam be designed and constructed to withstand seismic shaking.

Four active fault zones surround Puerto Rico:

1. Puerto Rico Trench Fault Zone (PRTFZ)
2. Muertos Trough Fault Zone (MTFZ)
3. Anegada Passage Fault Zone (APFZ)
4. Mona Passage Fault Zone (MPFZ)

A deterministic seismic hazard analysis (DSHA) was performed to determine the maximum credible earthquake from each source, and to calculate the acceleration response spectrum at the dam site. Earthquake magnitudes were estimated from empirical relationships between rupture area and moment magnitude (M). The acceleration response spectrum was determined using attenuation relationships developed specifically for subduction zones, such as those along the PRTFZ and the MTFZ. It was determined that the highest accelerations would be generated from a M 8.12 earthquake on the MTFZ. The horizontal spectral accelerations at 5% damping that should be used for design analysis of the MCE or maximum design earthquake are as follows:

Period (sec)	Acceleration at 5% Damping (g)
PGA	0.26
0.075	0.40
0.1	0.49
0.2	0.61
0.3	0.57
0.4	0.54
0.5	0.50
0.75	0.36
1.0	0.27
1.5	0.17
2.0	0.11
3.0	0.05

A recently completed probabilistic seismic hazard analysis (PSHA) for Carraizo dam was used to determine spectral accelerations for the operating basis earthquake (OBE). The OBE, as defined by the Corps of Engineers, is the earthquake with a 50% probability of exceedance over the service life of the project. Assuming a 100 year service life for the Rio Valenciano reservoir the OBE would have a return period of 144 years. The horizontal ground motion parameters recommended for OBE analysis are as follows:

Period (sec)	Acceleration at 5% Damping(g)
PGA	0.09
0.075	0.17
0.1	0.18
0.2	0.18
0.3	0.18
0.4	0.18
0.5	0.18
0.75	0.12
1.0	0.09
1.5	0.06
2.0	0.04
3.0	0.03

There is generally a strong vertical component of ground motion associated with thrust faults such as the MTFZ and the PRTFZ, and this must be included in the design analysis. The recommended method for determining vertical ground motion accelerations is to use ratios relating horizontal accelerations to vertical accelerations. For this site a ratio of 2/3 vertical to 1 horizontal is appropriate, giving vertical accelerations at peak ground acceleration (PGA) of 0.17 g and 0.06 g for the MCE and OBE, respectively.

No active faults are located in the vicinity of the Rio Valenciano reservoir, and therefore, there is no potential for surface rupture at the site due to fault movement. There is also no indication of landslides involving bedrock at the reservoir site, so only surficial soil slumping is likely to occur as a result of seismic shaking. Alluvial soils and weathered rock at the site are thin and are not adequate to support the dam. Therefore, the dam is expected to be founded on sound rock, and liquefaction is not an issue.

1.0 INTRODUCTION

The scope of this report is to:

1. Characterize the regional tectonic and geologic setting,
2. Identify the seismic source faults that will affect the dam site,
3. Determine the maximum credible earthquake (MCE) from the identified seismic sources,
4. Determine the operating basis earthquake (OBE), and
5. Recommend horizontal and vertical ground motion parameters for use in design analysis.

No field data were collected for this analysis or report. Instead, there was a reliance on published papers, public databases, and professional judgement for the development of the results and conclusions of this report.

The proposed Rio Valenciano dam is located about 2.2 km south of the town of Juncos at latitude 18.208 north and longitude -65.925 west. The reservoir will be used as a water source for the East-Central Regional Aqueduct Water Supply System, and will be fed by the Rio Valenciano River and runoff from the surrounding watershed.

2.0 TECTONIC AND GEOLOGIC SETTING

2.1 Tectonic Setting

The Greater Antilles islands of Puerto Rico, Hispaniola, Cuba, and the Virgin Islands are a part of a now volcanically inactive island arc. Formed from 120 to 45 million years ago (Ma), the island arc was developed on the leading edge of the Caribbean tectonic plate as it moved northeastward relative to the adjacent North American plate. This was a period of active subduction of the North American plate under the Caribbean plate along a trend extending from the Puerto Rico Trench (Figure 1) to the northern edges of Hispaniola and Cuba (Erikson et al., 1990). Volcanic activity and related sedimentary processes built the islands during this tectonic phase.

During Eocene time (~45 Ma) the tectonic style began to change as the buoyant Bahama platform reached the active subduction zone adjacent to Cuba. This greatly reduced subduction rate along this segment of the island arc, impeded any further movement of Cuba relative to the North American plate, and resulted in a major shift in relative plate motions to a generally east-west direction (Dolan et al., 1998). To accommodate the continued eastern advance of Hispaniola and Puerto Rico relative to Cuba, left lateral strike-slip faulting was initiated between Cuba and Hispaniola (Figure 1). The change in the direction of plate motions caused the major subduction zone between the Caribbean and North American plates to move southward toward what is now the Lesser Antilles. Active island arc development in the Caribbean is now located along the Lesser Antilles. There continues to be a subduction component along the former Greater Antilles subduction zone; however, this fault zone has become more strike-slip in nature over time.

About 4 to 5 Ma Hispaniola collided with the southern tip of the Bahama platform (Dolan et al. 1998) (Figure 1). This resulted in a mixture of thrusting and strike-slip faulting that extends onto northern Hispaniola. This collision slowed the eastward movement of Hispaniola relative to Puerto Rico causing normal faulting in the Mona Passage area to accommodate the differential movement of the two islands (Figure 1). The differential movement between Puerto Rico and Hispaniola is also probably the cause of strike-slip faulting along the Anagada Passage fault zone (Mason and Scanlon, 1991).

Puerto Rico currently lies within a 250 to 300 km wide fault block located between the Caribbean and North American tectonic plates. Although this area is dominated by left lateral strike-slip motion, there are compressional and extensional components along the complex edges of this deformation zone. To the north is an active fault through the Puerto Rico Trench. Although depicted on Figure 1 as a single fault trace running along the Puerto Rico Trench, it is actually several faults trending subparallel to each other. This active fault zone is located about 125 km north of the reservoir site. This fault was formed as a thrust fault during subduction, and therefore has a south dipping fault plane. Movement on this fault today is either pure strike-slip (Mason and Scanlon, 1991) or oblique slip with some component of thrusting still present (Dolan et al, 1998). Based on earthquake depths, Dolan et al. (1998) has contoured the top of the North American plate below Puerto Rico and found that it dips at about 45° south to a depth of 150 km before losing resolution. This puts the fault at between 100 and 125 km below the ground surface at the reservoir site.

South of Puerto Rico is the Muertos Trough fault zone (MTFZ) (Figure 1). There is general agreement in the literature that this fault is the site of active subduction. The MTFZ is situated about 100 km south of the reservoir. Dolan et al. (1998) was also able to define this fault zone at depth based on earthquake occurrences as it plunges to the north under Puerto Rico. Based on this analysis the fault is about 25 km below the reservoir.

About 25 to 30 km east of the reservoir area is the Anegada Passage fault zone (APFZ) (Figure 1). This fault is made up of numerous segments, and appears to have both normal and strike-slip components (Mason and Scanlon, 1991; van Gestel et al, 1998). The APFZ is active, but recent seismic activity is relatively sparse, especially compared to the PRTFZ and the MTFZ.

Northwest of Puerto Rico is an area of earthquake activity that corresponds to the Mona Passage fault zone (MPFZ). Geophysical imaging of this area indicates that this is a zone of extension bounded by normal faults trending about north-south (Mason and Scanlon, 1991; van Gestel et al, 1998). This zone is about 150 km northeast of the reservoir site.

2.2 Regional Geologic Setting

Puerto Rico is readily divided into three broad geologic provinces. The oldest and largest of these is the Cordillera Central province, an east-west trending spine of mountains that runs from the towns of Luquillo and Maunabo on the east coast to Rincon and Hormigueros on the west coast. Rocks of this province are predominantly volcanic with some minor limestone, which have been intruded by several stocks and batholiths. This suite of rocks ranges in age from lower

Cretaceous (120 Ma) to upper Eocene (40 Ma) (Jolly, et al. 1998), and represents the ancient island arc sequence described above in the tectonic setting. The Rio Valenciano Reservoir lies completely within this geologic province. The Cordillera Central province is recognized on the geologic map of Puerto Rico in Figure 2 as the area with various shades of green. Volcanic activity ceased on Puerto Rico 40 Ma, and is of no concern for this project.

Flanking this volcanic-plutonic core are the other two provinces, the northern and southern limestone provinces. These sedimentary rocks unconformably onlap the volcanic-plutonic rocks of the Cordillera Central province. Although predominantly limestone, there are conglomerates, sandstones, siltstones and shales included in this assemblage. These rocks range in age from Oligocene to Pliocene, and were deposited after the major subduction zone had shifted from the front of the Greater Antilles to the Lesser Antilles. This geologic province is recognized on the geologic map of Puerto Rico in Figure 2 as the area with various shades of red and orange.

Two major fault zones cross the island of Puerto Rico, the Northern Puerto Rico Fault Zone (NPRFZ) and the Southern Puerto Rico Fault Zone (SPRFZ) (Figure 2). The NPRFZ is only 1 to 2 km north of the dam location. This fault zone trends east-southeast, has left lateral strike-slip motion, and can be traced for 50 km (Jolly et al, 1998). There are no geologic units common to both sides of the fault, therefore, 50 km is assumed to represent the minimum displacement. The major movement on the NPRFZ has been determined by Jolly et al. (1998), based on the compositions of volcanic rocks, to have occurred about 85 Ma in the upper Cretaceous. However, movement on associated strike-slip faults can be seen cutting rocks as young as upper Paleocene (55 Ma) (Jolly, 1998) indicating movement took place over a prolonged period. The geologic map shown on Figure 2 shows that the NPRFZ does not cut any of the Oligocene or younger sedimentary rocks of the northern limestone province clearly indicating that this has been an inactive fault for at least 30 million years. This fault is therefore not considered a seismic source.

The other significant fault zone on the island is the SPRFZ that is located over 50 km to the south-southeast of the reservoir site (Figure 2). Erikson et al (1990) has studied this fault in detail. They were able to determine that the age of significant deformation along the SPRFZ is constrained to middle Eocene to early Oligocene (35 Ma). As with the NPRFZ, this is also clearly an inactive fault, and is not considered a seismic source.

The major geologic events effecting the Cordillera Central province from oldest to youngest are:

1. Deposition of island arc volcanic strata from 120 to 45 Ma.
2. Major movement on the North Puerto Rico fault zone about 85 Ma (Figure 2) (Jolly et al, 1998).
3. Intrusion of the San Lorenzo batholith around 60 to 67 Ma (Figure 2) (Jolly et al, 1998).
4. Major movement on the South Puerto Rico Fault Zone between 50 and 35 Ma (Figure 2) (Erikson et al, 1990).

3.0 SEISMIC HAZARD ANALYSIS

As discussed in Section 2.1, Puerto Rico is in a region of active tectonics and seismicity. Therefore, an estimate of future seismic ground motions at the Rio Valenciano Reservoir site is an important aspect of the dam and reservoir design parameters. This section presents the methodology, summarizes the results, and discusses the data and the professional judgements used to develop the site-specific response spectra to be used for design analysis.

Based on the U.S. Army Corps of Engineers Manual *Response Spectra and Seismic Analysis for Concrete Hydraulic Structures* (EM 1110-2-6050, 1999), two design earthquakes should be analyzed for: the operating basis earthquake (OBE) and the maximum design earthquake (MDE). The Corps defines these earthquakes as follows:

- Operating basis earthquake. The OBE is an earthquake that can reasonably be expected to occur during the service life of the project, that is, with a 50% probability of exceedance during the service. The associated performance requirement is that the project function with little or no damage, and without interruption of function. During seismic analysis of the structure, new hydraulic structures should resist the OBE excitation within the elastic range of the element stresses (or section forces) to avoid structural damage or yielding.

- Maximum design earthquake. The MDE is the maximum level of ground motion for which the structure is designed or evaluated. The associated performance requirement is that the project performs without catastrophic failure, such as the uncontrolled release of water from a reservoir, although severe damage or economic loss may be tolerated. The Corps sets the MDE equal to the maximum credible earthquake (MCE) for dams.

The approach used was to conduct a deterministic seismic hazard analysis (DSHA) to develop the MCE, and use probabilistic seismic hazard analyses (PSHA) to develop the OBE. The DSHA was performed for this report based on known sites of active faulting, a determination of the maximum credible earthquake capable of being generated by each seismic source, radial distance of the seismic source from the reservoir site, and the use of appropriate attenuation curves. This analysis is presented in Section 3.1. Two PSHA's have been performed in recent years for Puerto Rico. These analyses were used to develop the OBE, and the results are presented in Section 3.2.

3.1 Deterministic Seismic Hazard Analysis

The method used for the deterministic seismic hazard analysis is as follows:

1. Identify the seismic sources judged to be significant to seismic shaking at the Rio Valenciano reservoir site;
2. Determine the type of fault movement and the distance of each fault to the reservoir site;
3. Based on available data, determine the likely rupture area of individual fault segments from each seismic source;

4. Determine the maximum credible earthquake (MCE) for each fault segment based on published data relating rupture area to earthquake magnitude;
5. Compare calculated earthquake magnitudes to historic earthquakes and earthquake magnitudes from other studies of Puerto Rico to ensure an appropriate MCE is used for determining ground motion parameters at the site; and
6. Use appropriate attenuation curves to develop acceleration response spectral curves to be used in the dynamic analysis of the dam.

In order to accomplish this, published literature on Puerto Rico was relied upon, especially for the type of faulting, fault configurations, and fault segment delineation. No new data were collected for this study.

3.1.1 Seismic Sources

Puerto Rico lies in a seismically active area between the North American and Caribbean tectonic plates. Active faults surround, and in part cut, this interplate boundary region (Figure 1). Faults examined for this study include the Puerto Rico Trench fault zone to the north of the island, the Muertos Trough fault zone to the south, the Anegada Pass fault zone to the east, and the Mona and Yuma rift zones to the west. All of these faults lie offshore. This presents a problem in quantifying fault segment rupture areas based on surface trace lengths. Detailed geologic mapping of the surface expression of faults, or delineation of surface rupture length for individual earthquake events are not possible due to the subsea location of the faults. The other method most commonly used for determining the area of fault segments is to spatially plot the location of major events and the associated aftershocks. This will generate a very close approximation of the rupture area. Unfortunately, there have not been any major earthquakes around Puerto Rico since the installation of the seismic network in 1975. This inability to accurately define the rupture area introduces the largest uncertainty into the determination of the MCE's, and therefore to the resulting spectral accelerations calculated for the dam site.

As discussed in Section 2.2, the major faults crossing the island of Puerto Rico are clearly inactive and can not be considered seismic sources. The only reported onshore Holocene faulting occurs in the very southwestern corner of the island. Trenches excavated in that area have exposed Holocene sediments being cut by faults, but the trace of any one fault appears to be very limited. Whether these are capable faults is unknown, but the lack of increased seismicity associated with these faults, the low magnitudes of earthquakes from the area, and the distance from the Rio Valenciano reservoir site has precluded analysis of this faulting.

3.1.1.1 Puerto Rico Trench Fault Zone

The Puerto Rico Trench Fault Zone (PRTFZ) is generally considered to be an oblique thrust fault at the boundary of the North American Plate with the Puerto Rico Platelet and the Caribbean Plate (van Gestel, et al. 1998; Dolan, et al. 1998) (Figure 3). Both reverse and strike-slip components of movement can be observed in focal mechanism solutions for earthquakes along this fault system. Two general types of seismicity are associated with worldwide subduction zones: interface earthquakes caused by the result of the thrusting of one plate over the other, and intraslab earthquakes caused by the tensional forces developed in the downgoing plate as it descends and breaks up internally. Detailed studies along subduction zones throughout the world indicate that the two types of faulting occur at different depths (Byrne, et al., 1988; Tichelaar and Ruff, 1993), and that attenuation rates of fault motion are also different (Youngs et al. 1997). Therefore, each type of faulting will be addressed individually in this seismic hazard assessment.

3.1.1.1.1 Shallow Thrusting Along the PRTFZ

To develop the maximum credible earthquake (MCE) for the PRTFZ interface (shallow thrusting) fault rupture length was based on bathymetry of the trench with rupture width taken from empirical studies of similar faulting in other subduction zones. Figure 4 shows the bathymetry in the area of Puerto Rico. Based on this map, a relatively straight and uninterrupted segment of the PRTFZ extends along the south flank of the entire Puerto Rico trench for a distance of 265 km. Other workers have estimated the length of this fault segment from 180 km (McCann, 1994) to 290 km (LaForge and Hawkins, 1999).

To estimate the dip of the shallow interplate fault segment, the results of two different worker's efforts to define the upper plate boundary were compared (Figure 3). Both Dolan et al. (1998) and LaForge and Hawkins (1999) used earthquake location data to develop their interpretations. The LaForge and Hawkins model was used in this analysis because it will give the most conservative estimate of ground motions at the reservoir site due to its closer proximity. Work by Byrne et al. (1988) and Tichelaar and Ruff (1993) indicate that shallow interface earthquakes along subduction zones are confined to depths of 20 to 40 km. These depth limits were used in this study, which gives a width of 73 km for the PRTFZ shallow thrusting. To determine the earthquake from this source with the greatest impact on the dam, a series of distance/depth values based on the geometry of the fault shown on Figure 3 were run through the attenuation equation (Youngs et al. 1997). This was done because the closest source would not necessarily cause the highest ground accelerations because attenuation decreases with depth of the hypocenter.

3.1.1.1.2 Deep Intraplate Faulting Along the PRTFZ

The maximum size of earthquakes occurring within oceanic plates is constrained by the thickness of oceanic crust because faults occurring within oceanic plates are typically high-angle normal faults. The thickness of oceanic crust is generally a function of its age; younger plates have thinner oceanic crust. The North American plate is relatively old, and therefore should have relatively thick crust and larger intraplate earthquakes than areas with younger crust.

There is no information on the locations or dimensions of faults within the subducting North American plate in the Caribbean region, so we are unable to use rupture area to constrain maximum magnitudes. Instead, a review of worldwide magnitudes of deep intraplate faulting in subduction zones was used. In their report for the Oregon Department of Transportation, Geomatrix (1995) reviewed several compilations of intraslab earthquakes and found that the largest events have been about moment magnitude (M) 7.5. To be conservative, a M 7.75 earthquake will be used for intraplate faulting along the PRTFZ.

Intraplate faulting does not occur along the plate boundary shown in Figure 3, but rather normal to it or at a high angle. For distance calculations to the site, the earthquake hypocenter along this fault is assumed to be at the upper plate boundary to give a conservative value of seismic shaking at the reservoir site.

3.1.1.2 Muertos Trough Fault Zone

The Muertos Trough Fault Zone (MTFZ) is a north dipping subduction zone where the Caribbean plate is being overridden by the Puerto Rico platelet (Figure 3). At depth, the Caribbean plate appears to terminate against the North American plate (van Gestel, 1998). Fault segment length, based on the bathymetric map (Figure 4), is estimated at 160 km. The western end of this segment is at the location of a significant change in strike of the fault. To the east, the segment ends where the sharp topographic trough ends and the fault appears to be dying out as it approaches the Anagada Pass fault zone.

Fault width for the MTFZ was determined in the same manner as the PRTFZ shallow thrusting. Figure 3 shows two interpretations of the geometry of the subduction zone. The Dolan et al interpretation is used in this analysis because it gives a more conservative estimate of ground motion shaking at the reservoir site. Fault width was assumed, based on the investigations of others (Byrne et al, 1988 and Tichelaar and Ruff, 1993), to be confined to depths of 20 to 40 km. This gives a rupture width of 85 km.

3.1.1.3 Anegada Pass Fault Zone

The Anagada Pass Fault zone (APFZ) is an area of both strike-slip and normal faulting within the Puerto Rico platelet. Detailed bathymetric mapping by Janey et al. (1987), Mason and Scanlon (1991), Garrison (1972), Trumbull et al (1981), and McCann (1994) have led to the identification and delineation of 10 individual faults in the Anagada Pass region. These are well summarized by McCann (1994). The fault having the greatest potential impact on the reservoir site is shown approximately on Figure 4 and is about 65 km long. The width of this fault is estimated at 30 km, which is typical for both strike-slip and normal faults. The distance from the site to the fault was taken as the shortest distance to the surface expression of the fault since it is most likely a vertical fault because strike-slip movement dominates the area. Depth of the earthquake was set at 30 km because attenuation of seismic acceleration is less for deeper earthquakes.

3.1.1.4 Mona Passage Fault Zone

The Mona Passage Fault Zone (MPFZ) is located just northwest of Puerto Rico and extends northward to the Puerto Rico Trough (Figure 4). This is an area of normal faulting due to tensile stresses building up as Puerto Rico moves easterly with respect to Hispaniola. The longest and closest fault in this system is shown on Figure 4, and is the fault with the biggest potential impact on the reservoir. This fault defines the eastern edge of the Mona canyon, and is 65 km long. The width of the fault is estimated at 30 km, which is typical for this type of faulting. This normal fault dips westerly away from the reservoir site, so the closest distance will be defined by the surface trace of the fault, but to be conservative, the seismic source was assigned a depth of 30 km.

3.1.1.5 Random Earthquake Source

Maps of historic earthquakes in and around Puerto Rico show that most moderate to large earthquakes have occurred along identified faults or fault zones. However, as seen on Figure 5, there is scattered, diffuse seismicity that is not associated with identified faults or patterned into definable zones. Most of this diffuse and random seismicity is probably due to small earthquakes along either buried or unidentified faults, or to improperly locating hypocenters. Historic earthquakes within a 50 mile radius of the site are shown on Figure 5. Only one earthquake with a magnitude greater than 5.0 has occurred that is not clearly associated with a known fault. The other earthquakes on this Figure with magnitudes greater than 5.0 are part of the APFZ, including one with a magnitude of 7.5.

Since the historic earthquake catalog is not complete, and likely has not located all earthquakes correctly, or appropriately estimated their magnitudes, a conservative approach was taken for random seismicity. It was assumed that a magnitude 6.0 earthquake could occur randomly at any location at a minimum depth of 10 km. Based on the attenuation relationships used for this study, it was determined that the random earthquake producing the most shaking would be located 10 km directly below the dam site.

3.1.2 Determination of the Maximum Credible Earthquake From Each Seismic Source

Using the relationship developed by Wells and Coppersmith (1994) relating area of rupture to moment magnitude, the determination of the maximum credible earthquake (MCE) for each fault was calculated as follows:

$$M = 4.07 + 0.98 \log(RA)$$

Where: M = moment magnitude
RA = rupture area

Based on the above equation, and the fault segment sizes discussed in the previous sections, the MCE for each fault can be calculated:

Fault	Length (km)	Width (km)	Rupture Area (km^2)	Depth (km)	Magnitude (M)
PRTFZ – shallow thrust	265	73	19,345	40	8.27
PRTFZ – deep intraplate				50	7.75
Muertos Trough Fault Zone	160	85	13,600	30	8.12
Anegada Passage Fault Zone	65	30	1,950	30	7.29
Mona Passage Fault Zone	65	30	1,950	30	7.29
Random Earthquake				10	6.0

3.1.3 Magnitudes from the Historic Earthquake Catalog and Other Studies

Because of the number of assumptions included in the MCE calculation, a search of the historic earthquake catalog of Puerto Rico was made to ensure that calculated MCE magnitudes were not underestimated.

The largest earthquake in recent history occurred along the shallow interplate PRTFZ on August 4, 1946. It was located under the island of Hispaniola on a fault segment west of Puerto Rico. Surface wave magnitude estimates (M_s) have ranged from 7.8 (Pacheco and Sykes, 1992; and Russo and Villasenor, 1995) to 8.1 (Kelleher et al, 1973). Dolan et al. (1998) plotted the locations of the aftershocks to define the size of the rupture zone. The rupture length was about 190 km and the width about 90 km. Based on the Wells and Coppersmith (1994) relationship of rupture area to moment magnitude this should have produced a magnitude 8.22 earthquake, indicating that the Wells and Coppersmith relationship may overestimate earthquakes in this region. The rupture area of this fault segment and the reported magnitude are both smaller than the fault segment analyzed here assuming that M M_s for magnitudes >6.6.

The largest earthquake in Puerto Rico, since settlement by Europeans, is believed to have taken place on the PRTFZ in the shallow thrust zone (McCann, 1985) in 1787. Estimates of the magnitude of this quake from historic damage reports range from M_s 8.0 to 8.25. The MCE calculated for this fault is M 8.27, indicating that this historic event was the maximum earthquake.

No large historic earthquake (> M 7.0) has been attributed to either the deep intraplate faulting along the PRTFZ or to the MTFZ. Return periods for large ruptures on these faults may be sufficiently long that none has occurred since the early 1500's.

The APFZ region was the site of an earthquake in 1867 estimated to have had a magnitude of 7.3 (McCann, 1994). This is about equivalent to the magnitude 7.29 calculated as the MCE for this area. Since the fault system in this area has been well documented through bathymetric studies, the MCE is believed to be reasonable.

The largest earthquake attributed to the MPFZ was a magnitude 7.5 in 1918 (McCann, 1994). This exceeds the M 7.29 MCE calculated for this area; however, this was an unrecorded event that was reconstructed from historic damage reports. This same area produced a magnitude 7.5 to 7.8 event in 1943 that was found to be associated with the underlying PRTFZ rather than the Mona Canyon faults (Dolan et al., 1998). The normal faulting along the MPFZ reaches the surface so fault lengths are well controlled from available bathymetry, and the fault width of 30 km used in the MCE calculation is conservative. Therefore, it is likely that the 1918 event occurred on the subduction zone along the PRTFZ underneath MPFZ. No other earthquakes approaching the MCE of 7.29 calculated in this study have occurred in the area of the MPFZ.

Two probabilistic seismic hazard analyses (PSHA) have been completed recently specifically for Puerto Rico (McCann, 1994; and LaForge and Hawkins, 1999). Below is a table comparing the earthquake magnitudes used in those analyses with the MCE's calculated in this study. The mean plus one standard deviation MCE listed for this study is calculated as part of the acceleration attenuation determination, and is the value from which ground motion parameters will be determined for use in the seismic analysis of the dam.

	This Study		LaForge & Hawkins		McCann
Fault	Mean	Mean + 1	Mean	Mean + 2.5	Mean
PRTFZ – Shallow	8.27	8.89	8.0	8.16	8.0
PRTFZ – Deep	7.75	8.43	7.5	7.75	7.5
Muertos Trough	8.12	8.76	7.75	8.0	7.5
Anegada Passage	7.29	8.01	7.4	7.5	6.9 – 7.4
Mona Passage	7.29	8.01	7.4	7.5	6.5
Random Seismicity	6.0	6.85	6.0	6.5	None

= standard deviation

The earthquake magnitudes calculated for this study are larger than those used in these two PSHA's. This is to be expected, since these are probabilistic studies, but the size of the difference indicates that the accelerations calculated for the dam site in the deterministic seismic hazard analysis (DSHA) will be conservative estimates.

There is no evidence from either the historic record or from other workers that the MCE's calculated in this study are unrealistically low. Therefore, they will be used to determine ground motion response spectra for the MDE.

3.1.4 MDE Peak Horizontal Ground Motions

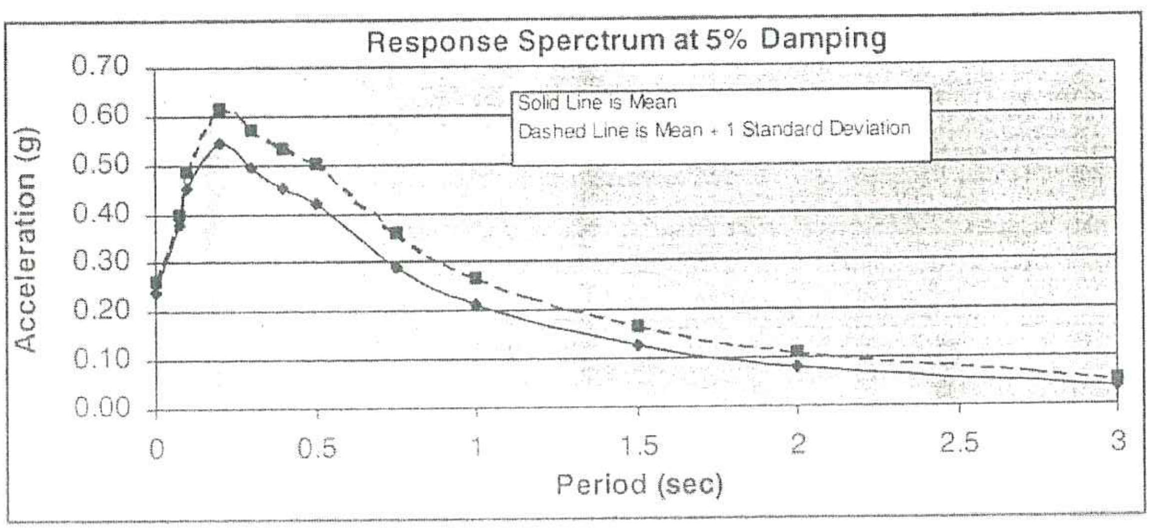
The MCE's calculated in this study are either greater than or equal to earthquake magnitudes in the historic catalog and those generated by others working in Puerto Rico. To be conservative in estimating ground motion accelerations, the values from the DSHA will be used for the maximum design earthquake (MDE) as defined in Section 3.0 of this report.

The attenuation relationships of Youngs et al (1997) were chosen for use in this study because they were developed specifically for subduction zones. These workers found that attenuation rates for subduction zones are lower than comparable rates developed for shallow intraplate faulting such as in California. Additionally, they were able to distinguish between the two types of subduction zone faulting, shallow interplate thrusting and deep intraplate faulting as was modeled along the PRTFZ (Figure 3). These attenuation relationships were used for all the faults investigated on this study. Therefore, the ground motions from shallow source normal and strike-slip faulting along the APFZ, MPFZ, and the random seismic source may be overestimated. Calculations of the peak ground acceleration (PGA) at the dam site for the mean and the mean plus one standard deviation are as follows at 5% damping:

		Peak Ground Acceleration (PGA) (g)	
Fault	Magnitude (M)	Mean	Mean + 1
PRTFZ – Shallow	8.27	0.15	0.19
PRTFZ – Deep	7.75	0.19	0.25
Muertos Trough	8.12	0.24	0.26
Anegada Passage	7.29	0.15	0.19
Mona Passage	7.29	0.03	0.06
Random Seismicity	6.0	0.19	0.23

Thrusting along the Muertos Trough fault zone is the controlling earthquake for this project. The complete spectral response at 5% damping in both tabular and graphical form for this event is as follows:

Period (sec)	Acceleration at 5% Damping (g)	Acceleration + 1 at 5% Damping (g)
PGA	0.24	0.26
0.075	0.38	0.40
0.1	0.45	0.49
0.2	0.55	0.61
0.3	0.50	0.57
0.4	0.45	0.54
0.5	0.42	0.50
0.75	0.29	0.36
1.0	0.21	0.27
1.5	0.13	0.17
2.0	0.08	0.11
3.0	0.04	0.05



Based on Corps of Engineer guidelines (EM 1110-2-6050, 1999), the mean plus one standard deviation should be used for design analysis.

3.2 Probabilistic Seismic Hazard Analyses (PSHA)

To determine accelerations for use in design analysis for the operating basis earthquake (OBE) the results of a PSHA must be used. This is because the OBE, as defined by the Corps of Engineers, is not based on the maximum credible earthquake, but rather is the earthquake with a 50% probability of exceedance during the service life of the project. This would equate to an earthquake with a return period of 144 years.

In the last six years, five PSHA's have been conducted which included Puerto Rico. These analyses have ranged from a site-specific proposed reservoir location to regional investigations covering all of North America, Latin America, and the Caribbean. The results and some of the important parameters of these studies are tabulated below, and the following five sections summarize each analysis.

Author of Study	Year	Ground Motion at the Rio Valenciano Site (g)	Period (sec)	Recurrence Interval (yrs)
McCann and Associates	1994	0.13	PGA	475
		0.15	PGA	950
		0.20	PGA	2475
LaForge and Hawkins	1999	0.36	PGA	5,000
		0.42	PGA	10,000
		0.50	PGA	25,000
		0.29	PGA	2475
NEHRP – FEMA	1997	0.32*	PGA	2475
		0.80*	0.2	2475
		0.32*	1.0	2475
Tanner and Shepherd	1994	0.13 – 0.26	PGA	475
		0.26 – 0.51	0.2	475
		0.13 – 0.26	1.0	475
		>0.51	0.2	2475
		0.13 – 0.26	1.0	2475
USGS – Shedlock	1999	0.19 – 0.26*	PGA	475

*Accelerations multiplied by foundation condition adjustment appropriate to the Rio Valenciano project.

3.2.1 McCann and Associates

In 1994, William McCann of Earth Scientific Consultants generated a series of seismic hazard maps for the island of Puerto Rico. This work was done for the Seismic Safety Commission of Puerto Rico. The region was divided into 12 seismic source areas, and many areas were further subdivided into subareas. Each area or subarea was assigned a mean earthquake magnitude value based on historic earthquake magnitudes, or on professional judgement where insufficient historic data was available. Recurrence rates were also assigned to each earthquake. The attenuation relationships of Donovan were used to calculate accelerations. To perform the probability analysis, the computer program SEISRISK III was utilized.

Three exposure periods were looked at: 1) 10% probability of exceedance in 50 years, 2) 10% probability of exceedance in 100 years, and 3) 10% probability of exceedance in 250 years. This is equivalent to return periods of 475, 950, and 2475 years, respectively. In addition, three variations on the return periods were also analyzed: 1) mean value, 2) mean plus one standard deviation, and 3) mean plus two standard deviations. The resulting accelerations of these permutations at the Rio Valenciano Reservoir site are tabulated below:

Return Period	Mean (g)	Mean + 1 (g)	Mean + 2 (g)
475 yrs	0.13	0.14	0.23
950 yrs	0.15	0.18	0.28
2475 yrs	0.20	0.22	0.36

McCann's accelerations are consistently lower than those calculated for the site specific DSHA performed for this report. One source of the discrepancy may be that McCann used significantly lower maximum magnitudes for the seismic sources, but he only reported the mean earthquake magnitude values for each fault segment and not the range of magnitudes used in his analysis. Another possible source of discrepancy is in the choice of attenuation curves. McCann used the attenuation curves of Donovan (1973) which calculate faster acceleration decay rates than the relationships developed for both shallow crustal earthquakes in California earthquakes and subduction zone earthquakes. This is likely a significant source of the differences between the two studies.

3.2.2 LaForge and Hawkins

LaForge and Hawkins (1999) conducted a PHSA specifically for the Carraizo Dam located about 15 km to the northwest of the Rio Valenciano dam site. This study was done for the Puerto Rico Electric Power Authority. The authors relied heavily upon the McCann analysis for source characterizations. Seven fault segments plus random seismicity were analyzed. A mean earthquake magnitude and the mean ± 2.5 standard deviations were assigned to each source along with distributions of slip rate and return period. The attenuation functions of Youngs et al (1997) were used for all faults except random seismicity, where the relation of Sadigh et al (1997) was used. To account for uncertainty in ground motions, attenuation relationships were distributed normally over a range of ± 2.5 standard deviations.

Uniform hazard maps for the five most significant sources were generated for return periods of 5,000, 10,000, and 25,000 years. These generated PGA's of 0.36, 0.42, and 0.50 g, respectively. All of these values are higher than the 0.26 g determined from the DSHA. Three primary reasons account for the high accelerations calculated by LaForge and Hawkins. The first and most significant reason is the use of a distribution of ± 2.5 standard deviations for the attenuation equations to account for uncertainties in ground motion parameters. This is significantly larger than the +1 standard deviation used in the DSHA to account for the uncertainties. The +1 standard deviation was chosen based on the recommendation of Corps of Engineer guidelines for concrete hydraulic structures (EM 11102-6050, 1999).

The second reason for the high accelerations is the use of very long earthquake return periods. The choice of these return periods was, according to LaForge (personal communication, 2000), determined by the Bureau of Reclamation engineers because the dam represented a "significant hazard" due to its potential impact of putting greater than 10 people at risk. The standard probability of exceedance used in seismic hazard studies is either 10% in 50 years or 2% in 50 years, which equates to return periods of 475 and 2475 years, respectively. Nowhere else are return periods approaching those used in the LaForge and Hawkins study being employed. Based on the graph of return period vs. peak horizontal acceleration included in the study by LaForge and Hawkins, an earthquake return period of 2475 years (the standard now used by NEHRP) yields a PGA of 0.29 g. The combination of very long return periods and the large distribution of possible ground motions used in the attenuation relationships generates high ground motions, although the likelihood of occurrence over the life of the project is very low. Earthquake magnitudes used by LaForge and Hawkins (1999) are shown in the table in Section 3.1.2. LaForge and Hawkins used a normal distribution of earthquake magnitudes about the numbers shown in this table, but clipped them at ± 2.5 standard deviations. So, the mean + 2.5 standard deviations shown is the maximum earthquake examined in their analysis. As can be seen, the magnitudes for all earthquakes associated with the PRTFZ and the MTFZ are lower than those calculated in this deterministic study, and the APFZ and MPFZ earthquake magnitudes are slightly higher in the LaForge and Hawkins study. The controlling earthquakes for the LaForge and Hawkins study are shallow thrusting on the PRTFZ.

The final reason for LaForge and Hawkins higher accelerations is that the Carraizo Dam site is about 20 km closer to the PRTFZ than the proposed Rio Valenciano Dam site. This accounts for most of the difference between the 0.29 g at a 2475 return period calculated by LaForge and Hawkins, and the 0.26 g calculated in the DSHA.

3.2.3 National Earthquake Hazards Reduction Program – FEMA

In 1997 the Federal Emergency Management Agency (FEMA, 1997) through contract with the Building Seismic Safety Council (BSSC) published the National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions For Seismic Regulations for New Buildings and Other Structures. This work included a PHSA for the U.S., Puerto Rico, and the U.S. Virgin Islands. The ground motions are based on a national seismic hazard study conducted by the U.S. Geological Survey. A total of 24 maps were generated covering the continental U.S., Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands. Maximum considered earthquake ground motion at spectral response accelerations of 0.2 and 1.0 seconds are shown for each map area at 5% damping.

The most significant change from the previous version of these maps is that the earthquake return period was increased from 475 to 2475 years for most of the area covered. This corresponds to a change in the probability of exceedance of ground motions from 10% in 50 years to 2% in 50 years.

The spectral response values for Puerto Rico are 1.0 g for 0.2 seconds, and 0.4 g for 1.0 second. Two modifications to this number are required to reach the design acceleration. First is a factor that takes into account foundation conditions. Map values are for rock with a shear wave velocity between 2500 and 5000 ft/sec. The sound foundation rock for the Rio Valenciano dam should exceed this value; therefore, the map values are multiplied by 0.8. This results in accelerations of 0.8 g at a period of 0.2 seconds, and 0.32 g for the 1.0 second spectral response. These accelerations are then multiplied by 2/3 because this has been judged to be the lower bound estimate of the margin against collapse for structures designed to the *Provisions*. This results in design spectral accelerations of 0.53 g at 0.2 seconds, and 0.21 g at 1.0 second. A formula given in the *Provisions* yields a PGA of 0.21 g for these spectral accelerations. All of these values are less than the mean values calculated for the DSHA performed for this report.

3.2.4 Tanner and Shepherd

Tanner and Shepherd (1994) of the Instituto Panamericano de Geografia y Historia completed a PSHA for the Steering Committee of the Seismic Hazard Project – Latin America and the Caribbean. This regional study was done at five levels of ground acceleration as follows:

1. 0 – 0.064 g
2. 0.064 – 0.13 g
3. 0.13 – 0.26 g
4. 0.26 – 0.51 g
5. > 0.51 g

Three maps were generated for a return period of 475 years: PGA, and spectral accelerations at 0.2 seconds, and 1.0 seconds. Additionally, maps for a return period of 2475 years were generated for spectral accelerations at 0.2 and 1.0 seconds. All the values reported by Tanner and Shepherd are either lower than the mean values calculated in the DSHA or the ranges includes the DSHA values (values are shown in the table in Section 3.2). The attenuation relationships used in this study were those developed by Climent, et al (1994), and likely underestimate ground motions, especially from the two subduction zones.

3.2.5 Shedlock – USGS

Kaye Shedlock (1999) of the U.S. Geological Survey generated a seismic hazard map of North and Central America and the Caribbean. The Caribbean portion of this map was developed using the historic parametric approach. Thus, the earthquake catalog for the Caribbean served as the source characterization for the seismic hazard map. No geologic information was used, and no source zones were drawn.

The only map generated for this study was for PGA at return period of 475 years. The acceleration value for all of Puerto Rico fell into the 0.24 to 0.33 g zone. These values were determined for rock with a shear wave velocity of 2500 to 5000 ft/sec. Therefore, as in the NEHRP example the values must be multiplied by 0.8 to account for the foundation conditions at the Rio Valenciano dam. These accelerations equate to a range of 0.19 to 0.26 g, which covers the 0.26 g calculated for the DSHA in this report.

3.3 Selection of Ground Motion Parameters for use in Design Analysis

3.3.1 Design Earthquakes

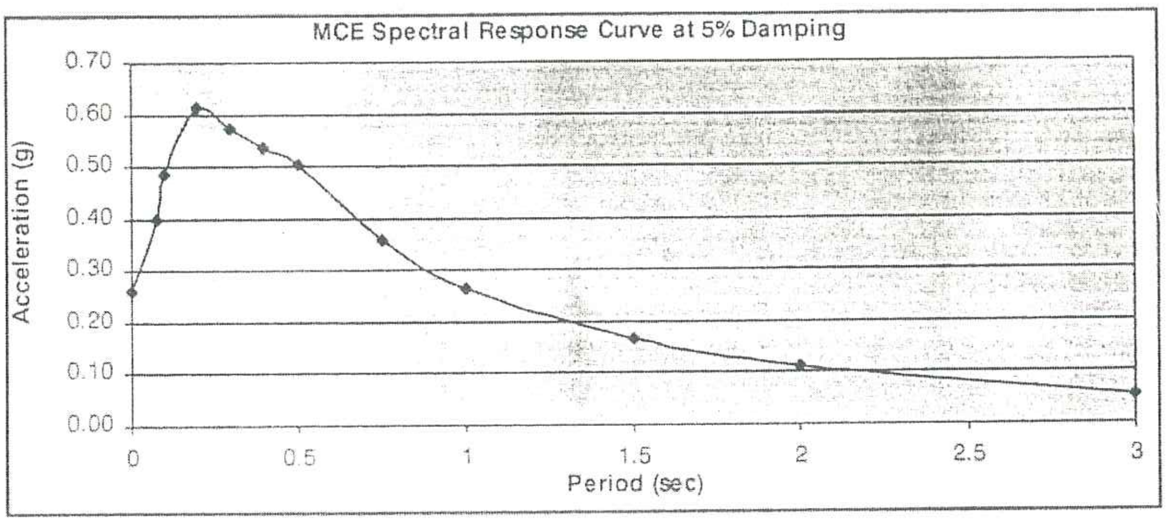
It is recommended that the seismic design analysis for the Rio Valenciano dam follow the format put forth by the Corps of Engineers in EM 1110-2-6050. The Corps recommends that the MCE be established using a deterministic seismic hazard analysis, and that a site-specific response spectrum should be estimated directly by using suitable attenuation relationships based on the tectonic setting. Additionally, the Corps recommends that ground accelerations used for design analysis should be the mean plus one standard deviation (84^{th} percentile).

For the OBE, the Corps recommends using the event with a 50% probability of exceedance during the service life of the project. Assuming that the service life of the Rio Valenciano reservoir is 100 years, an earthquake with a return period of 144 years would represent the OBE. The OBE must be established through the use of a PSHA because return periods are not taken into account in a DSHA.

3.3.2 MDE (MCE) Seismic Spectral Accelerations

Based on the deterministic analysis presented in Section 3.1 of this report, and the Corps of Engineers recommendations discussed in the Section 3.0, the following horizontal spectral accelerations should be used to analyze the dam for the maximum design earthquake (MDE) which is equal to the maximum credible earthquake (MCE):

Period (sec)	Acceleration at 5% Damping (g)
PGA	0.26
0.075	0.40
0.1	0.49
0.2	0.61
0.3	0.57
0.4	0.54
0.5	0.50
0.75	0.36
1.0	0.27
1.5	0.17
2.0	0.11
3.0	0.05

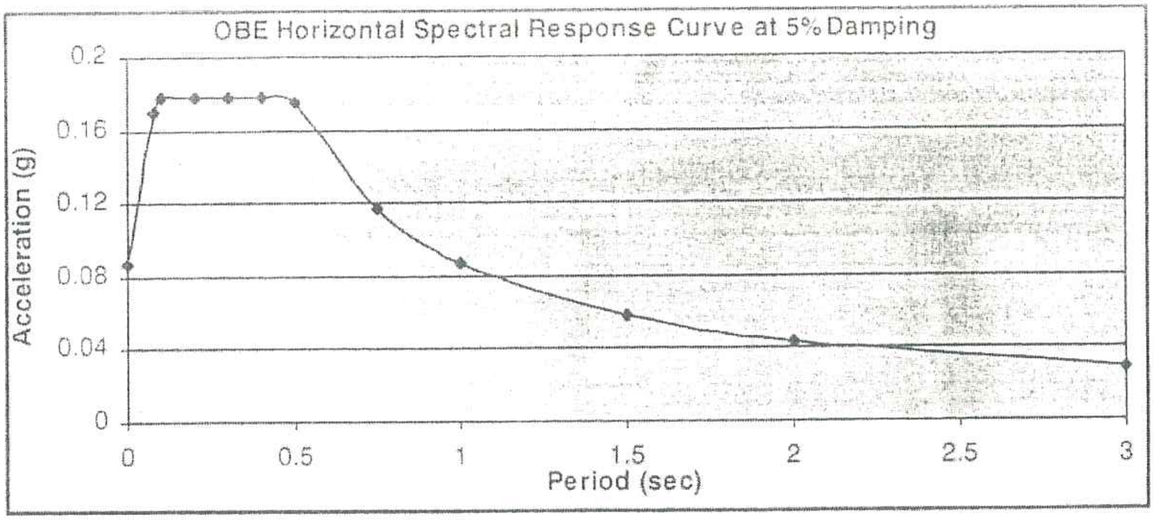


There is generally a strong vertical component of ground motion associated with thrust faults. This component must be addressed in the design analysis of the Rio Valenciano dam. To date, no direct method of calculating vertical accelerations has been developed. Instead, ratios of vertical to horizontal response spectral amplitudes are generally used to estimate vertical response spectra, given an estimate of horizontal response spectra. Recent studies (Silva, 1997) indicate that vertical-to-horizontal response spectral ratios are a function of period of vibration, earthquake source to site distance, earthquake magnitude, tectonic environment, and subsurface conditions. Based on the Corps of Engineers ratios for concrete hydraulic structures (EM 1110-2-6050, 1999), the vertical to horizontal ratio is 2/3 for a seismic source greater than 40 km from the dam site. This is in agreement with curves published by Silva (1997) for a period of 0.09 seconds and a distance to the seismic source of 40 km. It must be noted however, that these relationships have been developed for moderate sized earthquakes (M 6.5). Similar relationships for large earthquakes have not been published to date. Based on the relationships available, and the Corps guidelines, the vertical ground motion at PGA for the MCE on the PRTFZ deep intraplate event to be used in the dam analysis would be 0.17 g.

3.3.3 OBE Seismic Spectral Accelerations

The Corps recommends that the OBE be the earthquake with a 50% probability of exceedance during the service life of the project. Assuming that the service life of the Rio Valenciano reservoir is 100 years, an earthquake with a return period of 144 years would represent the OBE. The probabilistic analysis done for Carraizo dam (LaForge and Hawkins, 1999) will be used for the determination of the OBE ground motions. Carraizo dam is located 15 km northwest of the Rio Valenciano dam, and is therefore situated about 20 km closer to the PRTFZ. This will make ground motion estimates at Rio Valenciano slightly conservative because there would be more attenuation over the longer distance. Based on the LaForge and Hawkins study (1999, Figures 9 and 11), an earthquake with a return period of 144 years would have accelerations of 0.07 g at PGA and 0.13 g at 0.3 seconds. From the mean uniform hazard spectra curves for 5,000; 10,000; and 25,000 year return periods developed by LaForge and Hawkins (1999), it can be determined that PGA is approximately equal to the 1.0-second response, and that the 0.2 second response is 10% higher than the 0.3 response. From the estimated 0.2 and 1.0 second spectral responses the equations included in the NEHRP Provisions (1997) can be used to generate a complete acceleration response spectrum. Since the Corps recommends using the mean plus one standard deviation, acceleration values are increased by 25% (the standard deviation for reverse faults determined by Wells and Coppersmith (1994) in relating rupture area to magnitude). The horizontal ground motion parameters recommended for OBE analysis are as follows:

Period (sec)	Acceleration at 5% Damping(g)
PGA	0.09
0.075	0.17
0.1	0.18
0.2	0.18
0.3	0.18
0.4	0.18
0.5	0.18
0.75	0.12
1.0	0.09
1.5	0.06
2.0	0.04
3.0	0.03



The vertical acceleration at PGA for the OBE analysis would be 0.06 g calculated in the same manner as described in Section 3.3.2 for the MDE.

3.4 Surface Rupture Potential

As discussed in Section 2.2, the major faults crossing the island of Puerto Rico are clearly inactive and are not considered to be seismic sources, or likely to move in response to seismic activity elsewhere. A fault has been postulated to exist under the Rio Valenciano river and therefore to cross the dam foundation. This fault appears to be a splay of one of the major inactive faults and also very unlikely to move in response to seismic events on other faults. No indications of Holocene movement on either the nearby major fault or the postulated minor fault at the foundation location are present, and therefore the potential for future movement is considered to be very unlikely.

3.5 Seismically Induced Landslide Potential

The rim slopes are comprised of granodiorite overlain by a variable thickness of saprolite and topsoil. A review of the reservoir topography reveals that the vast majority of slopes that will be inundated are relatively gentle (all less than 2H:1V and most less than 4H:1V).

Aerial photographs were reviewed for areas having possible existing landslide morphology. One suspected area was identified, but upon field examination no indications of gravity failure were observed. The gentle slopes and lack of evidence for landslides make it very unlikely that any slope instability would occur along the reservoir rim involving bedrock, even considering future saturation and possible ground shaking associated with earthquakes.

There is however a high probability of small scale surficial slumps of soil and saprolite. Evidence of this type of gravity failure was observed in the field as arcuate scarps up to 5 m long and 20 cm high with trees that had been rotated downhill. This assessment agrees with the landslide susceptibility map of Puerto Rico developed by Monroe (1979). He has mapped the reservoir site as in an area of moderate landslide susceptibility, but states that no large landslide has occurred in the intrusive rocks, only small slumps of soil and weathered rock. This type of gravity failure will constitute no danger to the reservoir or problems to the surrounding area.

3.6 Liquefaction

The dam, as currently proposed, will be founded entirely on sound rock. Therefore, there is no potential for liquefaction.

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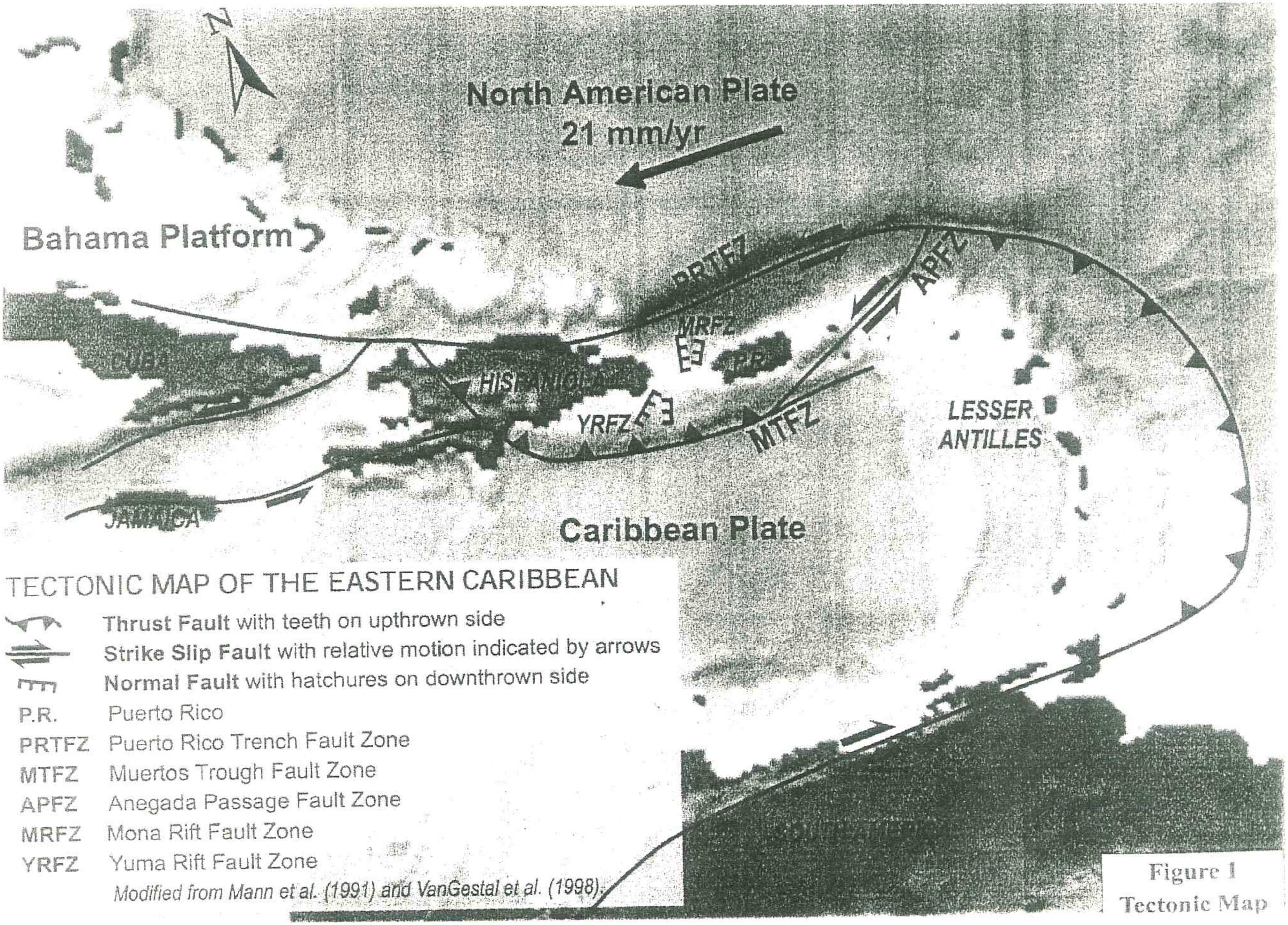
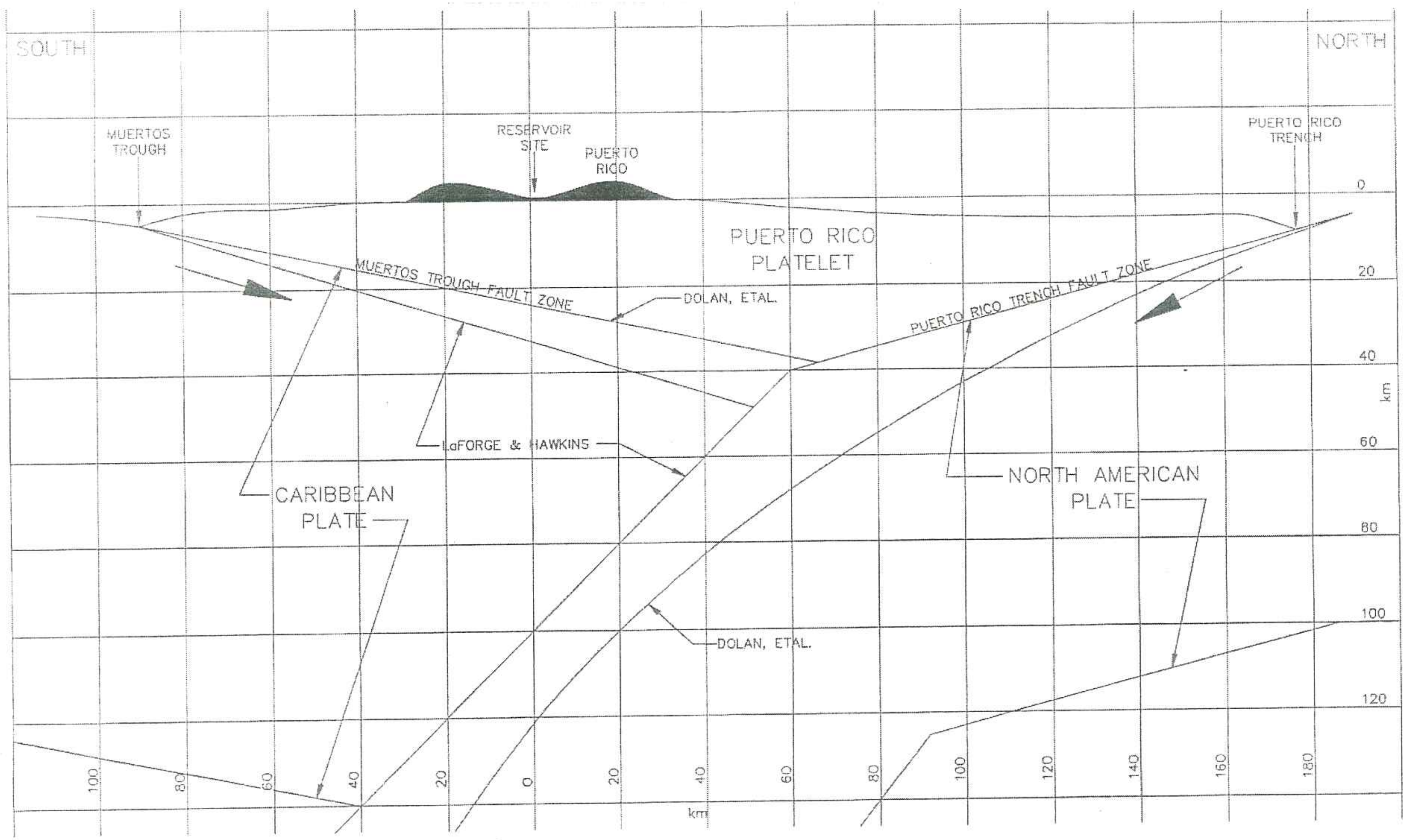


Figure 1
Tectonic Map



ECRA
RIO VALENCIANO RESERVOIR

CROSS-SECTION SHOWING THE RELATIONSHIP OF THE PUERTO RICO TRENCH FAULT ZONE AND THE MUERTOS TROUGH FAULT ZONE TO THE ISLAND OF PUERTO RICO

FIGURE 3
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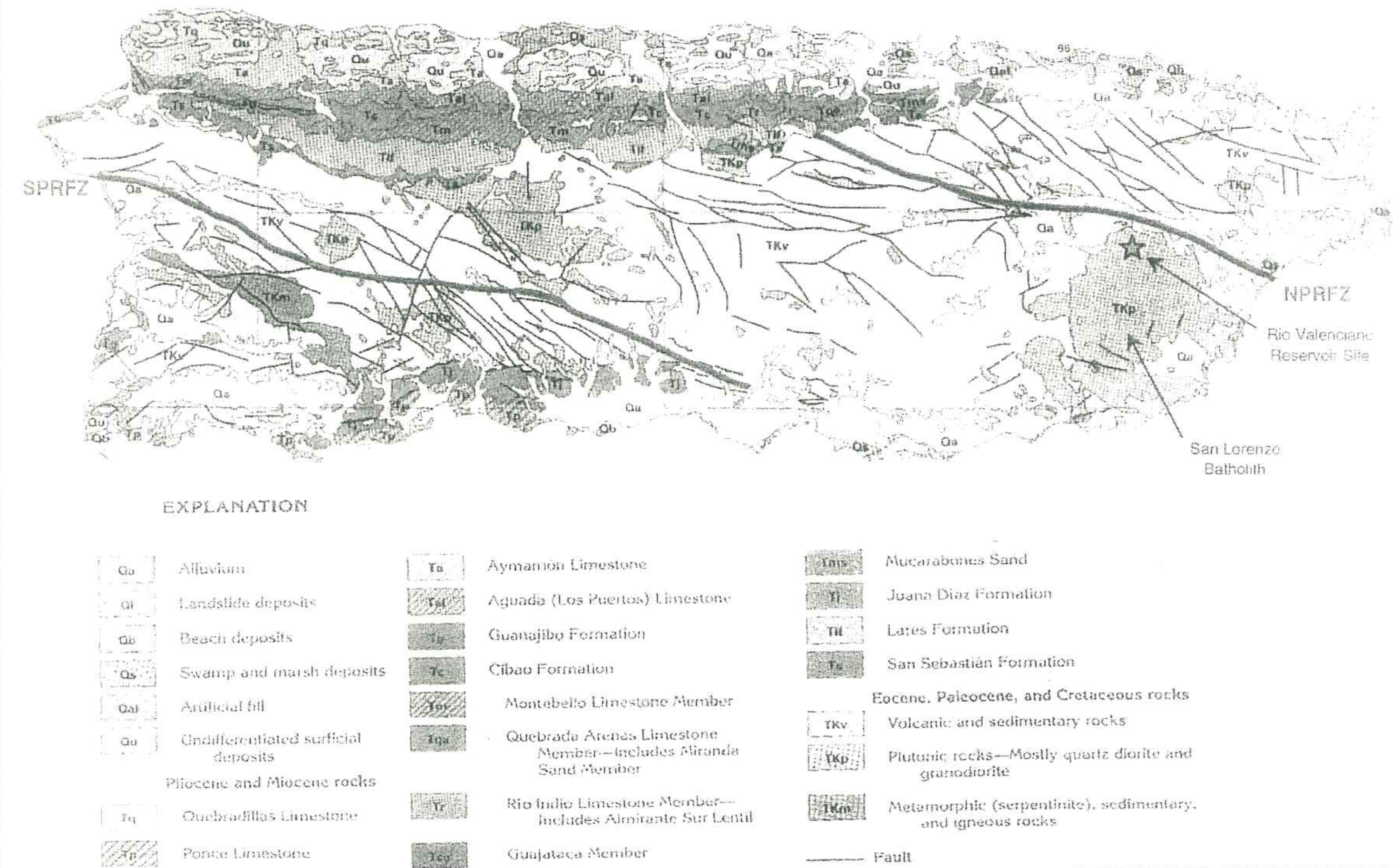
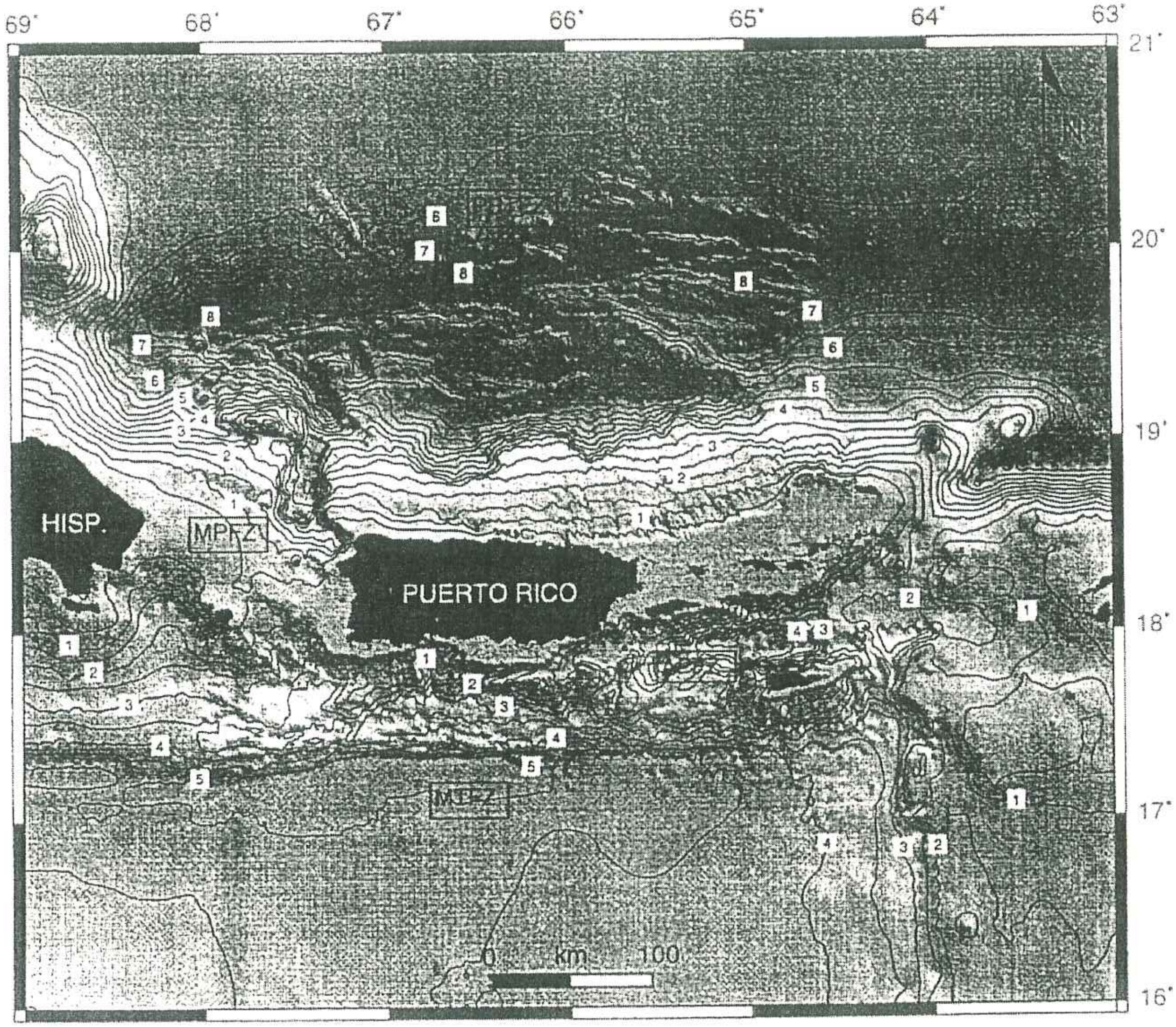


Map modified from Miller et al., 1997

Figure 2

Geologic Map of Puerto Rico



Bathymetric map with 500 m contour interval. Contour labels in km. Map shows fault segment lengths (light blue) used in deterministic seismic hazard study to develop MCE for each fault. PRTFZ is Puerto Rico Trench Fault Zone, MTFZ is Muertos Trough Fault Zone, AP is Anagada Passage Fault Zone, MP is Mona Passage Fault Zone.

Map from van Gestel et al. (1998)

Figure 4

Bathymetric Map of the Puerto Rico Area

Rio Valenciano Project, Earthquakes Within 50 Mile Radius

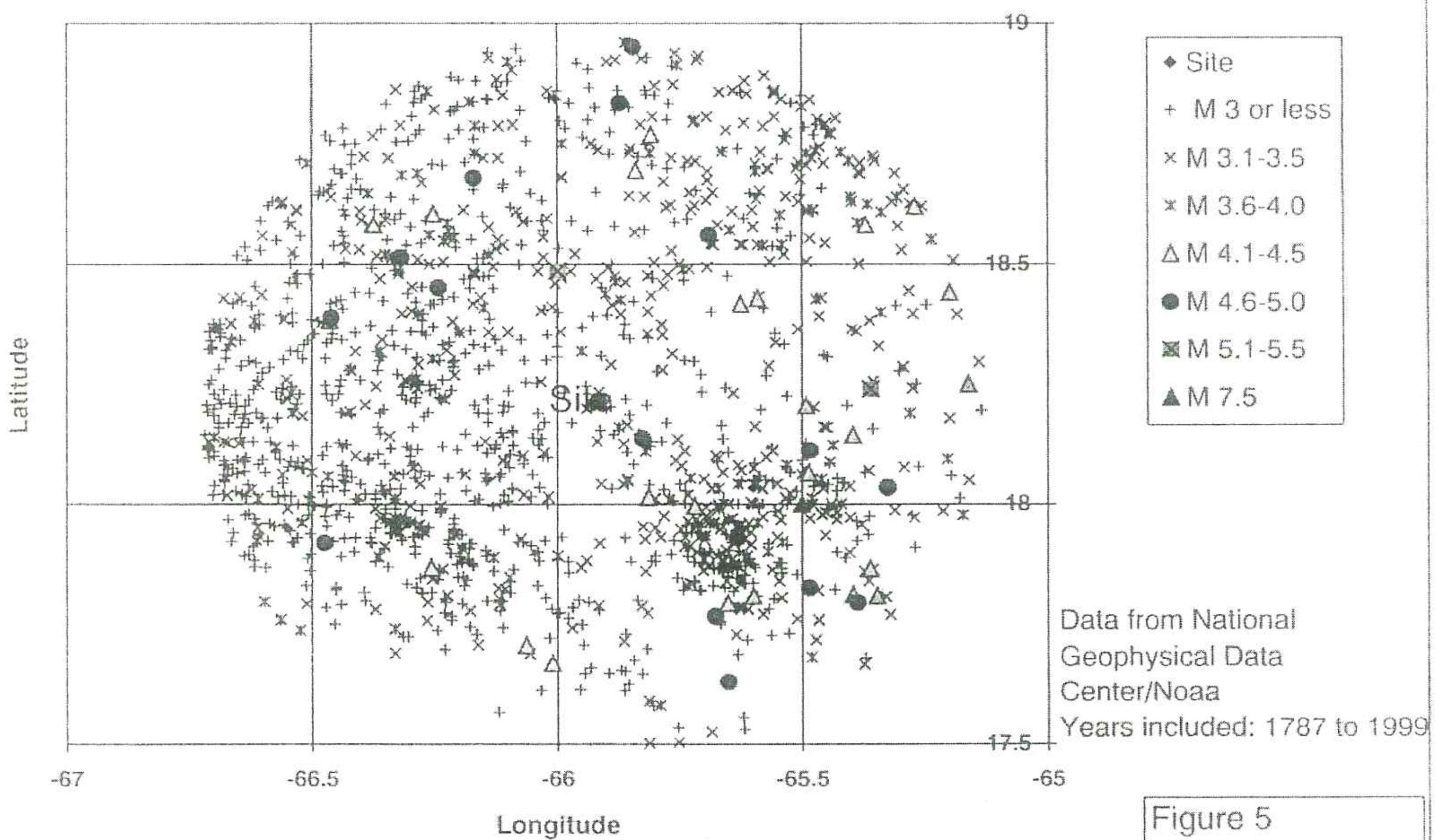


Figure 5
Local Earthqakes