SEISMIC HAZARD ANALYSIS
RIO VALENCIANO DAM SITE
JUNCOS, PUERTO RICO

Project No. 3557-06
January 30, 2007

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RIO VALENCIANO DAM SITE
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January 30, 2007

EXECUTIVE SUMMARY

This report presents the results of the first phase of an ongoing evaluation of the seismic hazard at a site on the Río Valenciano south of Juncos, Puerto Rico that the Puerto Rico Aqueduct and Sewer Authority is evaluating for the construction of a dam. The site is located 3 to 5 km. south of the Great Northern Puerto Rico Fault Zone (GNPRFZ), which up to recently was considered to have been inactive for millions of years. This was the case with all the mapped faults on the island, and seismic hazards were believed to originate in the large submarine fault systems that ring the Puerto Rico-Virgin Islands platform: the Puerto Rico Trench on the north, Mona Canyon on the west, and the Muertos and Anegada Troughs on the south and east, respectively. The recent discoveries of faulted sediment of Holocene age (last 12,000 years) on a previously unknown fault in the Lajas Valley in southwestern Puerto Rico and of paleoliquefaction features in north-central Puerto Rico suggestive of a strong local earthquake about 2800 years ago have, however, raised concerns that other onshore faults may be seismically active. This concern is heightened by Global Positioning System (GPS) measurements that show the island is being stretched in an east-west direction by 3 ± 2 millimeters per year because such strain would be accomodated by strike-slip and extensional motion along pre-existing faults that represent zones of crustal weakness. This is especially critical for the Río Valenciano Dam because previous site investigations report the presence of a fault below the river bed.

The purpose of this investigation is to determine if there are any regional or local faults capable of producing ground shaking or surface rupture at the dam site that would impact the operation and/or integrity of the dam structures, and to develop seismic parameters for dam design. The project scope of work includes detailed assessments of bedrock geology at and near the dam site, interpretation of neotectonic geomorphology along the GNPRFZ from aerial photography, LIDAR imagery, and field investigation, and evaluation of scenario earthquakes for local and regional faults and their likelihood to induce liquefaction in Late Quaternary (last 30,000 years) sand layers in the alluvial sediments of the nearby Blanco, Humacao, Gurabo, Valenciano, and Grande de Loíza rivers, and in the coastal areas between Humacao and Naguabo.

The dam site is underlain by medium- to coarse grained-granodiorite, a massive, competent rock that will provide adequate bearing support for the dam and appurtenant structures. Throughout most of the site, however, the sound rock is mantled by a residual sandy soil that grades into saprolite and eventually weathered granodiorite that would require excavation in order to found the structure on sound rock. Soil borings drilled for previous site studies indicated the thickness of the weathered zone varies up to 43 feet, but a reinterpretation of the boring data suggests it may reach 75 feet in places.

The granodiorite that outcrops throughout the general dam site area has three dominant joint sets. Two are vertical and oriented roughly north-south and east-west. The third dips northward at low angles (10 to 20 degrees). Moderately to steeply inclined joints of variable orientation also occur and may be locally abundant. The stability of joint-bounded rock wedges in the dam foundation and abutments will be evaluated during the second phase of this investigation. A seismic coefficient of 0.27g is recommended for this analysis.

The dam site is located approximately 500 meters south of the downstream end of a narrow, north-northwest (NNW) trending linear valley. Field observations made during this study support the notion that the roughly 2-kilometer long valley segment is fault controlled. A zone of sheared, fractured rock was observed at the downstream end of the linear valley, where the Río Valenciano bends into a northerly course. The shear-fracture zone has the same NNW trend and is perfectly aligned with the Valenciano valley. It is suspected that shear-fracture zone is representative of the condition of the rock within the river channel at the dam site.

The geomorphic assessment included review and analysis of U.S. Geological Survey digital elevation maps, Google Earth satellite images, and 1936-1937 aerial photography of the region, and the acquisition, processing, and preliminary review of LIDAR imagery. A number of topographic lineaments, deflected streams, and aligned river segments consistent with Late Quaternary faulting were identified, but no unequivocal evidence of fault activity within the GNPRFZ was observed. Following field inspection, however, sites near the confluence of the Río Gurabo and Río Loíza, in the Río Blanco rural community of Naguabo, and along the Río Humacao near Humacao were targeted for more detailed study, including trenching across the suspected fault traces. The trench walls will be studied in detail to confirm the presence, or absence of the suspect faults, and to collect any organic material that can be used for C^{14} radiometric dating to establish a time history of faulting.

A review of geotechnical soil borings drilled by the P.R. Highway Authority into Quaternary alluvial deposits along the Río Blanco, Río Gurabo, and Río Grande de Loíza shows the presence of numerous sand layers in these young sediments. Liquefaction potential analysis using the standard cyclic stress procedure indicates the majority of these sands would liquefy during the largest seismic events (scenario earthquakes) that are assumed would occur on both distant (**M**8.25 event on the Muertos Trough or the Puerto Rico Trench subduction zone) and local faults (**M**6.8-7.3 earthquake on one of the faults in the GNPRFZ). A study of aerial photographs, however, found only a few possible sand blows and lateral spreads that could have formed during past liquefaction events. It is possible that liquefaction features were destroyed by previous agricultural activity in the area, so field reconnaissance along river sections (identified during photointerpretation) that may present enough exposures of Quaternary deposits to assess the presence or absence of paleoliquefaction features will be undertaken during phase two of this investigation. Liquefaction features that are found will be document and dated, if possible. The potential impact of this evaluation for seismic design could be significant. Absence of liquefaction features would mean that the scenario earthquakes used in the liquefaction potential analyses may have been over-estimated, so that the analysis exaggerates the liquefaction potential of the area; in other words, the scenario earthquakes that are being used for seismic design may be too large.

Preliminary seismic design parameters have been calculated using earthquakes that originate in the known, distant seismic sources of the major fault systems that surround the PR-VI crustal block. The maximum design earthquake (MDE) corresponds to a **M**8.25 event on the Muertos Trough Fault Zone at a depth of 33 kilometers below the site producing a peak ground acceleration (PGA) of 0.46g at the dam site. The PGA for the operating basis earthquake (OBE) is 0.13g. Local earthquakes occurring within 10 kilometers of the site will be considered based on the results of the ongoing geologic, neotectonic, and paleoseismology studies. If no recently-active faults or liquefaction evidence of a local earthquake source are identified, the parameters for seismic design will continue to be based on the distant sources. If the paleolifiquecation analysis fails to find evidence of the widespread liquefaction predicted for scenario earthquakes on the Muertos Trough and Puerto Rico Trench, the design magnitude for these distant source events will be reassessed.

Field activities required to complete the different studies that make up this investigation are expected to conclude by the end of May 2007. Recommendations for additional work include compilation of seismicity data for the area and acquisition of GPS data currently being collected at continuous GPS stations in Fajardo, Humacao, and Rio Piedras. Additional exploratory core borings (including angled borings) are recommended to evaluate the condition of the foundation rock below the Río Valenciano channel and to verify the presence of the suspected shear-fracture zone at this location.

SEISMIC HAZARD ANALYSIS
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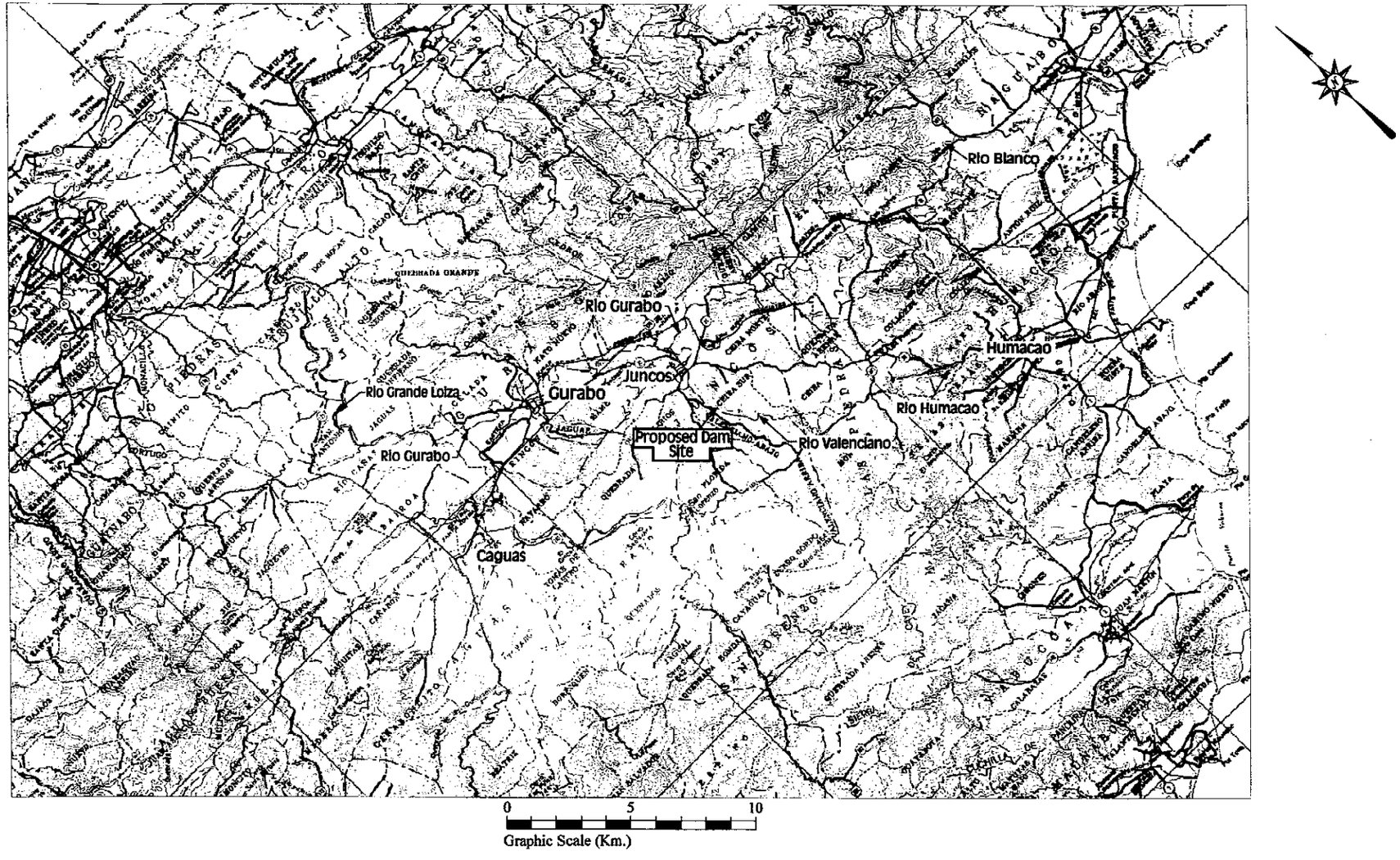
Project No. 3557-06
January 30, 2007

1.0 INTRODUCTION

This report presents the results of the first stage of an ongoing evaluation of the seismic hazard at the site of a proposed dam to be erected on the Río Valenciano about 2 kilometers (1.25 miles) south of the city of Juncos in east-central Puerto Rico (Figure 1). The evaluation was requested by CSA Group (CSA) which has been contracted by the Puerto Rico Aqueduct and Sewer Authority (PRASA) to prepare a Preliminary Environmental Impact Statement (P-EIS) for the project. The purpose of the investigation is to determine if there are any regional or local faults capable of producing surface rupture or ground shaking at the Río Valenciano Dam site that could adversely impact the operation and/or integrity of the dam structures. This evaluation supplements and expands upon a June 2000 study of seismic hazard at the dam site by Black & Veatch (B&V) of Kansas City, Missouri (Black & Veatch, 2000a) taking into consideration recently-published information about the tectonic setting and earthquake activity of Puerto Rico and the surrounding region.

The Río Valenciano Dam site is located approximately 3 to 5 kilometers (2 to 3 miles) south of the Great Northern Puerto Rico Fault Zone (GNPRFZ), one of two major fault systems that cross the island (Figure 2). Data available at the time of the B&V study was generally interpreted to indicate the GNPRFZ has been inactive for the last 50+ million years. Recent data, however, suggest the possibility of recent activity within the fault zone, leading to the investigations reported herein. For these, CSA assembled a team of stateside and local geoscientists charged with assessing active faulting within the general dam site area and providing revised seismic parameters and ground motion records for engineering design of the project, as may be needed.



Topographic map of east-central Puerto Rico that shows the location of cultural and geographic features mentioned in this report. The location of the proposed Río Valenciano Dam is indicated.

GeoCim LUIS O. GARCIA & ASSOCIATES GEOTECHNICAL ENGINEERING CONSULTANTS AMELIA DISTRIBUTION CENTER LOT. 26 A EMMA ST. GUAYNABO, PUERTO RICO 00968-8007	SEISMIC HAZARD ANALYSIS	RIO VALENCIANO DAM SITE JUNCOS, P.R. DATE: 01/30/07 JOB NO: 3357-06 CKD. BY. A.S. SCALE: .		DRW. BY: G.O.G. FIGURE NO: 1

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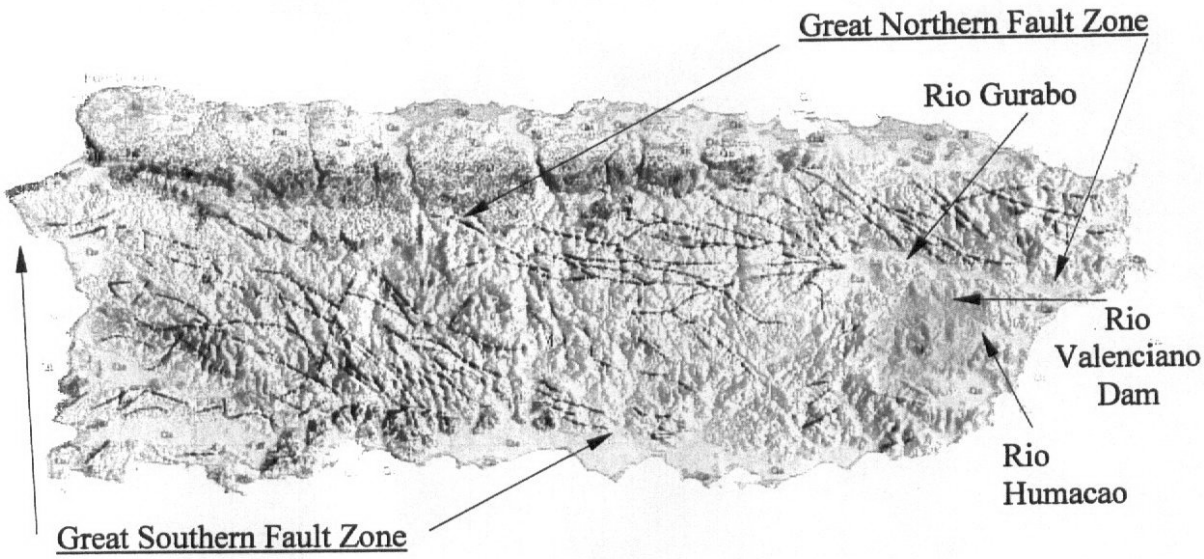
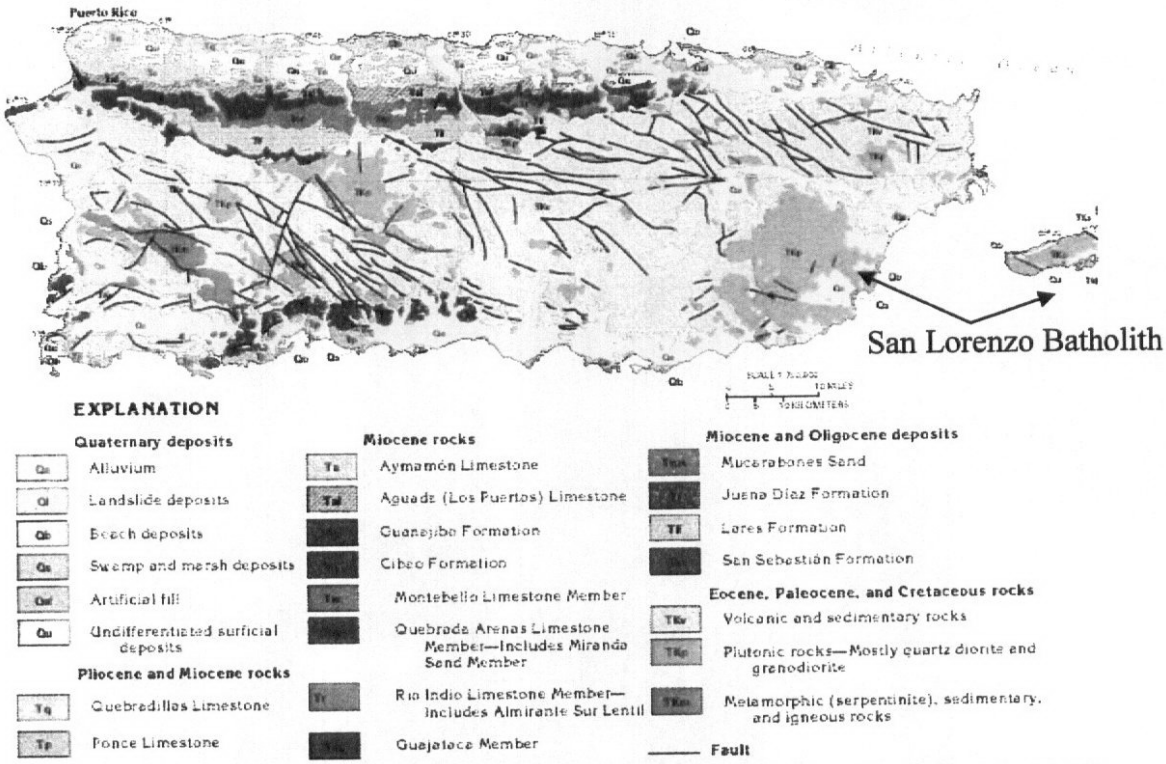


Geology of Puerto Rico



Raised relief and geologic maps of Puerto Rico; reproduced from Joyce (Appendix E)

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The following paragraphs describe the various studies that are being performed, and present their preliminary findings, conclusions, and recommendations. The studies include detailed assessments of the bedrock geology of the Río Valenciano Dam site area with emphasis on structural features associated with tectonic faulting, interpretation of neotectonic geomorphology from aerial photography, LIDAR imagery, and field investigation, and preliminary evaluation of scenario earthquakes for local and regional faults and their likelihood to induce liquefaction in Late Quaternary (last 30,000 years) sandy deposits in the study area, as well as development of preliminary estimates of the maximum design earthquake (MDE) and the operating basis earthquake (OBE) for dam design. Essential aspects of the investigations have yet to be completed but the field activities required for this have been scheduled with the goal of completion by the end of May 2007. The final reports will be submitted thereafter.

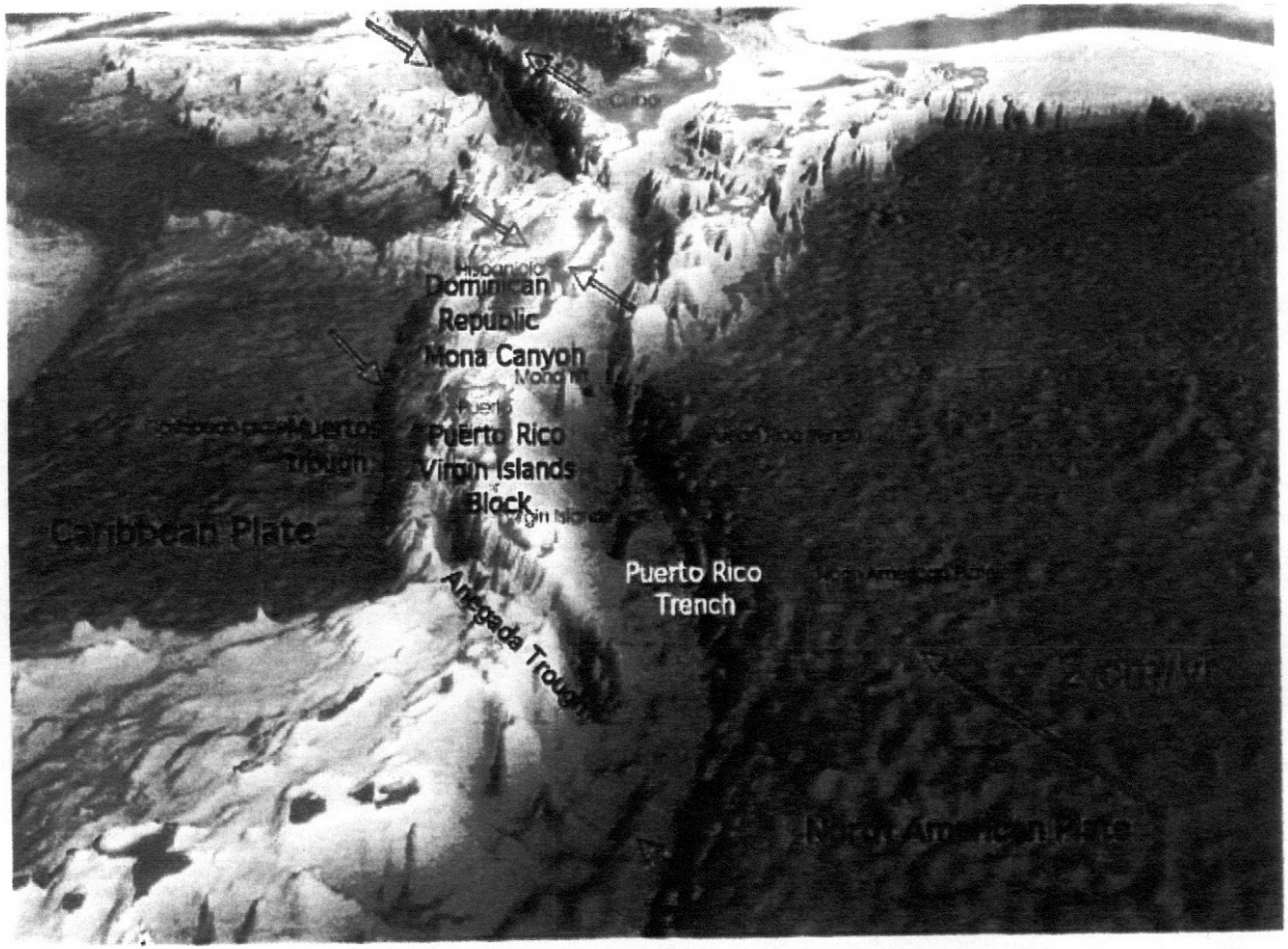
The following personnel have collaborated in the project:

- Mathew Moses, PE, of CSA Group in San Juan, Puerto Rico– Project Manager;
- Martitia Tuttle, PhD, of M. Tuttle & Associates in Georgetown, Maine – Consultant in paleoseismology and earthquake hazard assessment, including identification, dating, and interpretation of paleoliquefaction features, neotectonic interpretation of aerial photography, and technical review of reports;
- Patrick Williams, PhD of Williams Associates of West Tisbury, Massachusetts – Consultant in paleoseismology including tectonic geomorphology and fault trenching studies, and LIDAR data processing and interpretation;
- James Joyce, PhD, Professor of Geology, UPR-Mayagüez, Mayagüez, Puerto Rico – Report preparation and consultant in engineering and structural geology and local seismo-tectonics;
- Jim Swaisgood, PG, PE of Swaisgood Consulting in Conifer, Colorado– Consultant in engineering geology and seismic design; and,
- Alejandro E. Soto, PG, of Geo Cim Inc.-Luis O. García & Associates in Guaynabo, Puerto Rico – Project coordination, data analysis, and report preparation.

2.0 BACKGROUND

The June 2000 B&V seismic hazard report included in Appendix A (Black & Veatch, 2000a) contains a comprehensive description of the geologic and tectonic setting of the Río Valenciano Dam site. Hence, these will only be summarized here; the reader is referred to the B&V document for a more detailed description of these topics. In brief, Puerto Rico (PR), its surrounding islands, and the northern Virgin Islands (VI) to the east are the subaerial expressions of a small crustal block situated between the much larger North American and Caribbean tectonic plates (Figure 3). North of Puerto Rico, the North American Plate is presently moving west-southwest at a rate of approximately 2 centimeters a year relative to the Caribbean Plate located to the south. Present-day interaction between the two large plates generates stresses that cause the smaller block to tilt, rotate, and deform.

The PR-VI block is part of an old volcanic arc that formed during subduction along the North American-Caribbean plate boundary in Cretaceous to Eocene time (110 to 45 million years before present). It consists of volcanic, volcaniclastic, and intrusive rocks with a discontinuous cover of Middle Tertiary limestone and associated carbonate platform strata. The block margins are active faults that form prominent features on the seafloor topography (Figure 3). On the north is the Puerto Rico Trench where the North America Plate slides past (strike-slip faulting) with a component of underthrusting (reverse faulting) below the PR-VI block. The Muertos Trough forms the south boundary of the block; this feature is produced as Caribbean crust is subducted beneath the PR-VI block. To the west are a series of north-south trending extensional basins that include Mona Canyon where the sea floor subsides (normal faulting) as the PR-VI block moves away from Hispaniola. To the east is the northeast-trending Anegada Trough which consists of a complex series of basins and ridges that appear to have formed by a combination of both strike slip and normal faulting. The three most damaging historic earthquakes felt in Puerto Rico have been centered in these offshore seismic zones: the 1918 Mayagüez Earthquake (**M**7+) centered in Mona Canyon, an 1867 event (**M**7+) in the Anegada Trough, and a 1787 tremor (**M**8+) suspected of originating within the Puerto Rico Trench seismogenic zone (McCann, 1985; USGS, 2001).



Morphology of the PR-VI block. Prominent topographic-tectonic features are indicated. Arrows denote relative plate motions.

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SEISMIC HAZARD ANALYSIS

RIO VALENCIANO DAM SITE, JUNCOS, P.R.

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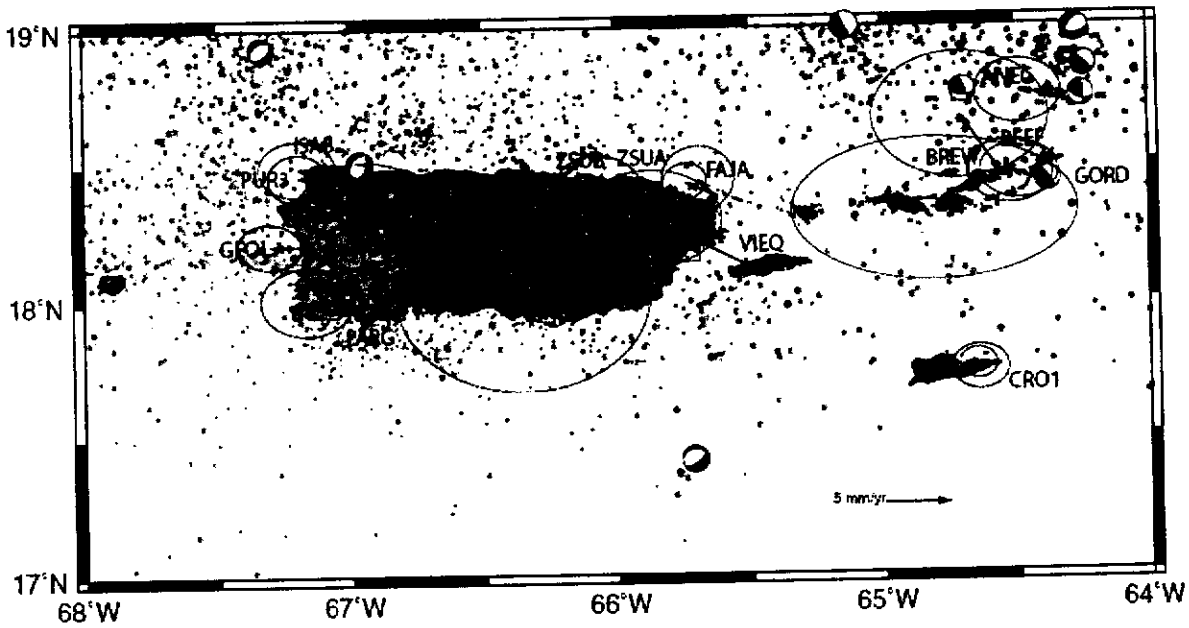
Despite the occurrence of upwards of 400 to 500 yearly microseismic events throughout Puerto Rico, it has generally been believed that recent tectonic deformation within the PR-VI block has been restricted to the submarine block margins and nearby offshore areas. One of the strongest arguments presented in support of this notion has been the absence of documented evidence of post-early Miocene (last 20 million years) on-land faulting. Field studies by the USGS have produced detailed geologic maps (1:20,000 scale) of most of the island that identify hundreds of geologic faults, including two major, west-northwest trending fault zones (Figure 2) dominated by left-lateral displacements: the Great Southern Puerto Rico Fault Zone (GSPRFZ) and the Great Northern Puerto Rico Fault Zone (GNPRFZ). The faults are mapped within the older complex of Cretaceous to Eocene rocks that outcrop throughout the island's central mountainous spine, and in the overlying Oligocene to Miocene (30 to 20 million years before present) carbonate platform rocks of southern Puerto Rico. Nowhere had a fault been demonstrated to offset younger geologic horizons. In the case of the north-northwest trending GNPRFZ, whose trace passes 3 to 5 kilometers north of the Río Valenciano Dam site, no faulting has been observed in the large areas of Quaternary (last 2 million years) alluvium that extend from the east coast at Humacao and Naguabo to Caguas, nor is there offset where several branches of the NPRFZ project into the extensively exposed late Oligocene carbonate belt west of San Juan. To the southeast the fault zone locally offsets Cretaceous bedrock units that outcrop near the valley margins, but the mapped fault traces disappear under Quaternary alluvial sediment of the Río Antón Ruiz and Río Blanco river valleys and the coastal deposits of the Naguabo-Humacao area.

During the past thirty years, new geologic techniques have been developed to study recency of faulting and the earthquake potential of active faults. Recent application of these paleoseismic techniques resulted in the discovery of faulted sediment of Holocene age (past 12,000 years) on a previously unknown fault in Lajas Valley in southwestern Puerto Rico (Prentice and Mann, 2005) and of paleoliquefaction features in north-central Puerto Rico suggestive of a strong local earthquake about 2800 years ago (Tuttle et al., 2005). These findings have raised concerns that other onshore faults may be seismically active.

Another significant new development derives from the collection of precise survey (triangulation) data using Global Positioning System (GPS) technology. Recent GPS measurements (Jansma and Mattioli, 2005) indicate the island is being stretched in an east-west direction by 3 ± 2 millimeters per year (Figure 4), although the locus of the extension is not well defined. It is likely that such strain would be accomodated by strike-slip and extensional motion along pre-existing faults which represent zones of crustal weakness. This is especially critical for the Río Valenciano Dam not only because of its proximity to the GNPRFZ, but also because the north-northwest trending river section in which the dam site is located appears to follow an old, unmapped fault, as reported in a geotechnical report for the dam site prepared by B&V (Black & Veatch, 2000b). The B&V geotechnical report is included as Appendix B herein.

The geologic map of the Juncos 7½' topographic quadrangle (Broedel, C.H., 1961) prepared by the U. S. Geological Survey (USGS) shows the Río Valenciano originates and for most of its length flows within the San Lorenzo Batholith (Figure 5), a large, late Cretaceous plutonic body that outcrops throughout an area of about 400 square kilometers (Figure 2) extending between the municipalities of Caguas, Juncos, Humacao, and Patillas. The plutonic rock is fairly uniform throughout the outcrop, consisting of medium to coarse grained granodiorite and quartz diorite. The rock is generally massive with uniform fabric; foliation is typically absent. From an engineering standpoint, it is a high quality, competent rock that will provide adequate foundation support for large engineering structures.

The Río Valenciano generally flows north toward the west-northwest trending Guarabo valley where it joins the Río Guarabo at the town of Juncos. Approximately 3.6 kilometers south-southeast of the confluence, the Río Valenciano flows west-southwest along a short straight segment and then curves into a long, relatively straight valley oriented north-northwest that continues for a distance of about 2.2 kilometers (Figure 5). It then curves to the northeast and enters another relatively straight stretch that continues trending north for a distance of about 800 meters before curving east and flowing through a shorter northeast-trending reach before reaching the Río Gurabo floodplain. The proposed Río Valenciano Dam site is located within the longer, north-northwest trending reach.



Map showing the results of recent GPS measurements that show crustal motion in Puerto Rico and the Virgin Islands relative to St. Croix. Arrows represent GPS-derived velocity (scaled to arrow at lower right). Dots represent earthquake epicenters as of November 2005. Comparing FAJA and ZSUB to the western Puerto Rico vectors, PUR3, GEOL, and PARG indicates 1-2 mm/yr differential motion between these locations. Reproduced from Appendix F.

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SEISMIC HAZARD ANALYSIS

RIO VALENCIANO DAM SITE, JUNCOS, P.R.

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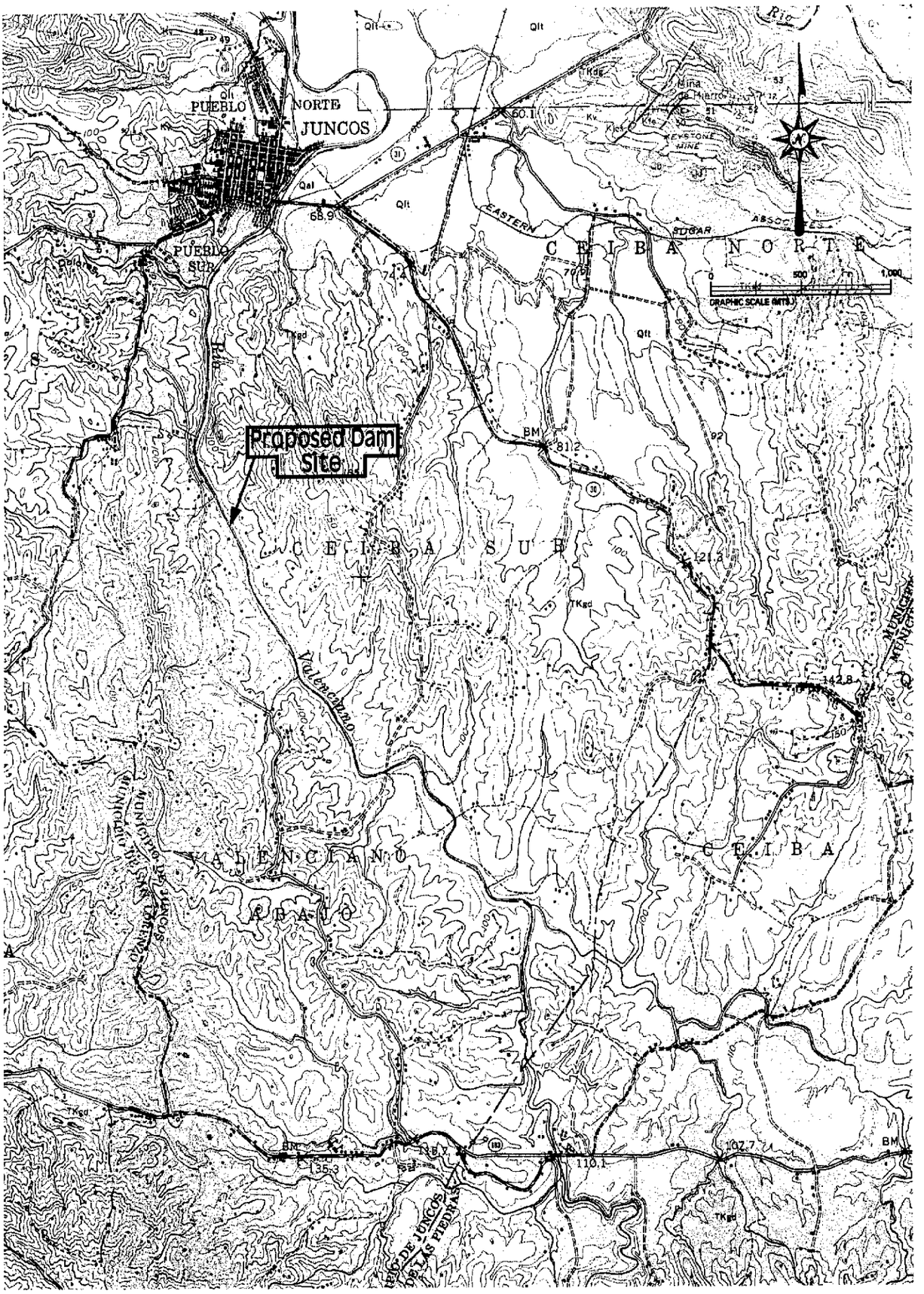

Portion of the U.S. Geological Survey map (Broedel, 1971) that shows the geology of the Río Valenciano watershed. The proposed dam site is indicated. The bluish gray pattern (TKgd) shows the granodiorite outcrop.

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		DATE: 01/30/07	JOB NO: 3557-06	CKD. BY: A.S.	SCALE: N.T.S.	FIGURE NO: 5

Giovanni: F:/Auto Cad/drawings/3557-06 Rio Valenciano/Fig. 1

Geologic faults and other structural features (for example, joints, inclined contacts between different rock types) are frequently zones of increased rock permeability; hence, rocks in fault zones tend to weather and erode faster than non-faulted rock near the fault, which creates a propensity for the formation of relatively straight topographic lows or valleys along fault traces. The Juncos quadrangle geologic map does not show any faults within the straight Río Valenciano reaches (Figure 5). Nevertheless, the linearity and length of the river segments, particularly the north-northwest trending reach, are suggestive of some type of underlying structural control. Given the proximity of the straight reaches to the GNPRFZ, it is prudent to evaluate whether the straight portions of the valley are fault-controlled.

3.0 FIELDS OF STUDY AND TECHNICAL FINDINGS

The activities that are being performed for this evaluation are designed to determine if there is evidence of Late Quaternary faulting or strong seismic shaking in the vicinity of the Río Valenciano Dam site and surrounding area, to further define the seismic hazard posed by local and regional faults, and to modify the seismic design parameters for the dam accordingly. The activities include detailed evaluations of the geology of the dam site and immediate vicinity, mapping of tectonic geomorphology and identification of recent faulting and earthquake-induced liquefaction features (that provide evidence of past strong ground shaking) using various techniques, analysis of scenario earthquakes and their likelihood to induce liquefaction in Quaternary sediments in alluvial valleys associated with the GNPRFZ, and development of seismic parameters for dam design. The following sections summarize these activities and our findings to date.

3.1- Site Geology

The dam site and surrounding area are underlain by fairly homogenous intrusive rock consisting mostly of granodiorite. The rock usually weathers into sand-rich (quartz) residual soil that grades down into friable saprolite and highly weathered rock material that in turn grades into sound rock, the latter transition typically occurring over a relatively narrow depth range of less

than 10 feet. Corestones of hard, strong rock formed by spheroidal weathering are common within the residual horizon and are often left behind littering the ground surface as the surrounding soil is eroded.

Several studies of the geology and geotechnical characteristics of the dam site and nearby areas have been conducted. The first appears to have been an early 1970s evaluation of the Río Valenciano Dam site by the New Jersey engineering consulting firm Buck, Seifert and Jost (BSJ), which is described in a report titled *Memorandum on Design of Proposed Dam and Reservoir of the Rio Valenciano* dated July 16, 1971. CSA provided us with a copy of the text of this report that is included in Appendix C. The BSJ study included the drilling of 17 exploratory borings distributed in 3 parallel lines with the central line oriented along the dam axis; the report, however, provides only a cursory description of the geology of the site and there are no boring logs. We were also provided with a copy of an undated document apparently prepared after the BSJ report by the U.S. Army Corps of Engineers (USACE) for an alternate dam site located approximately 760 meters (2500 feet) north of the current Río Valenciano Dam site. This report is included in Appendix D herein. It makes reference to the BSJ borings and states that eight borings were drilled at the alternate site. The report describes the geology of the alternate site but, unfortunately, the boring logs are missing.

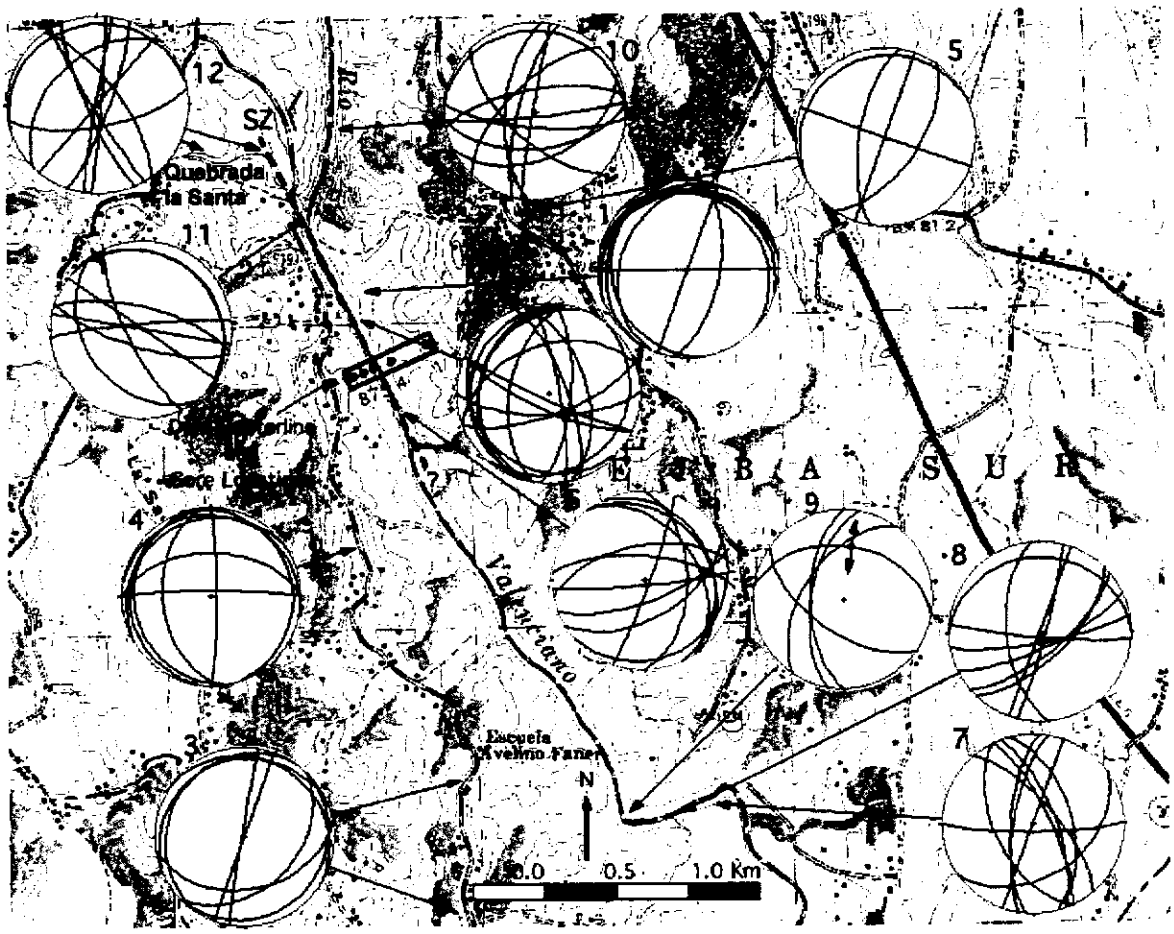
The B&V geotechnical report (Appendix B) is the most detailed of the earlier reports. B&V described subsurface conditions at the Río Valenciano Dam site based on field observations and 6 new exploratory core borings drilled to supplement the 17 core borings previously drilled by BSJ (boring depths for the entire complement of borings ranged from 22 to 110 feet). Their description of the subsurface stratigraphy at the site generally corresponds to the typical subsurface profile found throughout the batholith described above, with the depth to sound rock ranging between 1.5 and 43 feet. The depth to competent rock at the alternate downstream dam site studied by the USACE ranges between about 18 and 26 feet. B&V recommended removing this overburden material in order to found the dam on sound rock.

The other critical geology-related consideration for the Río Valenciano Dam project is rock fracturing, including the possibility of a fault beneath the Valenciano River that passes

under the dam site. Both topics are covered by the B&V geotechnical report (Appendix B) and in the Joyce report prepared for this project, which is included as Appendix E herein. Rock fractures are significant pathways for groundwater movement (i.e., dam seepage), particularly in tight, massive formations like the granodiorite that underlies the dam and reservoir footprints, and are weak surfaces along which otherwise competent rock masses can slide in response to shear stress. The stability of the dam embankment and reservoir slopes will in large measure depend on the abundance and orientation of rock fractures such as joints and faults. A fault in the dam foundation can similarly act as an avenue for seepage, particularly if it contains a wide zone of sheared, broken-up rock. A fault, if present, would also represent a zone of weakness, particularly if the rock is highly weathered, whose foundation support capacity must be evaluated. Furthermore, displacement along the fault could rupture the dam and produce strong ground shaking in the vicinity of the structure.

Both B&V and Joyce recorded a large number of fracture orientation measurements[1], and the USACE document mentions the primary joint orientations observed but does not provide any actual orientation data (see Appendices B, D, and E). For this study, Joyce has undertaken a comprehensive fracture survey, which covered much of the Río Valenciano channel for a distance of about 2.5 kilometers upstream (south) and 700 meters downstream (north) of the dam, several Valenciano tributary drainages, and rock exposures along route PR-919 (west of the river). Figure 7 of his report shows stereographic plots of his joint measurements and is reproduced here as Figure 6. The three investigations concur that high-angle joints with average strikes oriented roughly north-south and east-west are common in the area. It is noteworthy that the north-south orientation coincides with the trend of a roughly 800-meter stretch of Río Valenciano that begins approximately 500 meters north of the dam; the Joyce report (Appendix C) contains photos that clearly illustrate joint control over this section of the river.

[1] The B&V report refers to rock mass discontinuities whereas Joyce uses the terms joints and fractures. The two are complementary: rock mass discontinuities are boundaries or breaks that divide a rock mass into smaller units that typically control the mechanical behavior of the rock mass; common examples are bedding planes, unconformities, joints, and faults. The latter 2 are the most common discontinuities in massive rocks such as granodiorite. Also, both are fractures, the difference being that joints do not exhibit any measurable relative motion between the opposing rock faces and faults do.



Topographic map showing the locations of outcrops where Joyce obtained fracture orientation data with stereographic plots of joint measurements (reproduced from Appendix E).

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Joyce also documents the abundance and characteristics of low-angle joints that formed in response to stress relief (unloading due to erosion of the batholith). These typically dip 10 to 20 degrees northward, an inclination that Joyce attributes to post-Miocene northward tilting of the island. Where exposed, the low angle joints exhibit significant lateral extent on the order of 5 to 15 meters, with some possibly extending across the Río Valenciano valley as inferred from the B&V boring logs (see Appendix E). They also tend to have the largest separation between opposite faces (up to 5 centimeters) and sometimes have a clayey or sandy infilling. Joyce also indicates that they define the upper and lower boundaries of the corestones produced by spheroidal weathering. B&V commented on the abundance of these joints and that they generally dip less than 20 degrees but made no systematic measurements of their orientation.

All three geologic studies recognize secondary or subsidiary joints of variable orientation and steep to moderate dips that may be locally abundant. Joyce describes one of particular relevance to this study. In exposures numbered 11 and 12 located just upstream of the point where the river course changes from north-northwest to north (Figure 6) he observed zones of highly fractured rock, which he termed fracture zones, that included closely-spaced high-angle joints with north-northwest trends. Evidence of shear was observed at both sites, including slickensides suggestive of right-lateral slip with a normal component on one of the north-northwest joints at exposure No. 11. Exposure No. 12 is located at a bend in Quebrada la Santa, a Río Valenciano tributary that enters the main stream north of exposure No. 11. The two shear-fracture zones, a north-northwest trending segment of Quebrada la Santa just downstream of exposure No. 12, and an intermittent drainage that joins the Quebrada from the north are aligned along a north-northwest trend that if projected to the south enters into the similarly oriented segment of Río Valenciano that includes the dam site. Joyce posits that these outcrops are representative of the condition of the rock within the river channel at the dam site, supporting the notion that the north-northwest orientation of the Río Valenciano is fault controlled.

As noted above, the Juncos quadrangle geologic map (Figure 5) does not show any faults within the Río Valenciano valley. It must be considered, however, that this map was published as a preliminary map; it shows few geologic structures, including the Cerro Mula fault which has

been mapped in the Humacao, Gurabo, and Aguas Buenas Quadrangles to the east, north, and northwest, respectively (M'Gonigle, 1978; Seiders, 1971; Pease, 1968) A subsequent USGS map (Cox and Briggs, 1973) shows a west-northwest trending fault (parallel to the GNPRFZ) that follows the Río Humacao valley (the Humacao Fault) and then extends into the Quebrada de los Muertos, a tributary to Río Valenciano, before dying out approximately 1.2 kilometers southeast of the north-northwest trending Valenciano reach. Joyce (Appendix E) speculates the Humacao Fault may continue up the Río Valenciano valley beyond the Quebrada de los Muertos confluence into the north-northwest reach on which the dam site is located (see Figure 2 in Appendix E). This supposition is supported by the alignment of local crustal earthquakes parallel to these features (see Figures 2 and 3 in Appendix E that show earthquakes recorded by the Puerto Rico Seismic Network in the general site area during the period 1995 to early January 2006).

3.2- Fault Geomorphology and Trenching Studies

As discussed in Section 2.0, linear valleys are topographic features that can be intimately related to geologic faults. Faulting can be reflected on the Earth's surface in a myriad other ways. Vertical fault motion produces relief and displaces existing topographic features, lateral (strike-slip) faults offset surface features such as streams, terraces, ridges, or vegetation patterns, and oblique fault motion produces a little of both. Faulting also juxtaposes different rock types allowing differential weathering and erosion to produce different landscapes on opposite sides of the fault. The purpose of the geomorphic component of this study is to detect surface features that could have been produced by recent fault activity, more specifically fault movement that has displaced late Quaternary sediments or soils with the ultimate goal of locating optimum places for trenching to determine the age and displacement characteristics of the faulting.

The neotectonic geomorphology study is being performed by Williams Associates with assistance from M. Tuttle Associates; copy of the Williams Associates report for the first phase of the investigation is included in Appendix F. The first phase of the study has focused on the identification of geomorphic features that could have been produced by Quaternary faulting and

to locate the surface trace of the causative faults. Phase two will consist of the excavation of trenches across the suspected fault traces. The exposed trench walls will be studied in detail to confirm the presence, or absence of the suspect fault, and to collect any organic material that can be used for C^{14} radiometric dating to establish a time history of faulting at the trench site.

The general study area is shown on Figure 7 reproduced from the Williams Associates report. It comprises the GNPRFZ extending from Humacao and Naguabo on the east coast of the island continuing westward through Juncos and Gurabo to the northeast corner of Caguas, an area of approximately 200 square kilometers. The work completed to date includes review of the USGS geologic maps for the Naguabo, Humacao, Juncos, Gurabo, Caguas, and Aguas Buenas topographic quadrangles, review of USGS digital elevation map images of the region, analysis of Google Earth satellite imagery, photointerpretation of aerial photography of the area dating from 1936 and 1937, and the acquisition, processing, and preliminary review of LIDAR[2] imagery. This resulted in the identification of a variety of features such as linear alluvial stream segments, aligned bends in streams, and aligned terrace risers, often near the traces of mapped bedrock faults, all of which could be the consequence of Quaternary faulting. A number of potential fault sites were identified through these activities. These included the area approximately 2 kilometers south of the dam site where the Río Valenciano flows west-southwest between right-angle bends.

The study area was then field checked, focusing on possible fault-related features identified during the analysis of the Google Earth satellite imagery, aerial photographs, and LIDAR data. No conclusive evidence of recent faulting has been found to date; however, three sites that merit more detailed exploration by trenching were identified; these are shown on Figure 7. They are:

1. Caguas-Gurabo Site: located east-southeast of the confluence of the Río Gurabo and Río Loíza, near the mapped trace of the Cerro Mula Fault; geomorphic evidence includes aligned slope breaks and stream deflections.
2. Río Blanco Site: located in the Río Blanco rural community of Naguabo along the mapped trace of the Peña Pobre fault; geomorphic evidence includes stream deflections.

[2] In simple terms, LIDAR ,which stands for Light Detection and Ranging, is a remote sensing technology that uses laser pulses bounced of the Earth's surface to create detailed images of the topography.

Google Earth image that shows the area covered by the Williams Associates fault evaluation. Prominent bedrock faults are colored blue. Prominent lineaments (permissive faults) are denoted by red lines. Possible active fault features selected for continuing investigation are colored pink. Yellow, black, and white rectangles identify detailed planning maps of candidate trench sites, 1936-1937 air photos with suggestive fault features, and areas proposed for further study, respectively, that are shown in the Williams Associates report (Appendix F), from which this image is reproduced.

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SEISMIC HAZARD ANALYSIS

RIO VALENCIANO DAM SITE, JUNCOS, P.R.

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3. Humacao Site: located south of Río Humacao and along the trace of the Humacao Fault; geomorphic features include topographic lineaments in alluvium aligned with a prominent linear valley.

3.3- Paleoliquefaction Study

Saturated loose to medium-dense cohesionless sediment (usually sand) can experience a complete loss of frictional (shear) resistance when subjected to strong ground shaking, a state known as liquefaction. When this occurs, the sediment is capable of flow as a viscous fluid. Unsupported slopes such as river banks and coastal bluffs that are underlain by the liquefied sediment can slide laterally (lateral spreading) and collapse and the slurry of sand-bearing water can be injected into cracks and fissures in the overlying confining soils, at times reaching the ground surface to form sand blows. The injected sand remains as dikes that evidence the past liquefaction. Sand blows and surface deformation produced by collapse and lateral spreading can be preserved on the surface, or buried by younger deposits to record past seismicity in the stratigraphic sequence. Radiocarbon dating of horizons that bound sand blows provides estimates of the timing of past earthquakes. By mapping the areal distribution and size of similar-age sand blows and by evaluating the likelihood of scenario earthquakes to induce liquefaction, it may be possible to infer the source and magnitude of past earthquakes (Tuttle et al., 2001). Once a paleoearthquake chronology is established for a source area, it may be possible to estimate the frequency of large magnitude events.

The paleoliquefaction study that is underway as part of this project includes reconnaissance for and dating of earthquake-induced liquefaction features within the coastal sediments between Humacao and Naguabo and in the alluvial sediments within and marginal to the GNPRFZ (where it crosses the floodplains of the Río Blanco, Río Grande de Loíza, Río Gurabo, Río Humacao, and Río Valenciano), and evaluation of the likelihood of scenario earthquakes to induce liquefaction in these sediments. The scenario earthquakes include maximum magnitude earthquakes that might be produced by local and regional faults. Comparison of observed and predicted liquefaction will be used to constrain estimates of the

sources and magnitudes of paleoearthquakes. The liquefaction study will serve as an independent check on estimates of maximum magnitude earthquakes derived from fault evaluations.

The paleoliquefaction study is being undertaken by M. Tuttle & Associates with assistance from K. Dyer-Williams; copy of the M. Tuttle & Associates liquefaction report for the first phase of the evaluation is included in Appendix G. The first phase has focused on two tasks. First, a review of the 1936 and 1937 aerial photographs and recent Google Earth satellite imagery to identify anomalous soil patterns and other surface features that could be related to liquefaction, and to identify river sections that may present enough exposures of Quaternary deposits to assess the presence or absence of liquefaction features, features that in the words of Tuttle Associates represent "proof positive of strong ground shaking". The review identified some "features resembling sand blows and lateral spreads resulting from earthquake-induced liquefaction ... in close proximity to mapped faults", but no evidence of widespread liquefaction was observed.

The second task consisted of an evaluation of scenario earthquakes for local and regional faults. This involved calculating "worst case" maximum magnitude earthquakes originating at potential seismogenic sources (including faults within the GNPRFZ), compiling data on the stratigraphy and relative density (represented by N-values or blow counts[3]) of the alluvial and coastal sand deposits from existing geotechnical borings logs, and performing liquefaction potential analysis of these data to determine if liquefaction is likely to occur during the scenario earthquakes. M. Tuttle and Associates reviewed the logs for 41 geotechnical borings drilled by the Puerto Rico Highway and Transportation Authority into Quaternary alluvial deposits along the Río Blanco, Río Gurabo, and Río Grande de Loíza. Representative layers were selected for liquefaction potential analysis based on the following "liquefiability" criteria: sandy soils below the water table (i.e., the soil is saturated), within 50 feet of the ground surface, and with N-values (blow counts) less than 30.

[3] The N-value is the number of blows required to drive the last 12 inches of the standard, 18-inch long split-spoon soil sampler during the performance of the Standard Penetration Test (ASTM D-1586). It is an empirical measure of soil density and consistency. The propensity of a sand layer to liquefy depends on its density, making the N-value a convenient parameter to use in liquefaction analyses.

The liquefaction potential analysis was performed using the cyclic stress procedure first developed by Seed and Idriss (1971) and subsequently updated by Youd and Idriss (2001). It entails comparing a set of site conditions representing soil density, as characterized by the N-value, and the seismic loading from the predicted scenario earthquakes with corresponding information from a worldwide data base of soils that have undergone liquefaction, supplemented with data from laboratory liquefaction tests. The analysis was performed for several distant and nearby scenario earthquakes using attenuation models deemed appropriate for the style of faulting at each source (details can be found in Appendix F). The results reveal that widespread liquefaction would occur during ground shaking from a great (M8.25) earthquake on the Muertos Trough or the Puerto Rico Trench, or from a large to very large (M6.8-7.3) earthquake occurring on one of the local faults in the GNPRFZ.

Field reconnaissance will be performed to locate earthquake-induced liquefaction features along selected reaches of Río Blanco, Río Grande de Loíza, Río Gurabo, Río Humacao during phase two of the paleoliquefaction study. Liquefaction features that are found will be document and dated, if possible. Additional scenario earthquakes will be evaluated for comparison with field observations of liquefaction features to constrain estimates of the source and magnitude of paleoearthquakes.

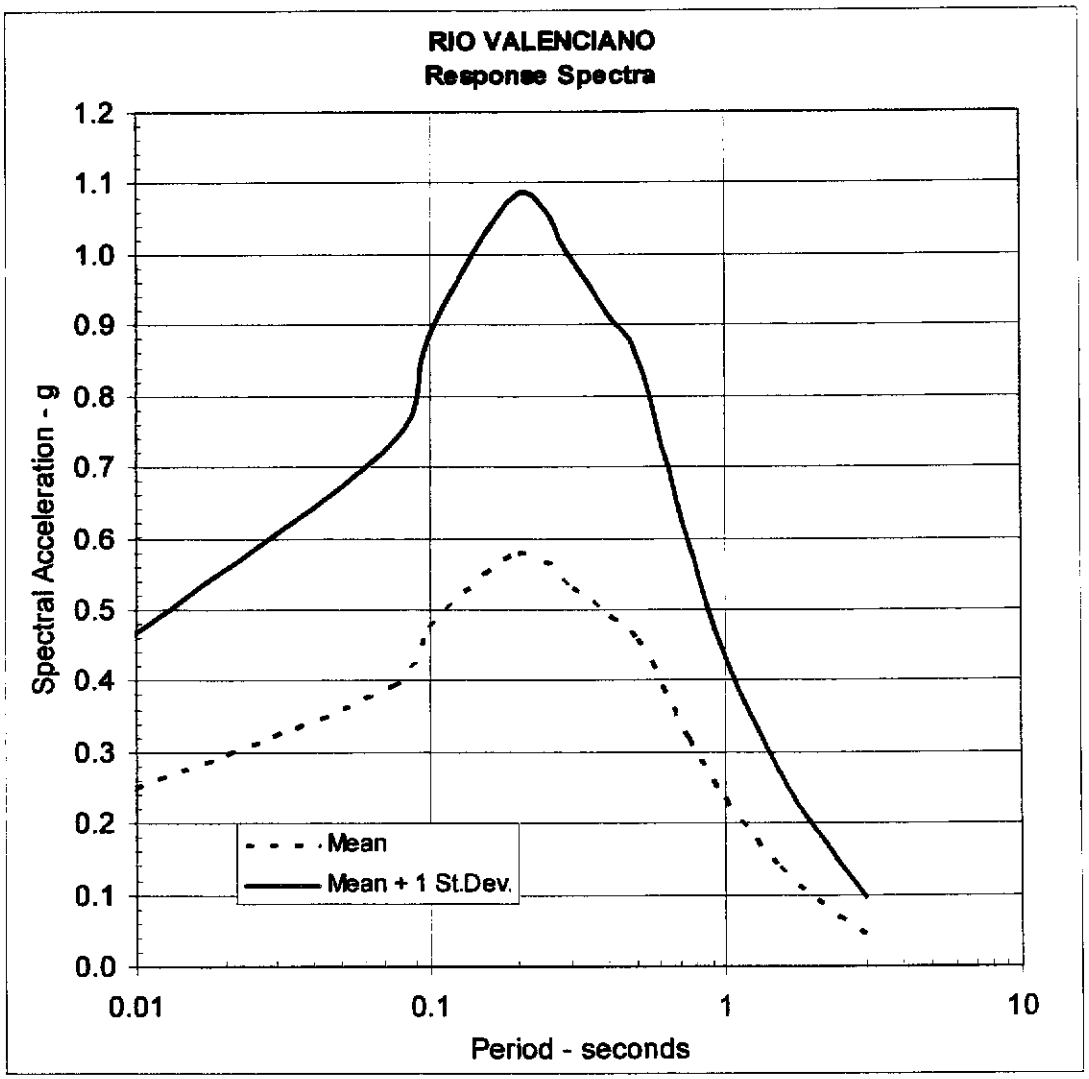
3.4-Preliminary Seismic Design Parameters

Given the possibility that the Río Valenciano Dam, when constructed, could be subjected to earthquake ground shaking, the design of the dam must account for the earthquake forces it will experience. The ultimate goal of the investigations described above is to compile information about the seismotectonic setting of the dam site and the maximum magnitude earthquakes likely to occur on local and regional faults in order to estimate the earthquake ground motion parameters to be used in the design of the dam. Swaisgood Consulting has performed a preliminary determination of seismic design parameters based on our current knowledge of likely earthquake sources; these parameters will be updated and revised as needed once the ongoing investigations are completed. The procedures used in the analysis are

consistent with current guidelines for dam design recommended by the U.S. Army Corps of Engineers, the Federal Energy Regulatory Commission, the U.S. Bureau of Reclamation, and the U.S. Committee On Large Dams.

The Swaisgood Consulting report is included in Appendix H. The analysis considered only distant seismic sources associated with the major offshore fault zones that surround the PR-VI crustal block (Figure 1 in Appendix H); no local seismic sources were evaluated pending results of the fault and paleoliquefaction investigations. The Maximum Credible Earthquake (MCE) expected to originate in each source (the scenario earthquake of M. Tuttle & Associates) was established based on consultation with other members of this investigation team and are in general agreement with the magnitudes used in similar evaluations by others, including the B&V seismic hazard report (Black & Veatch, 2000a [Appendix A]) and seismic hazard assessments for two sites in Ponce, Puerto Rico (Geomatrix, 1988; Golder Associates, 1994, URS Corporation, 2004). The peak ground acceleration (PGA) that each MCE would generate at the site was then calculated using earthquake ground motion attenuation relationships appropriate for each seismic source zone. The maximum PGA calculated corresponds to a **M**8.25 event on the Muertos Trough Fault Zone occurring at a depth of 33 kilometers below the site; this is the Maximum Design Earthquake (MDE). Figure 8 reproduced from the Swaisgood Consulting report shows response spectra for the mean and mean plus one standard deviation (mean+σ) developed for the MDE; the latter represents the highest level of ground motions expected at the site. The mean+σ MDE parameters and response spectrum is recommended to be used for the design analysis. The corresponding PGA value is 0.46g.

A probabilistic seismic hazard analysis was performed to determine the Operating Basis Earthquake (OBE), defined as the largest earthquake that reasonably could be expected to affect the dam during its operating life, assumed to be 100 years. The results are shown on Figure 9 reproduced from the Swaisgood Consulting report. The report recommends a PGA of 0.13g be used as the Valenciano Dam OBE.



Maximum Credible Earthquake response spectra for the Río Valenciano Dam site; reproduced from Swaisgood Consulting report (Appendix H).

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RIO VALENCIANO DAM SITE, JUNCOS, P.R.

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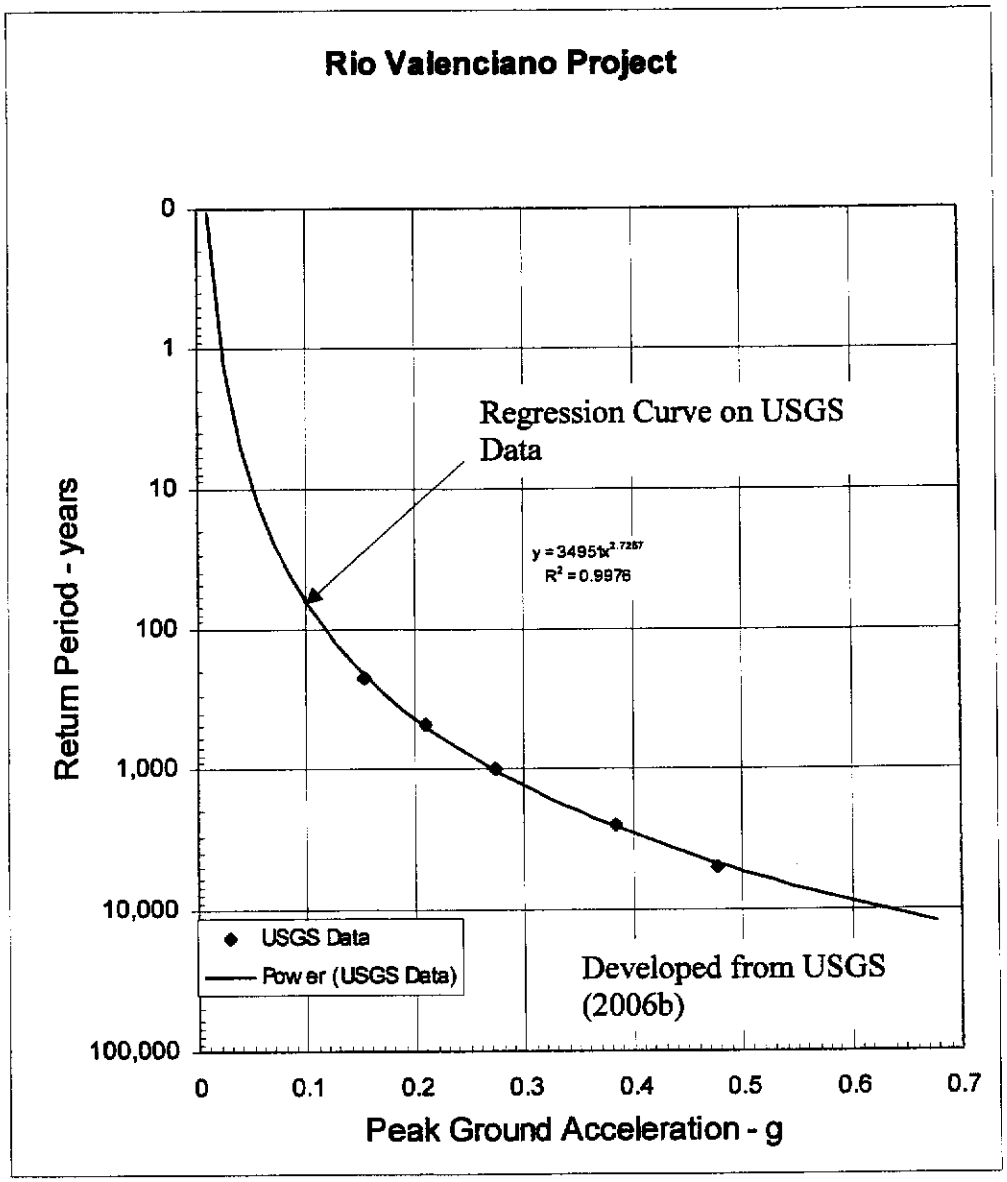

Probabilistic seismic hazard for the Operating Basis Earthquake (OBE); reproduced from the Swaisgood Consulting Report (Appendix H).

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Finally, Swaisgood Consulting calculates a seismic coefficient of 0.27g for pseudostatic analyses of the sliding stability of the dam and potentially unstable rock blocks in the dam foundation and abutments.

4.0 PRELIMINARY CONCLUSIONS

This evaluation of seismic hazard for the Río Valenciano Dam site encompasses studies of the geology and structure, engineering geology, neotectonic geomorphology, and paleoseismicity of the dam site and nearby areas. The project has been characterized by extensive collaboration and exchange of information and ideas between the various specialists involved in the project. Although the various studies have not been completed, some preliminary conclusions are provided below. These may be revised or refined on the basis of the results of the work that is still pending. Direct quotations are made from the consultant's reports where deemed pertinent.

1. The proposed Río Valenciano Dam site is underlain by medium- to coarse grained granodiorite, a massive, competent rock that will provide adequate bearing support for the dam and appurtenant structures. Although scattered rock outcrops occur at the dam site, a weathering residuum mantles the bedrock throughout most of the dam footprint. It consists of residual sandy soil that grades into saprolite and eventually weathered granodiorite. B&V have recommended that the residuum be removed so that the dam structure bears on sound rock, a recommendation we second. Soil borings drilled for previous site studies indicate the thickness of the residuum varies from 1.5 to 43 feet. Joyce (Appendix E) notes that cores of sound rock surrounded by weathered rock and soil produced by spheroidal weathering extend to depths of up to 75 feet, so deeper excavation may be required in places.
2. The granodiorite is broken up by three dominant joint sets that were seen throughout the general area of the dam site. Two are vertical and oriented roughly north-south and east-west. The former appears to control the orientation of the north-south river section that begins approximately 500 meters north of the dam site. The third prominent joint set dips

northward at low angles (10 to 20 degrees). One of the tasks for the second phase of this study will be to assess if joint-bounded blocks of rock are susceptible to slippage along the low angle joints when porewater pressures in the joints increase as the Valenciano Dam Reservoir is filled. There are also secondary or subsidiary joints with variable orientations that are significant locally. These may form unstable rock wedges in the dam excavation slopes and will have to be removed or stabilized as needed.

3. Williams Associates (Appendix F) notes strong joint-control of tributary stream patterns in the Río Valenciano watershed based on inspection of historical aerial photographs and LIDAR imagery. Field observations by Joyce (Appendix E) support this interpretation.
4. Field observations by Joyce (Appendix E) also support the notion that the roughly 2-kilometer long valley segment that includes the dam site is fault controlled. He documented the existence of a shear-fracture zone that "emerges" from the north-northwest trending river channel at the point where the river bends to a northerly course (field site No. 11 in Figure 6); the shear-fracture zone then continues along the north-northwesterly trend within a reach of Quebrada la Santa before disappearing into a similarly-oriented secondary drainage. The trend of the shear-fracture zone is shown on Figure 6.
5. The geomorphic assessment by Williams Associates (Appendix F) found topographic lineaments, deflected streams, and aligned river segments consistent with Late Quaternary faulting but no "unequivocal evidence of activity" on the mapped faults in the GNPRFZ in the area between Naguabo-Humacao and the east margin of Caguas. Many of the suggestive fault features were inspected in the field, and three sites were selected for further study; all three are located on or near faults mapped by the USGS. Two of these sites "exhibit features consistent with activity during the past 35,000 years". These sites will be evaluated by trenching during the next stage of this investigation.
6. M. Tuttle & Associates (Appendix G) began a paleoliquefaction study in the region surrounding the Valenciano dam site. Geotechnical borings previously drilled in the Río Blanco, Río Gurabo, and Río Grande de Loiza alluvial valleys were reviewed and

information regarding loose sandy deposits was tabulated. These data were then used to perform a liquefaction potential analysis to evaluate "worst case" scenario earthquakes for local and regional faults. The analyses indicate that sediment in the alluvial valleys is susceptible to liquefaction and that great (M8.25) earthquakes produced by the Muertos trough, the Puerto Rico Trench subduction zone, and large to very large (M6.8-7.3) earthquakes generated by faults in the GNPRFZ would likely induce widespread liquefaction in the region. A study of aerial photographs found surficial features in a few areas that may be sand blows and lateral spreads that formed in response to earthquake-induced liquefaction. It is, however, possible that liquefaction features were destroyed or damaged beyond recognition during the 100+ years of intensive agricultural activity in the area before the 1936-37 air photos were taken. Therefore, the interpretations of the aerial photographs will be field checked during the second phase of the study. If these interpretations are found to be true, they would suggest that ground shaking during the Quaternary was strong enough "to induce liquefaction in these areas, but not so strong as to produce widespread liquefaction". In other words, the scenario earthquakes used in the liquefaction potential analysis, and also for seismic design, may be too large. The next phase of this project will include field reconnaissance for paleoliquefaction features along selected river reaches and evaluation of smaller magnitude scenario earthquakes; the potential impact of this evaluation for seismic design could be significant.

7. The design of the Río Valenciano Dam requires information about the earthquake ground motions that are likely to occur at the site. Swaisgood Consulting (Appendix H) has determined preliminary seismic design parameters for the Río Valenciano Dam. These were calculated using earthquakes that originate in the known seismic sources of the major fault systems that surround the PR-VI crustal block. Local earthquakes occurring within 10 kilometers of the site will be considered based on the results of the ongoing geologic, neotectonic, and paleoseismology studies. If no recently-active faults or liquefaction evidence of a local earthquake source are identified, the parameters for seismic design will continue to be based on the distant sources. If the paleolifiquecation

analysis fails to find evidence of the widespread liquefaction predicted for scenario earthquakes on the Muertos Trough and Puerto Rico Trench, the design magnitude for these distant source events will be reassessed.

5.0 RECOMMENDATIONS

The evaluations underway will be determinant in establishing the criteria for the seismic design of the Río Valenciano Dam and should be concluded. Key aspects of work yet to be completed include: additional analysis of structural features in the dam site area including outcrops of previously mapped faults in the area, trenching at sites of possible Quaternary faults, and reconnaissance for liquefaction features. In addition, existing information pertinent to the study should be compiled and evaluated by the study team. This includes:

1. The complete copies of the BSJ and USACE site studies: those that were provided were incomplete. Key sections that were missing include maps and boring logs.
2. The USACE core boring samples: the USACE has a warehouse in Ponce where soil and rock core boring samples are stored. It is likely that the samples collected during the alternate Valenciano Dam site exploration are still there.
3. Joyce obtained data about seismic events in east-central Puerto Rico during the period 1995 to early January 2006 (Figure 3 in Appendix E) from the Puerto Rico Seismic Network. Seismicity in the area during this period was relatively sparse but five of the events occurred within several kilometers of the north-northwest trending Río Valenciano reach or the Humacao Fault to the southeast (Figure 2 in Appendix E). Joyce recommends expanded "monitoring and definition of the crustal seismic activity" in the area.
4. Joyce further recommends the acquisition of GPS data currently being collected at continuous stations in Fajardo, Humacao, and Rio Piedras by stateside research organizations. The GPS data will improve our understanding of crustal deformation within the study area.

We also recommend drilling three angled core borings along the Río Valenciano channel margins and two vertical core borings within the channel itself to evaluate the condition of the foundation rock below the channel and verify the presence of the suspected shear-fracture zone at this location.

Swaisgood Consulting calculated preliminary design parameters for the Río Valenciano Dam. These are contained in Figures 8 and 9 reproduced from the Swaisgood Consulting report. The MDE corresponds to a **M**8.25 earthquake on the Muertos Trough Fault Zone at a depth of 33 kilometers below the site producing a PGA of 0.46g at the dam site. The PGA for the OBE is 0.13g. Finally, a seismic coefficient of 0.27g is recommended for the analysis of dam and rock wedge sliding stability.

Finally, we observed considerable volumes of sand in transport along the river bed, where downstream migration of sand ripples can be seen even during low flow periods. Sediment transport within the river should be evaluated so that measures to prevent rapid sediment infilling of the reservoir become part of project design.

6.0 CLOSURE

This report was prepared for CSA Group (CSA) for use in its evaluation of the proposed Río Valenciano Dam in Juncos, Puerto Rico. It describes several interrelated studies undertaken for the assessment of seismic hazards at the dam site that when completed will provide the basis for the determination of final seismic parameters for the design of the structure. Although the goal of the investigations is site-specific, the results will be applicable to the entire east-central portion of the island, and will help constrain estimates of the magnitude of seismic events that originate in the major fault zones most critical to the coastal areas to the north, including the San Juan metropolitan area.

The undersigned acknowledges the contribution of Dr. Joyce who provided valuable suggestions and editorial support for the report. Drs. Tuttle and Williams kindly reviewed the draft report providing useful additional suggestions and editorial comment.

Respectfully submitted,

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Associate

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APPENDIX A

SEISMIC HAZARD STUDY REPORT
RIO VALENCIANO RESERVOIR – BLACK AND VEATCH

Seismic Hazard Study
Rio Valenciano Reservoir

Black & Veatch Puerto Rico
June 30, 2000

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

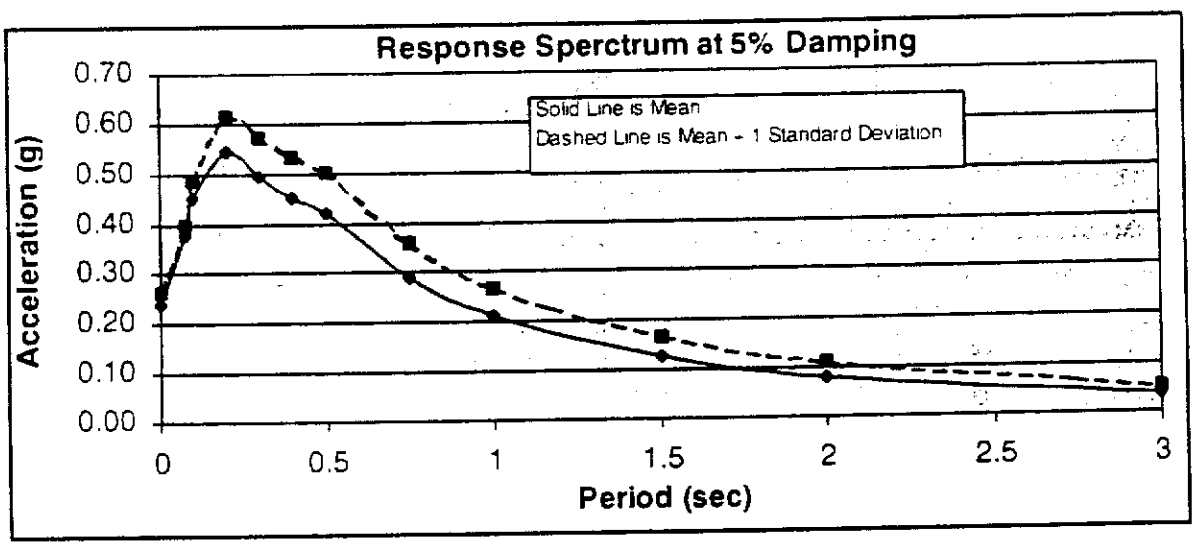
The MCE's calculated in this study are either greater than or equal to earthquake magnitudes in the historic catalog and those generated by others working in Puerto Rico. To be conservative in estimating ground motion accelerations, the values from the DSHA will be used for the maximum design earthquake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

Fault	Magnitude (M)	Peak Ground Acceleration (PGA) (g)	
		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 [illegible] the Ri[illegible]	[illegible]	[illegible]
McCann and Associates	1994	0.13	PGA	475
		0.15	PGA	950
		0.20	PGA	2475
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
LaForge and Hawkins	1999	0.36	PGA	5,000
		0.42	PGA	10,000
		0.50	PGA	25,000
		0.29	PGA	2475
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
NEHRP – FEMA	1997	0.32*	PGA	2475
		0.80*	0.2	2475
		0.32*	1.0	2475
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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

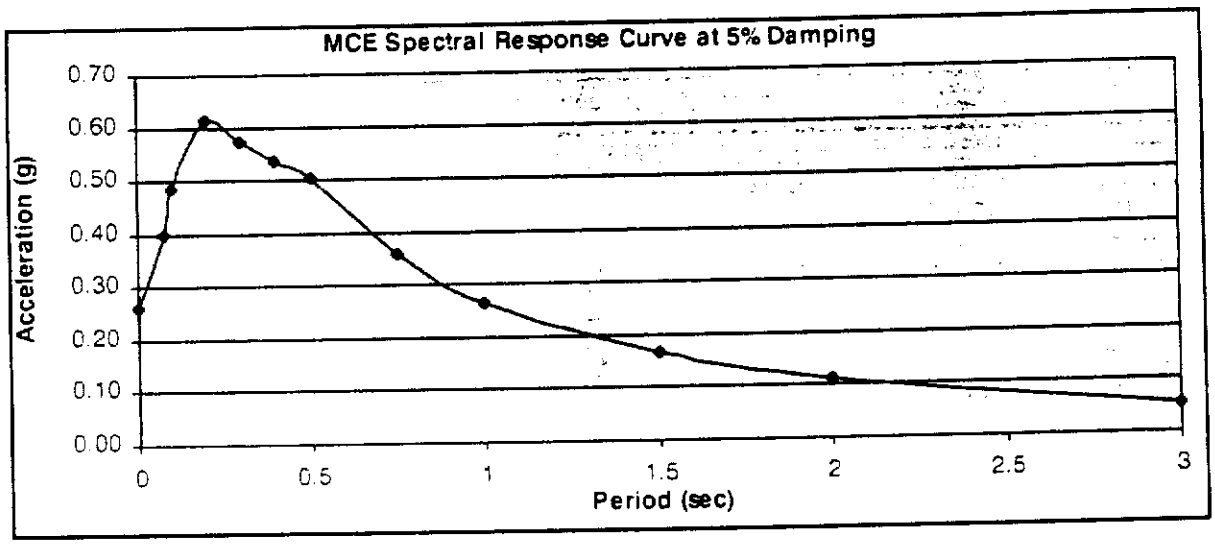
It is recommended that the seismic design analysis for the Rio Valenciano dam follow the format put forth by the Corps of Engineers in EM 1110-2-6050. The Corps recommends that the MCE be established using a deterministic seismic hazard analysis, and that a site-specific response spectrum should be estimated 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 (84th 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



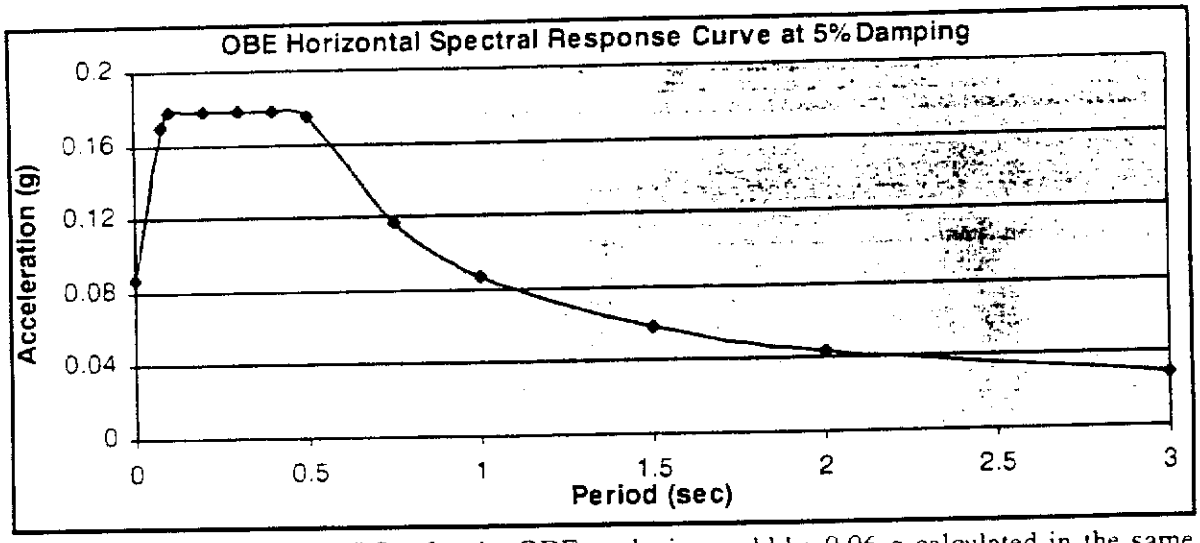
There is generally a strong vertical component of ground motion associated with thrust faults. This component must be addressed in the design analysis of the Rio Valenciano dam. To date, no direct method of calculating vertical accelerations has been developed. Instead, ratios of vertical to horizontal 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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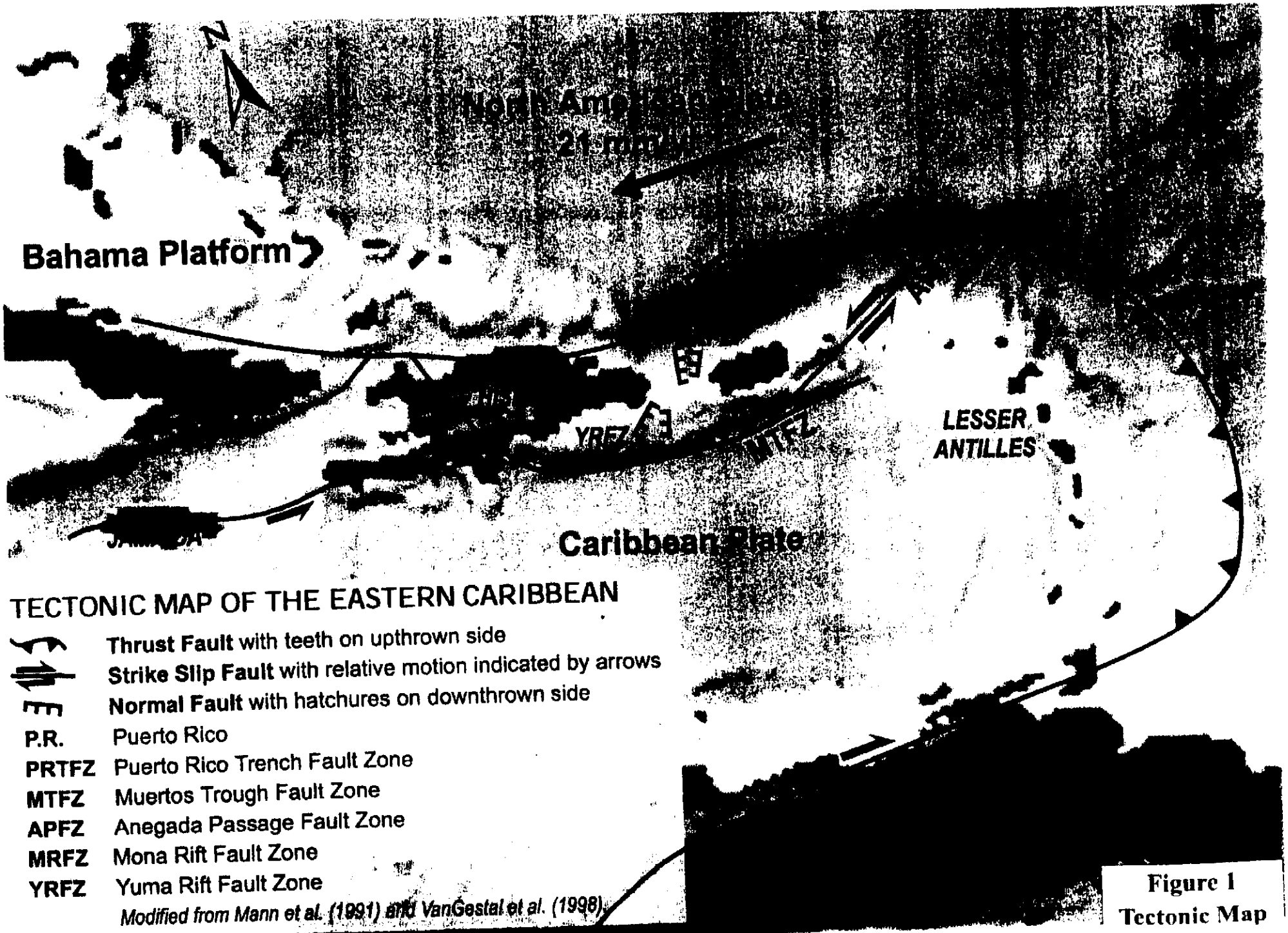
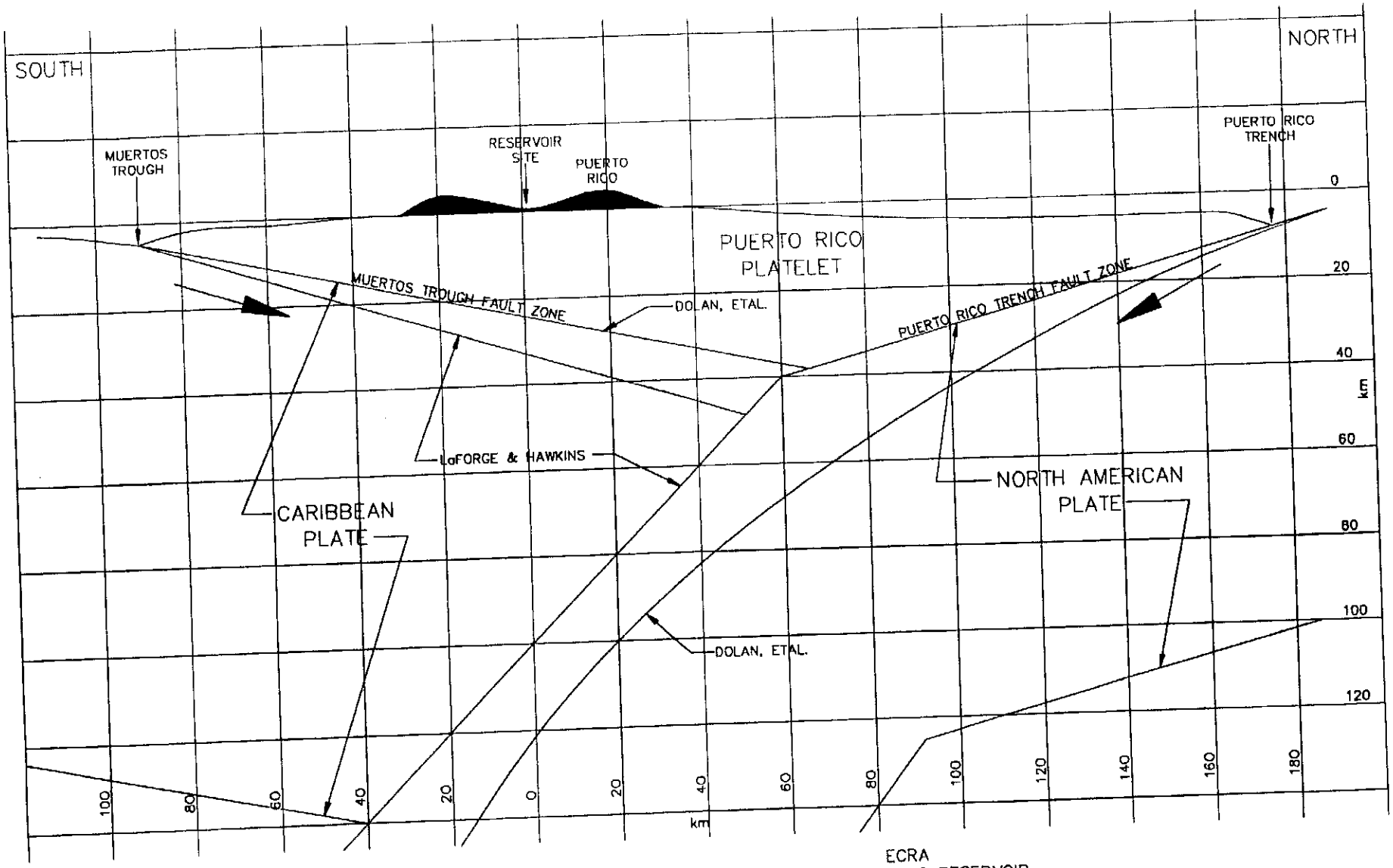


Figure 1
Tectonic Map



ECRA
RIO VALENCIANO RESERVOIR

FIGURE 3
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CROSS-SECTION SHOWING THE RELATIONSHIP OF THE PUERTO RICO TRENCH FAULT ZONE AND THE MUERTOS TROUGH FAULT ZONE TO THE ISLAND OF PUERTO RICO

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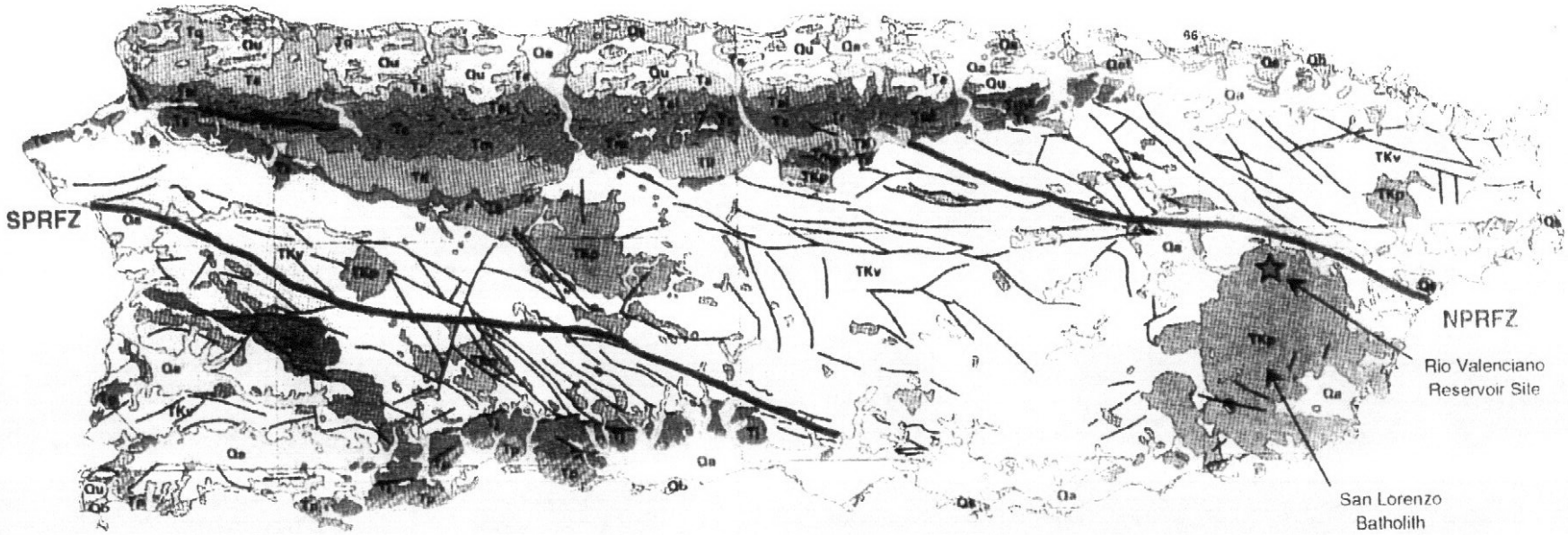


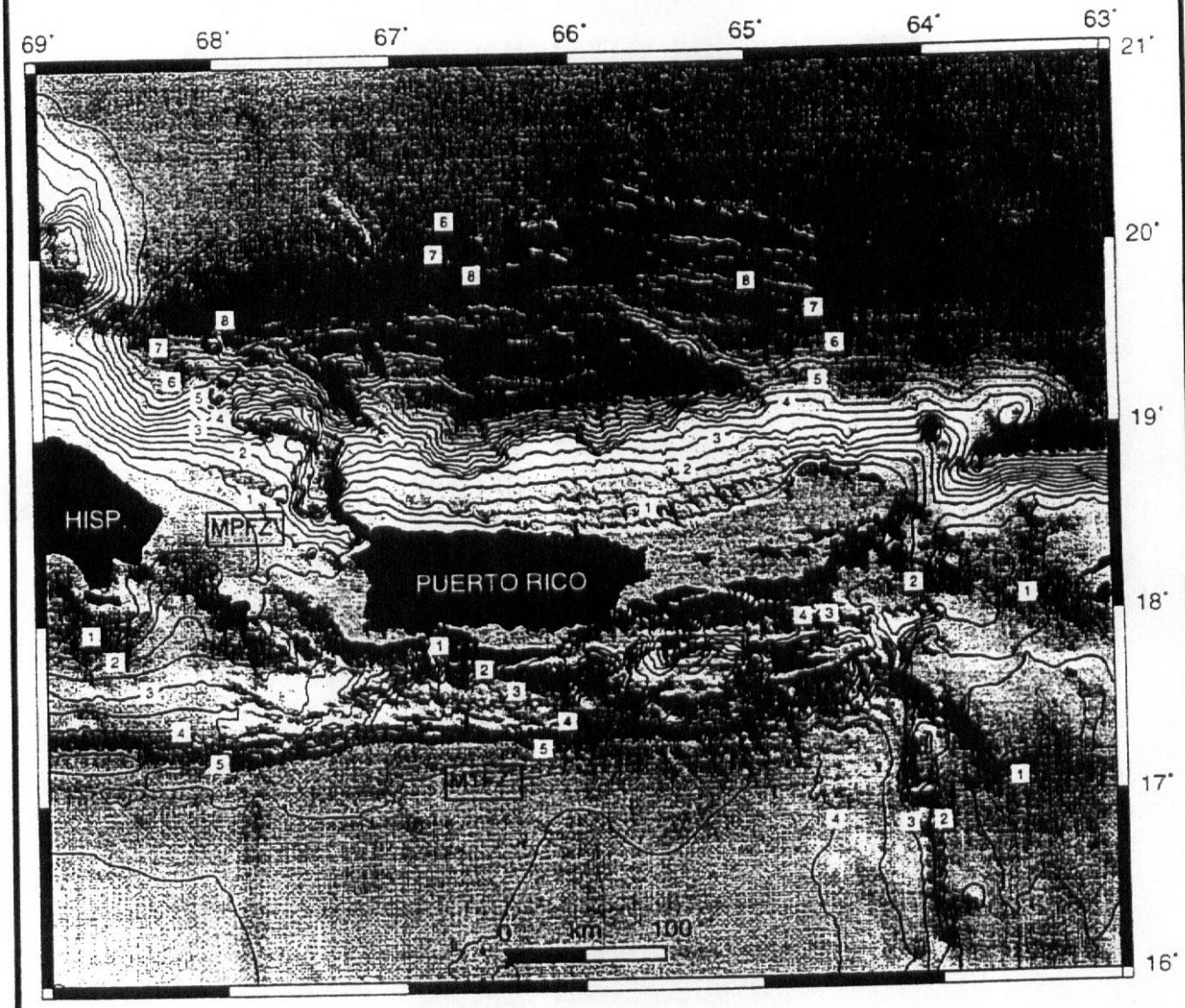
EXPLANATION

Qa	Alluvium
Ql	Landslide deposits
Qb	Beach deposits
Qs	Swamp and marsh deposits
Qal	Artificial fill
Qu	Undifferentiated surficial deposits
	Pliocene and Miocene rocks
Tq	Quebradillas Limestone
Tp	Ponce Limestone
Ta	Aymamon Limestone
Tal	Aguada (Los Puertos) Limestone
Tir	Guanajibo Formation
Tc	Cibao Formation
Tm	Montebello Limestone Member
Tqa	Quebrada Arenas Limestone Member—Includes Miranda Sand Member
Tr	Rio Indio Limestone Member—Includes Almirante Sur Lentil
Tep	Guajataca Member
Tms	Mucarabones Sand
Tj	Juana Diaz Formation
Tll	Lares Formation
Ts	San Sebastian Formation
	Eocene, Paleocene, and Cretaceous rocks
TKv	Volcanic and sedimentary rocks
TKp	Plutonic rocks—Mostly quartz diorite and granodiorite
TKm	Metamorphic (serpentinite), sedimentary, and igneous rocks
	Fault
	Major Fault Zone
NPRFZ	Northern Puerto Rico Fault Zone
SPRFZ	Southern Puerto Rico Fault Zone

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

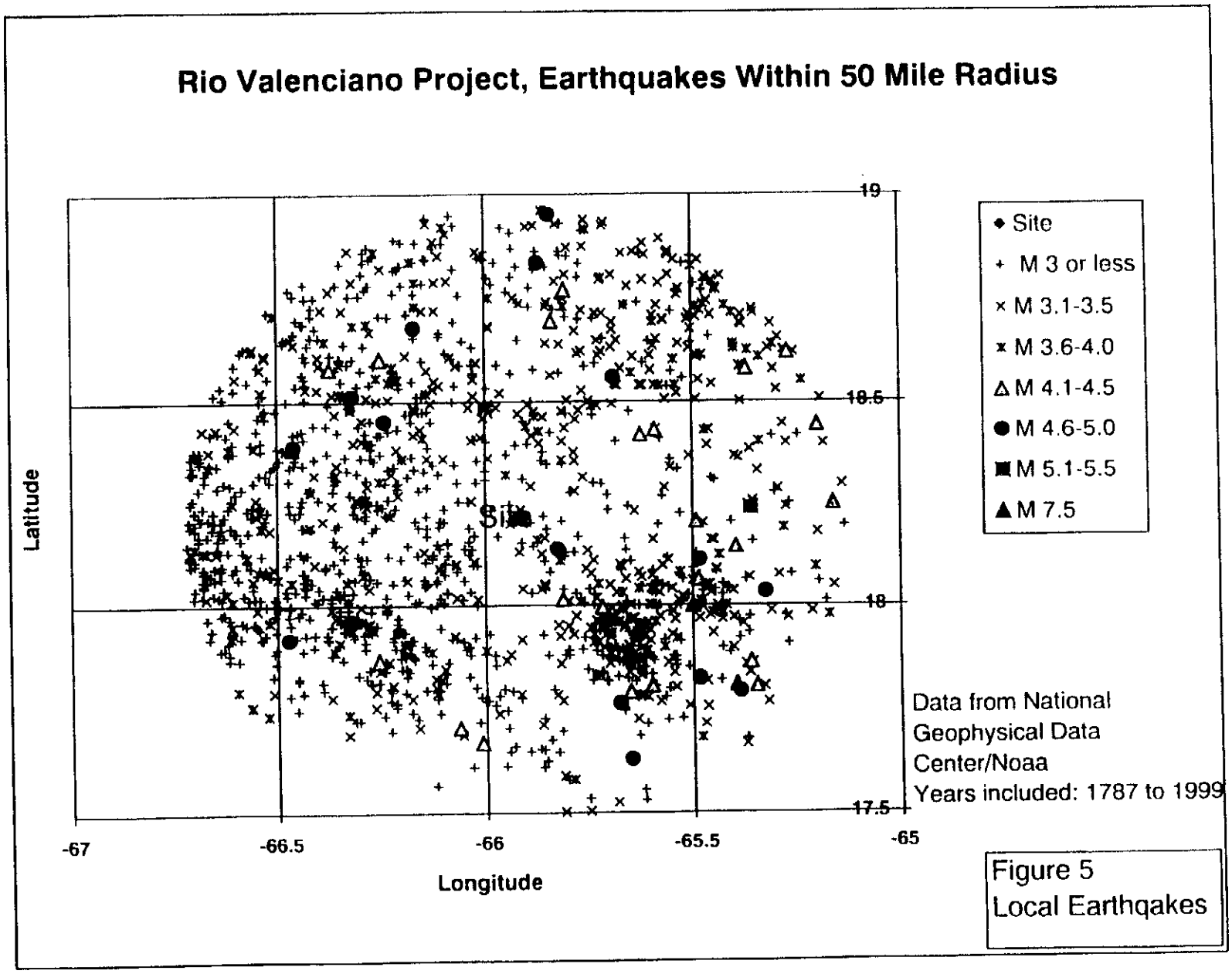


Figure 5
Local Earthqakes

APPENDIX B

RIO VALENCIANO RESERVOIR GEOTECHNICAL REPORT
BLACK AND VEATCH

Rio Valenciano Reservoir Geotechnical Report

Black & Veatch Puerto Rico
June 30, 2000

Rio Valenciano Reservoir
Geotechnical Report

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Appendices

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Appendix B Hydraulic Conductivity Tests

Appendix C Seismic Refraction Surveys

Appendix D Test Pits

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1.0 GENERAL

1.1 Project Description

The Rio Valenciano Dam will be a 30-meter high dam that will close the valley of the generally north flowing Rio Valenciano at a point about 2.2 kilometers south of Juncos, PR. The reservoir has a tributary area of 38.8 square kilometers and will supply an average of 14.4 million gallons of water per day (MGD) for treatment and distribution to municipalities in east central region of Puerto Rico.

1.2 Purpose of Investigation

This geotechnical investigation was undertaken to provide basic site data for the preparation of the RFP documents for the Design-Build contract. The investigations provide geologic and geotechnical data on the foundation conditions at the proposed dam site. This data was used in the selection of the roller-compacted concrete gravity dam alternative presented in the bid documents, and to assess the seepage potential through the foundation.

The results of the investigation presented in this report are intended to be used by the Design-Build contractor to assist in bid preparation and final design. However, the type of dam to be built is not finalized, and application of the data to other dam-type alternatives can be made as appropriate. The extent of available material resources for dam construction was not investigated and is considered a responsibility of the Design-Build contractor.

1.3 Scope of the Report

The scope of this report is to:

- Present the results of the geotechnical investigation undertaken during February and March 2000,
- Discuss the engineering considerations resulting from the geotechnical investigation,
- Evaluate the likelihood of reservoir induced seismicity, and
- Evaluate the stability of the reservoir rim.

1.4 Sources of Data

Sources of data for this report included the present geotechnical investigation, which encompassed the following:

- Geologic mapping
- Air photo interpretation
- Soil and rock borings
- Field hydraulic conductivity tests
- Test pits
- Seismic refraction surveys
- Laboratory testing of soil and rock samples

In addition, relevant data was available from the Buck, Seifert and Jost investigation in 1978 along the same dam alignment as this investigation, and the Corps of Engineers investigation in 1974 where the dam alignment was 800 m downstream from the present location.

2.0 GEOLOGY OF THE RESERVOIR AREA

The Rio Valencio reservoir site lies on the northern edge of the San Lorenzo batholith (Figure 1). This granitic rock was intruded into volcanic rocks during upper Mastrichtian or lower Paleocene time. Just north of the batholith is one of two major faults crossing Puerto Rico, the northern Puerto Rico fault zone (NPRFZ) (Figures 1 and 2). This fault is only 1 to 2 km north of the dam location. The NPRFZ trends east-southeast, has left lateral strike-slip motion, and can be traced for about 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 (1998), based on the compositions of volcanic rocks, to have occurred about 85 million years ago (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. Major movement according to Jolly (1998) would have preceded emplacement of the San Lorenzo batholith, but minor movements would have postdated it.

A fault has been postulated to cross the reservoir that would appear to be related to the NPRFZ (Figure 2). Evidence for this fault includes:

- The straight and narrow river valley segment that includes the dam location and extends for over 2 km.
- Shear zone 13.5 wide with fault gouge observed in a Corps of Engineers core boring located about 500 m downstream of the proposed dam axis.
- A sheared and/or hydrothermally altered dike in the streambed about 100 m north of the proposed dam location and trending parallel to the river.
- A suspected sheared and/or hydrothermally altered dike in boring BSJ-13 near the river on the proposed dam axis.
- A thin dike observed in boring BV-5 adjacent to the river on the dam axis.

This postulated fault most likely strikes along the course of the river to the south where it would appear to merge with a fault mapped by others parallel to the NPRFZ. To the north, there is topographic evidence from maps and air photos that this fault continues up to the broad valley north of Juncos that is the location of the NPRFZ. The orientation of this fault matches almost exactly the orientation of theoretical reverse faults forming in an area between two right-stepping, left lateral strike-slip faults such as the NPRFZ and the parallel fault mapped to the south. The entire NPRFZ system has been inactive for at least 55 million years, and therefore poses no threat as a seismic source.

The other significant fault zone on the island is the southern Puerto Rico fault zone (SPRFZ) (Figure 1). This fault has been studied in detail by Erikson et al. (1990). They were able to

conclude that the age of significant deformation along the SPRFZ is constrained to middle Eocene to early Oligocene (35 Ma). This is also clearly an inactive fault.

3.0 EXPLORATION PROGRAM

3.1 General

Field exploration and laboratory testing for the Rio Valenciano Reservoir included:

- Geologic mapping and air photo interpretation
- Soil and rock borings
- Hydraulic conductivity tests in boreholes
- Groundwater level monitoring
- Seismic refraction surveys
- Test pits
- Laboratory testing

A summary of the scope of each of these investigations is discussed in the following sections.

3.2 Geologic Mapping

Geologic mapping was undertaken to document rock types, identify lithologic contacts, obtain joint orientations, identify shear and fault zones, observe surface weathering, and evaluate geologic hazards. Mapping included the integration of previous work in the area, field checking of previous mapping efforts, and evaluation of aerial photography. The geologic map is presented in Figure 2, and a stereonet of joint orientations is shown on Figure 5.

3.3 Soil and Core Borings

Six soil and core borings were completed during this investigation (BV-1, BV-2, BV-4, BV-5, BV-7, and BV-8). Borings BV-3 and BV-6 were deleted from the original investigation plan due to schedule constraints. The borings were advanced with a hollow stem auger and sampled with a split spoon until reaching refusal. Beyond this, the borings were advanced with an NX-size double tube coring system. These borings are in addition to 17 borings drilled during the Buck, Seifert and Jost investigation in 1978. Boring logs from this investigation along with a description of the procedures used for drilling and sampling are presented in Appendix A. Boring locations are shown on Figure 3.

3.4 Hydraulic Conductivity Tests

Packer tests were conducted on the five borings drilled along the dam alignment to evaluate *in-situ* hydraulic conductivity of the bedrock. Packer tests were performed generally in intervals 11 feet long, and successive tests were overlapped by 1 foot. The boreholes were tested from the bottom of the hole to the top of competent rock.

Five-stage pressure tests were typically performed in each interval. The stages were generally as follows:

0.5	P_{BL}	
0.75	P_{BL}	
1.0	P_{BL}	
0.75	P_{BL}	
0.5	P_{BL}	where P_{BL} = baseline pressure (generally 1 psi per foot of depth)

As can be seen, the first three stages were conducted at increasingly higher pressures, and the fourth and fifth stages at the same pressure as the second and first stages, respectively. The five-stage test allowed interpretation of fracture changes during testing such as dilation, washout, and fracture filling. Test pressures were controlled to produce data most representative of intrinsic bedrock permeability and did not exceed a pressure factor of 1 psi per foot of hole measured from the ground surface to the center of the test interval, except in boreholes BV-4 and BV-5. Boreholes BV-4 and BV-5, located on the valley floor, were tested at pressures commensurate with the planned reservoir head to evaluate the potential for hydraulic jacking of the rock mass discontinuities. Packer tests were typically run for 5 minutes at each pressure step.

Water take and pressure data were used to calculate hydraulic conductivity values in centimeters per second and lugeon values for each test. Test procedures and results are included in Appendix B, and representative lugeon values from each test are presented in tabular form in Section 5.0 of this report.

3.5 Groundwater Level Monitoring

Groundwater levels were measured once during this investigation. This occurred just prior to packer testing of the borings. All borings had a minimum of two weeks to equilibrate between the cessation of drilling activities and the start of packer testing. Three of the borings (BV-1, BV-5, and BV-8) were completed as monitoring wells for future observation. Well completion logs are included in Appendix A. Water levels are shown on the dam axis cross-section in Figure 4.

3.6 Seismic Refraction Surveys

Seven seismic refraction surveys were conducted in the dam footprint area in order to estimate the depth of weathering and the seismic velocities of bedrock materials (Figure 3). Refraction lines SR-1, 2, 5, 6, 7 and 8 were essentially perpendicular to the river channel with SR-5 and 6 nearest to the dam centerline, SR-1 and 2 upstream of the dam centerline, and SR-6 and 7 downstream of the dam centerline on the right bank and left banks respectively. Line SR-3 paralleled the river on the right bank. An eighth seismic line, SR-4, intended to parallel the river on the left bank was not completed because of the highly irregular topography.

For each survey, a 140 pound hammer dropped 8 feet from a drilling tripod to a metal plate provided the seismic impulse, and the wave arrival times were recorded using a 24-channel StrataView S-24 exploration seismograph. A 10-foot geophone spacing with the shot points located about 5-feet from the end geophones in each line provided total survey line lengths of

230-feet. The time/distance data, data plots and interpretations for the completed lines are contained in Appendix C.

The data obtained from the seismic refraction lines is of limited use. Due to equipment problems Channel 12 was not recorded in several of the survey line seismograms, the geophones nearest several shot points did not detect the wave arrivals, and arrival data could only be resolved in one direction for lines SR-6 and 8. The seismic refraction method works best to resolve distinct subsurface interfaces between layers of contrasting seismic velocity. Granitic rocks such as the granodiorite underlying the dam site typically do not weather to produce distinct contrasting layers. Weathering penetrates along joints and fracture zones to produce weathered seams separating rounded but intact rock corestones with the average seismic velocity of the mass generally increasing gradually with depth. The sloping irregular topography of the dam site further complicates interpretation of the seismic refraction data.

What is highlighted by the seismic refraction surveys is the irregularity of the subsurface materials. The time/distance plots tend to be wavy and rounded without distinct breaks in slope. The data interpretations obtained from a computer software package show irregular interfaces. Several of these interpretations are clearly questionable, suggesting that the subsurface conditions are too complex to be fitted to simple models. The seismic refraction survey results generally confirm the subsurface conditions indicated by both the earlier Buck, Seifert and Jost borings and the present drilling program that the weathering profile beneath the dam site is irregular. Significant relief can be expected on the excavated foundation surface.

3.7 Test Pits

Five test pits were excavated to obtain bulk samples of the soils overlying bedrock at the site. The pits ranged from 3 to 6 feet deep and were backfilled after completion. All the pits extended down into extremely weathered and saprolitic bedrock.

The pits were excavated with a small backhoe mounted on a Caterpillar rubber tired tractor. A bench cut at about half the total depth in the deeper pits allowed examination and sketching of the side walls. Samples of the various materials encountered were stockpiled during excavation and later put into plastic buckets for delivery to the laboratory for testing. Test pit logs are presented in Appendix D, and locations are shown on Figure 3.

3.8 Laboratory Testing

Selected soil samples from drilling and test pits, and rock core samples were tested to evaluate engineering properties. This testing included:

- Sieve and hydrometer tests
- Density tests
- Moisture content
- Atterberg limits
- Standard Procter tests
- Unconfined compression tests on rock

Results of these tests are presented in Appendix E.

4.0 GEOLOGIC CHARACTERIZATION

4.1 Lithology

4.1.1 Granodiorite

The dam foundation area and the entire reservoir inundation area are underlain by the San Lorenzo batholith (Figure 2). The roughly circular surface exposure area of this intrusive body is about 17 miles in diameter (Figure 1). The age and boundary conditions of the batholith are discussed in Section 2.0 of this report.

Based on surface exposures and core from borings, the batholith is predominantly composed of granodiorite. The typical slightly weathered to fresh granodiorite is medium- to coarse-grained, gray, strong, and very hard. The major mineral constituents in order of abundance are feldspar, quartz, and hornblende. In core there appears to be some areas where the rock grades from granodiorite into granite due to an increase in the percentage of potassium feldspar at the expense of plagioclase feldspar, but there are no associated changes in the engineering characteristics of the rock. The rock is massive with no oriented fabric. A characteristic of the rock is the abundance of mafic inclusions. These inclusions are generally well-rounded bodies ranging in size from 0.25 to 3 feet in diameter, and composed of fine-grained feldspar and hornblende. They are thought to be an early crystallization product of the magma.

4.1.2 Dikes

Two different types of dikes were encountered in the exploration program. One was observed in boring BV-7 as a dark gray to black, aphanitic intrusive with black phenocrysts (pyroxene?). The total length in core was 2.2 feet, and the two contacts with the granodiorite were not parallel. Although float of similar material was observed in several areas, this type of dike was never observed in outcrop during field mapping.

The other dike was observed in outcrop just downstream of the diversion dike for the existing water treatment plant intake. This dike is granitic in composition, and could not be distinguished from the surrounding granodiorite except by the finer grain size. It was also characterized by banding caused by shearing and/or hydrothermal alteration. The dike appeared to be oriented parallel to the river, and dipping near vertical. In boring BSJ-13 a 45-foot interval of "metamorphic granitic rock" was encountered that is thought to be equivalent to this dike. The banding was probably mistaken for a planar metamorphic fabric.

4.2 Weathering Characteristics

The weathering profile observed in field exposures, cores, and test pits consistently shows a surface layer of topsoil, a clayey sand layer, a variable thickness of saprolite, and little to no intermediately weathered rock before reaching the top of sound rock. The borings drilled by

Buck, Seifert and Jost (BSJ) are in general agreement with the B&V borings, however, there are some inconsistencies in terminology and possible misidentification of materials in the saprolite and soil sections of the BSJ boring logs.

The soil section of the weathering profile is best described in the test pits, because the boring locations were all prepared by a dozer. All five test pits contained 0.5 to 1.0 feet of organic rich topsoil at the top. Below this was a layer of clayey sand to sandy clay that ranged in thickness from 0.6 to 3.0 feet, except in BVTP-4, where it was absent. The saprolite below the soil is extremely weathered and friable granodiorite with the parent rock texture still intact (for an explanation of rock weathering terms see Appendix A). The saprolite layer observed in the B&V borings ranged in thickness from 0 feet in BV-2 to 33.3 feet in BV-4. A similar range in thickness was observed in the BSJ borings. The transition from saprolite to sound rock or slightly weathered rock is very abrupt. The intervening layer of moderately weathered rock was never more than 5 feet thick in any of the 23 borings drilled. The depth from the surface to sound rock for all 23 borings ranged from 1.5 to 43 feet, and averaged 18.2 feet.

Another characteristic of weathering in the granodiorite is the formation of core stones. Core stones are relatively unweathered rock surrounded by weathered seams developed along fractures that, after exposure to the effects of erosion, will form boulders on the surface. Core stones could be observed in place in several areas around the reservoir site (Figure 6), and the residual boulders are ubiquitous throughout the area. The top of sound rock that was determined in boreholes, and shown on the sections in Figure 4, is most likely the top of core stones. Evidence of this could be seen in cores as intervals of highly weathered rock with core loss underlying the upper interval of slightly weathered rock. For instance, in boring BV-1 the top of slightly weathered rock was encountered at 13.9 feet, but weathered rock and no recovery zones at 25.6-28.5 feet and 33.2-33.9 feet probably define the boundaries of core stones. This type of weathering will produce a hummocky excavated surface with highs on the top of corestones and deeper excavation into the weathered seams separating them.

Seismic refraction surveys were performed to help determine the depth to the top of sound rock between boreholes. This data was determined to be an unreliable predictor of this interface for reasons discussed in Section 3.6 of this report.

4.3 Rock Strength

Unconfined compressive tests were run on rock core to determine the strength of the rock. A total of 31 tests were run. Results of these tests are tabulated in Appendix E. Most samples were taken from the 10 feet just below the top of sound rock. The upper sample in each boring was the first piece of core greater than 4 in long below the top of sound rock. The average strength of the 31 tests was 18,353 psi, and the range was from 2,811 to 27,241 psi. The low value was from a piece of core with a partially healed fracture with iron oxide coating the joint surfaces. The next lowest value was 8,531 psi.

4.4 Rock Mass Discontinuities

Rock mass discontinuity data was collected from surface outcrops around the dam location. All data was taken from the San Lorenzo granodiorite. Figure 5 presents the orientation data collected during field mapping. Four primary joint sets are recognized from this data set:

Joint Set	Strike	Dip
1	N14E	84 SE
2	N8W	90
3	N80E	80 NW
4	N56W	85 SW

A low angle joint set was also observed in the field with dips less than 20°. This joint set is not represented on Figure 5 because strike orientations are difficult to accurately determine on surfaces dipping this shallowly. Joint sets 1 and 2, with a difference in average strike orientation of only 22°, may represent a single joint set. If these joints do represent a single joint set, then the average strike would be very close to north-south. These joints, oriented close to perpendicular to the axis of the dam, offer the most direct route for seepage. Grout holes should be oriented to maximize intersections with these joints.

Since most of the joint sets are steeply dipping, joint spacing must be estimated from surface exposures with near horizontal surfaces rather than core. Outcrops were generally characterized by one joint set being dominant with joint spacing on this set generally 1 to 3 ft. Subsidiary joint sets had spacing in the 5 to 10 ft range.

A characteristic seen in all the cores was the presence of quartz and calcite filled discontinuities. These features were healed and tight. These were common in slightly weathered to fresh cores, and were generally 0.1 to 0.2 in wide. Comprehensive water quality sampling and testing was conducted by Black & Veatch from 12/8/99 to 12/31/99, and from 1/13/00 to 1/20/00 on raw water from the Rio Valenciano. The pH of water from these two time periods ranged from 7.70 to 8.08 and 7.76 to 8.38, respectively. Regular daily alkalinity testing of raw Rio Valenciano river water taken for the operation of the Ceiba Sur Filtration Plant from October 1998 through October 1999 had only three tests with a pH under 7.0. USGS data on the Rio Valenciano collected during the period 3/9/71 to 9/10/85 had an average pH of 7.39, a range of 6.2 to 8.3, and a standard deviation of 0.53. This data, taken together, indicates that dissolution of calcite in joints is very unlikely to occur.

Open joints observed in core had slightly rough surfaces coated with iron oxide, and were planar. Most joints, observed in outcrop and core, appeared very narrow (<0.1 in).

5.0 HYDRAULIC CONDUCTIVITY

A total of 15 packer tests were conducted in the five borings along the dam axis. All tests were below the top of slightly weathered rock. Water takes ranged from 0 to 84 lugeons, representing hydraulic conductivity values from 0 to 8.4 x 10^{-4} cm/s. Results of these tests are as follows:

Boring No.	Test Interval (depth in ft)	Hydraulic Conductivity (cm/s)	Lugeons	Test Interval Measured From Top of Sound Rock (ft)
BV-1	17 - 28	3.0 x 10^{-4}	30.4	3.1 – 14.1
	26 - 37	2.3 x 10^{-5}	2.4	12.1 – 23.1
BV-4	43 - 54	2.4 x 10^{-5}	2.4	0 – 11
	53 - 65	0	0.0	10 – 22
BV-5	22 - 33	4.8 x 10^{-4}	48.1	3 – 14
	32 - 43	4.2 x 10^{-5}	4.2	13 – 24
	42 - 53	1.9 x 10^{-4}	19.5	23 – 34
	52 - 63	2.7 x 10^{-4}	27.1	33 – 44
	62 - 74	4.6 x 10^{-5}	4.5	43 – 55
BV-7	30 - 40	2.2 x 10^{-4}	19.1	2.8 – 12.8
	40 - 50	0	0.0	12.8 – 22.8
BV-8	22 - 33	2.7 x 10^{-5}	1.5	0.5 – 11.5
	32 - 43	8.4 x 10^{-4}	84.4	10.5 – 21.5
	42 - 53	0	0.0	20.5 – 31.5
	52 - 63.5	0	0.0	30.5 – 42

As can be seen from this data, 6 out of 15, or 40%, of the tests had water takes greater than 5 lugeons. Of the 6 tests with significant water takes, 3 were in the uppermost test interval and 3 were below this. Based on this limited data, a grout curtain will be necessary to control both seepage and uplift pressures. In addition, some consolidation grouting may be necessary since the upper zone of every boring had some water take.

The Corps of Engineers conducted packer tests at a proposed dam site about 500 m downstream of the site investigated for this report. Although this site is somewhat removed, the underlying rocks are the same. Results of these tests are as follows:

Boring No.	Test Interval (depth ft)	Lugeons
CB-S1	23 - 41.5	0
	46 - 64.8	0
CB-1	22 - 68.9	2.8
CB-2	32.7 - 60.3	0
CB-3	5 - 25	56
	25 - 61.5	0
CB-4	10 - 19.2	45
	21 - 29	0
	29 - 39	0
	39 - 49	0
	49 - 59	0
	59 - 69	0
	69 - 79	0
CB-5	4 - 15	200
	17 - 27	0
	27 - 37	0
	37 - 47	4.3
	47 - 57.3	0
	57.3 - 70.7	0
CB-6	5.6 - 15.6	7.2
	15.6 - 25.6	12.6
	35 - 63.5	0
CB-7	32.9 - 43.1	0
	43.1 - 53.1	0.2
	53.1 - 63.1	0.7
	63.1 - 81.1	0

Of these tests only 5 out of 26 had water takes greater than 5 lugeons, and of these 5, four of the tests were at least partially in saprolite. Therefore, to compare these test results to those done for this investigation, the 4 tests with takes in saprolite must be eliminated. In the Black & Veatch tests 40% had takes greater than 5 lugeons versus only 5% of the tests done by the Corps. This indicates that either there is a difference in the hydraulic conductivity of the rock at the two sites, or the small number of tests does not accurately represent the statistical variation. The lugeon data from both the Black & Veatch (B&V) and the Corps of Engineers (COE) packer tests are plotted by depth on Figure 7. Each symbol is placed at the depth of the center of the tested interval.

6.0 GEOLOGIC HAZARDS

6.1 Local Fault Considerations

No Holocene faulting (evidence of movement within the past 11,000 years) is known to exist at the project site, or within the geologic block between the Northern and Southern Puerto Rico Fault Zones (NPRFZ and SPFZ) (Figure 1). Prior to this study, the closest faults mapped in the area were the faults associated with the Northern Puerto Rico Fault Zone about 2 km to the northeast of the dam axis, and a small unnamed fault mapped about 3 km to the southeast (Figure 2). Based on observations during this investigation, a fault is thought to trend along the portion of the Rio Valenciano riverbed that includes the dam location. The strike of this fault, and the proximity to faulting associated with the NPRFZ, suggests that it is related to the NPRFZ. The last documented movement of the NPRFZ was Paleocene time (55Ma). Therefore, it is anticipated that the local fault crossing the dam axis is inactive and poses no threat as a seismic source.

There are seismic considerations that must be addressed in the design if the Rio Valenciano dam due to active tectonics surrounding the island of Puerto Rico. These issues are addressed in a separate report entitled: Seismic Hazard Study, Rio Valenciano Reservoir.

6.2 Reservoir Induced Seismicity

Simpson et al. (1988) have identified two causes for reservoir induced seismicity: 1) the elastic stress due to the load of the reservoir, and 2) the gradual diffusion of water from the reservoir to hypocentral depths. Direct loading from the reservoir will cause increase shear stresses at depth, and increase pore pressures, thereby decreasing the effective normal stress across potential planes of failure. Likewise, diffusion of reservoir water will also increase pore pressure. In either case, the predominant energy released in the triggered earthquake is from preexisting tectonic strain (Yeats, et al., 1997).

Only a small percentage of reservoirs have triggered significant earthquakes. Attempts to determine the unique characteristics of those that do trigger earthquakes has produced five significant correlations:

(1) Triggered events are more likely associated with large or deep reservoirs
(2) Triggered events are more likely in areas of normal and strike-slip faulting
(3) Large events have occurred predominantly in areas of late Quaternary faulting
(4) Triggered events are more likely during periods of rapid change in water level
(5) Triggered events are more likely to occur in reservoirs on sedimentary rocks

Based on Baecher and Keeney's (1982) discussion of these characteristics, the following tabulation ranks the reservoir characteristic according to the likelihood of having reservoir triggered seismicity (RTS). Shading indicates classifications into which the Rio Valenciano Reservoir falls.

Attribute	Most Likely RTS	Intermediate RTS	Least Likely RTS
Depth	Very Deep > 150 meters	Deep 92 – 150 m	Shallow < 92 m
Volume	Very Large 10^{10} m^3	Large $0.12 - 1 \times 10^{10}$ m^3	Small $< 0.12 \times 10^{10}$ m^3
State of Stress	Shear (strike-slip)	Extensional	Compressional
Fault Activity	Active Fault Present	---	No Active Fault Present
Geology	Sedimentary	Metamorphic	Igneous

The only characteristic that the Rio Valenciano reservoir will share with reservoirs prone to reservoir induced seismicity is that it is in an area of strike-slip faulting. It is therefore very unlikely that any reservoir triggered earthquakes will be occur at this site.

6.3 Landslide Potential

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

Aerial photographs were reviewed for areas exhibiting landslide morphology. One suspected area was identified, but upon field examination no other indications of landsliding were observed. The gentle slopes and lack of evidence for landslides make it very unlikely that any slope instability involving bedrock would occur in the reservoir slopes, 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. The only other type of failure that is foreseeable would be granitic boulders rolling downslope. The reservoir will not hasten this ongoing process.

7.0 ENGINEERING CONSIDERATIONS

7.1 Foundation Conditions

Foundation conditions are favorable for dam construction. If a gravity type dam is chosen, the soil and saprolite should be removed and the dam should be founded on sound rock. Depths to sound rock ranged from 1.5 to 43 feet (0.5 to 13 m) and averaged 18 feet (5.5 m) in the 23 borings drilled in the area of the proposed dam. The strength of the saprolite should allow stable temporary excavation slopes of 1.5H:1V, and possibly 1H:1V.

The foundation surface at the top of sound rock will be uneven due to corestones in the underlying sound granodiorite. Foundation preparation will require over excavation of the weathered material between corestones, and backfilling with dental concrete. Additional concrete to even the surface between corestones may be required prior to starting RCC placement. There is a high probability that a fault zone running perpendicular to the axis of the dam exists below the river. This will also likely require over excavation and backfill with concrete prior to starting dam construction. Depending on the depth and extent of weathering along this feature, stitch grouting may be required to sufficiently limit seepage.

If an embankment dam is built at this site the saprolite may provide sufficient strength for a foundation surface based on STP blow counts. This will need to be confirmed by additional testing in the field and laboratory. If the dam is founded on saprolite, it is recommended that a cutoff wall socketed into sound rock be included in the design.

7.2 Grouting Recommendations

The primary purpose of foundation grouting will be to limit seepage under the dam. A two-row grout curtain with shallow consolidation grouting would be acceptable for this purpose. The consolidation grouting will serve to improve the curtain grouting efficiency by limiting surface grout leakage.

All the packer tests with lugeon values over 5 were less than 45 feet (13.6 m) below the anticipated excavation surface at the top of sound rock (see table in Section 5.0). Based on these results, a grout curtain depth of 25 m will likely be sufficient to inhibit seepage under the dam. In general, a tight foundation below a depth of 45 feet was confirmed, but with limited data.

Since the foundation granodiorite is not susceptible to solution and cavern formation, the use of only neat cement grouts is anticipated.

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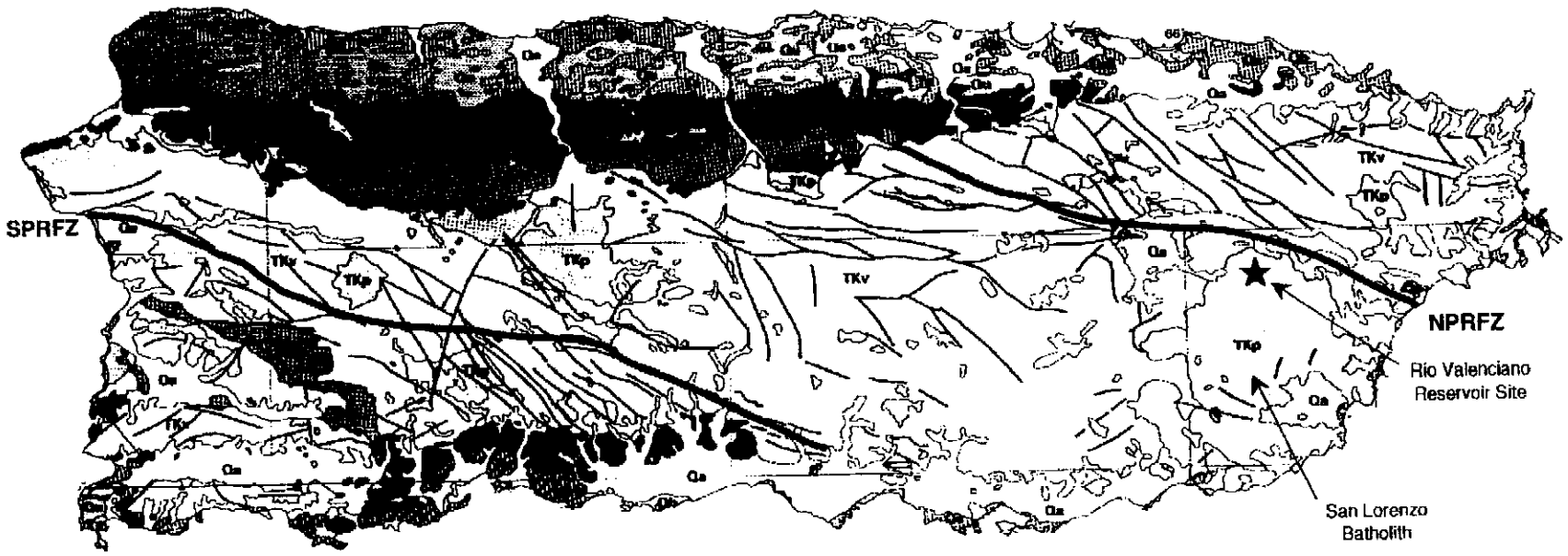


EXPLANATION

- Qa — Alluvium
- Ql — Landslide deposits
- Qb — Beach deposits
- Qs — Swamp and marsh deposits
- Qf — Artificial fill
- Qu — Undifferentiated surficial deposits

Pliocene and Miocene rocks

- Tq — Quebradillas Limestone
- Ponce Limestone
- Aymamón Limestone
- Aguada (Los Puertos) Limestone
- Guanajibo Formation
- Cibao Formation
  - Montebello Limestone Member
  - Quebrada Arenas Limestone Member—Includes Miranda Sand Member
  - Río Indio Limestone Member—Includes Almirante Sur Lentil
  - Guajataca Member
- Mucarabones Sand
- Juana Díaz Formation
- Lares Formation
- San Sebastián Formation

Eocene, Paleocene, and Cretaceous rocks

- TKv — Volcanic and sedimentary rocks
- TKp — Plutonic rocks—Mostly quartz diorite and granodiorite
- TKc — Metamorphic (serpentinite), sedimentary, and igneous rocks

Fault

Major Fault Zone

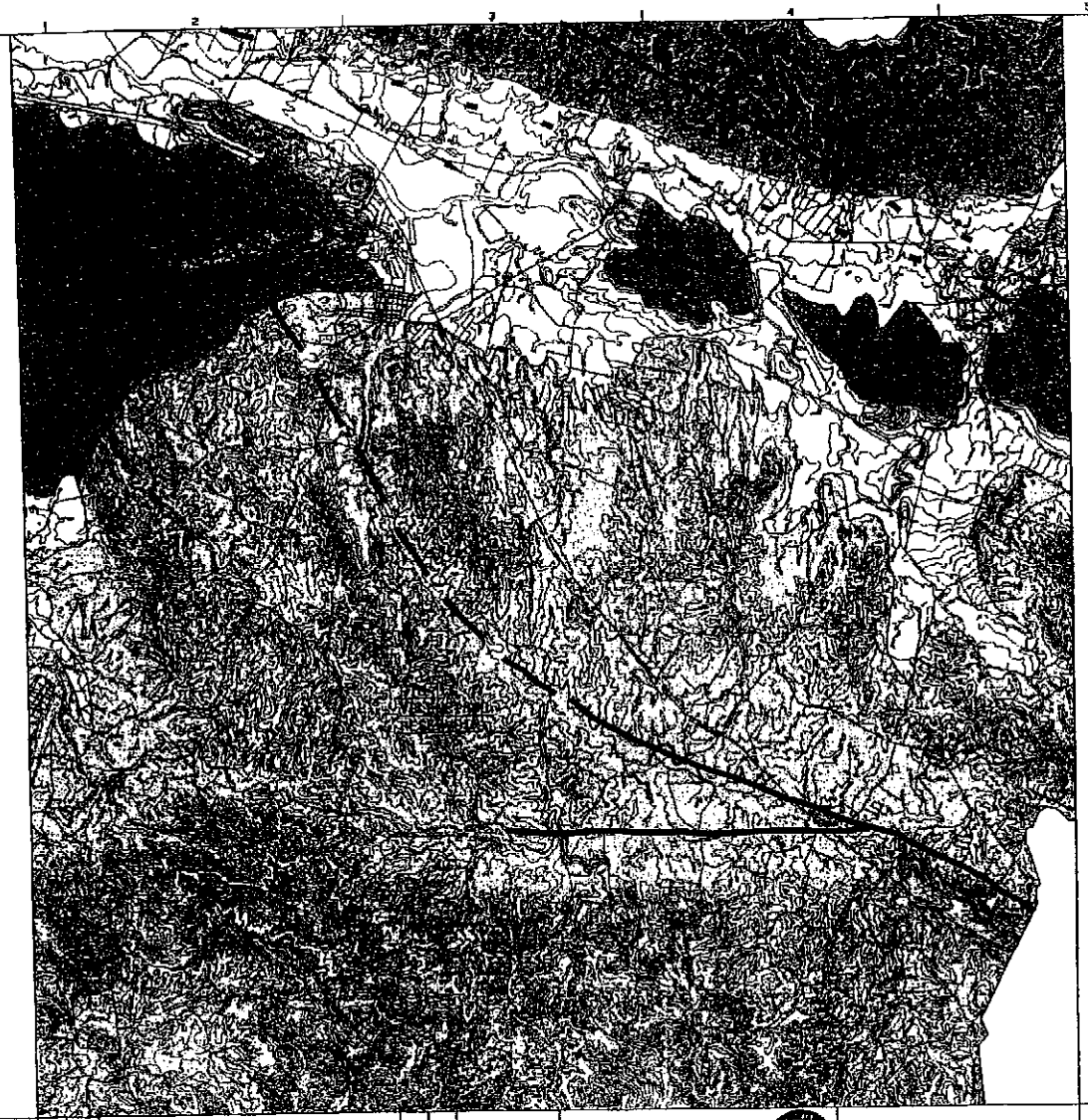
NPRFZ Northern Puerto Rico Fault Zone

SPRFZ Southern Puerto Rico Fault Zone

Map modified from Miller et al., 1997

Figure 1

Geologic Map of Puerto Rico



QUATERNARY ALLUVIUM, PIEDMONT FAN, ALLUVIAL TERRACE DEPOSITS

UPPER CRETACEOUS OR EOCENE HYDROTHERMALLY ALTERED ROCKS, CHEIFLY QUARTZ, SERICITE, AND PYRITE

UPPER CRETACEOUS SAN LORENZO BATHOLITH, CHEIFLY GRANODIORITE

VOLCANIC ROCKS OF THE NORTHEASTERN VOLCANIC-PLUTONIC SUBPROVINCE

VOLCANIC ROCKS OF THE CENTRAL VOLCANIC-PLUTONIC SUBPROVINCE

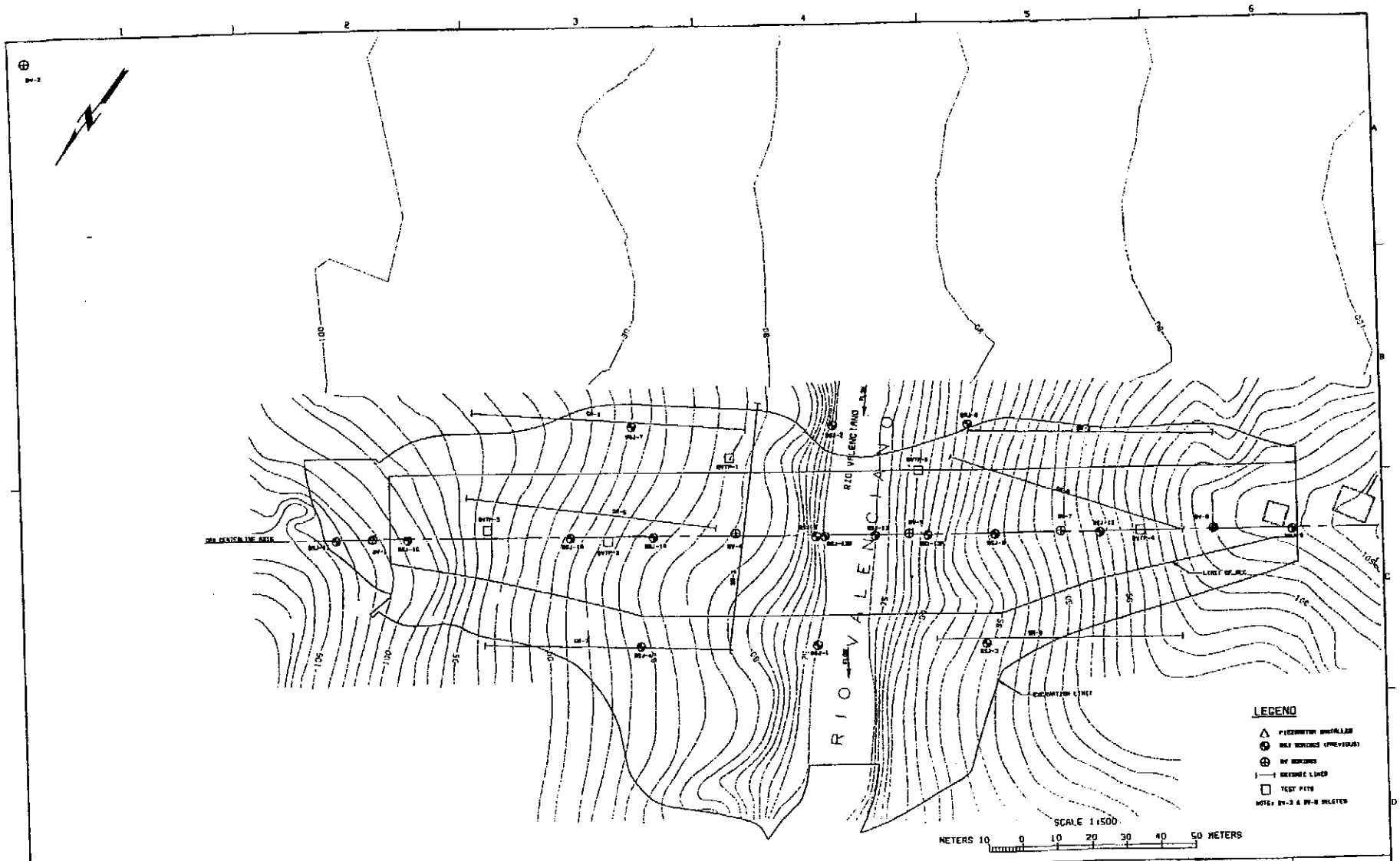
FAULT, DASHED WHERE UNCERTAIN, DOTTED WHERE PROJECTED UNDER UNITS

NPRFZ NORTHERN PUERTO RICO FAULT ZONE

MODIFIED FROM COX, D.P. ET AL.(1973), AND BROEDEL, C.H. (1961)

PRELIMINARY NOT FOR CONSTRUCTION	DSGN RCB DR FWH CHK APVD	NO.	DATE	REVISION	BY	APVD	SCALE AS INDICATED ON DRAWING	AFI AAA INITIATIVE	EAST-CENTRAL REGIONAL AQUEDUCT	SHEET DWG DATE 03/31/00 PROJ 098628

Figure 2,
GEOLOGIC MAP OF THE
RIO VALENCIANO RESERVOIR AREA

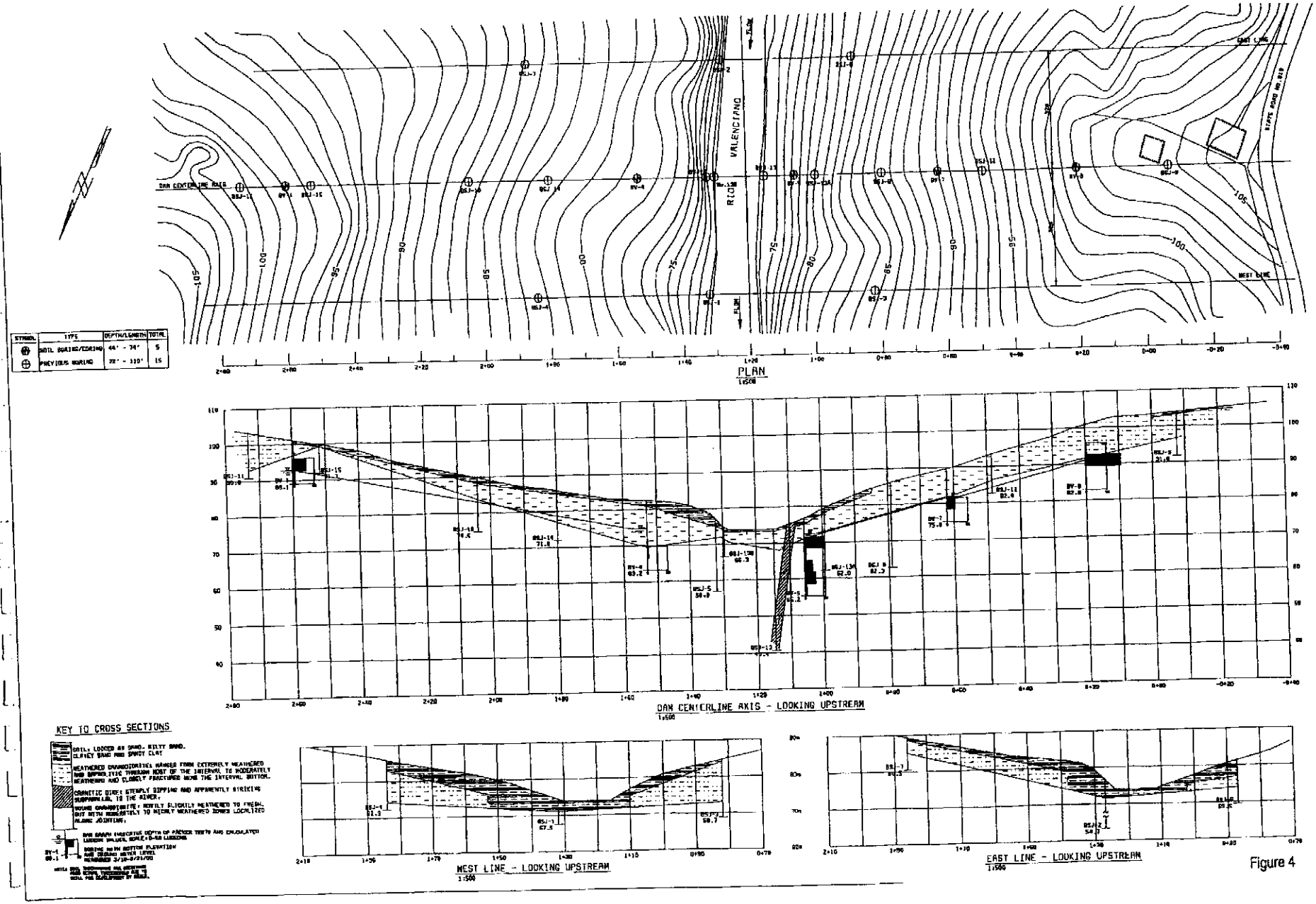


PRELIMINARY NOT FOR CONSTRUCTION	DSGN RCB DR KCH CHK APVD	NO.	DATE	REVISION	BY	APVD	SCALE AS INDICATED ON DRAWING	AFI AAA INITIATIVE	EAST-CENTRAL REGIONAL AQUEDUCT

FIGURE 3

GEOTECHNICAL INVESTIGATION PLAN

SHEET
DWG C-5
DATE 08/23/00
PROJ 086628



DAM CENTERLINE AXIS
RIO VALENCIANO
FLOW
EAST LINE
WEST LINE
PLAN
1:500
DAM CENTERLINE AXIS - LOOKING UPSTREAM
1:500
WEST LINE - LOOKING UPSTREAM
1:500
EAST LINE - LOOKING UPSTREAM
1:500
KEY TO CROSS SECTIONS

Figure 4