SEISMIC HAZARD ANALYSIS
RIO VALENCIANO DAM SITE
JUNCOS, PUERTO RICO

Project No. 3557-06
January 7, 2008

GeoCim LUIS O. GARCIA & ASSOCIATES
GEOTECHNICAL ENGINEERING CONSULTANTS

Partners
Luis Oscar García, MSCE, CE, PE
Carlos García Echevarría, MSCE, PE
James A. Baigés, MSCE, PE

Associate
Alejandro E. Soto, MS, PG

SEISMIC HAZARD ANALYSIS
RIO VALENCIANO DAM SITE
JUNCOS, PUERTO RICO

Project No. 3557-06
January 7, 2008

TABLE OF CONTENTS

		PAGE
TABLE OF CONTENTS		i
LIST OF FIGURES		i
LIST OF APPPENDICES		ii
EXECUTIVE SUMMARY		iii
1.0	INTRODUCTION	1
2.0	TECTONIC SETTING	3
3.0	FIELDS OF STUDY AND TECHNICAL FINDINGS	6
3.1	Background and Precious Work	6
3.2	Bedrock Fault Structural Analysis	9
3.3	Neotectonics Study	11
3.4	Paleoliquefaction Study	13
3.5	Seismic Design Parameters	15
4.0	CONCLUSIONS	16
5.0	CLOSURE	19
REFERENCES		20

FIGURES

FIGURE 1	Google Earth image showing the location of the proposed Río Valenciano Dam and prominent physiographic/cultural features of the study area
FIGURE 2	Morphology of the PR-VI block. Prominent topographic-tectonic features are indicated. Arrows denote relative plate motions.
FIGURE 3	Raised relief and geologic maps of Puerto Rico.
FIGURE 4	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.
FIGURE 5	Topographic map showing the locations of outcrops where Joyce obtained fracture orientation data with stereographic plots of joint measurements (reproduced from Appendix E).

AMELIA DISTRIBUTION CENTER, EMMA STREET NO. 26A, GUAYNABO, PR 00968-8007
TEL. (787) 792-2626 • FAX (787) 782-5990

FIGURE 6 Google Earth image showing location of trenches excavated to assess the occurrence of recent fault rupture. The most prominent bedrock faults, colored blue, and derived from several source of USGS quadrangle mapping. Heavy red lines denote primary topographic lineaments that are related to the mapped faults. The location of the Valenciano Dam site is noted.

FIGURE 7 Maximum Credible Earthquake response spectra for the Río Valenciano Dam site; reproduced from Swaisgood Consulting report (Appendix H).

FIGURE 8 Probabilistic Seismic Hazard for the Operating Basis Earthquake (OBE); reproduced from the Swaisgood Consulting Report (Appendix H).

APPENDICES

APPENDIX A Seismic Hazard Study Report, Rio Valenciano Reservoir – Black and Veatch

APPENDIX B Rio Valenciano Reservoir Geotechnical Report – Black and Veatch

APPENDIX C Memorandum on Design of Proposed Dam And Reservoir on the Rio Valenciano – Buck, Seifert, and Jost

APPENDIX D Rio Valenciano Study, Foundation and Materials, Technical Appendix B – U.S. Army Corps Of Engineers

APPENDIX E Rio Valenciano Dam Project: Site Geology and Geologic Structure Analysis – Dr. James Joyce

APPENDIX F Rio Valenciano Dam Project – Bedrock Fault Structural Analysis – Dr. James Joyce

APPENDIX G Geologic Evaluation Studies for the Rio Valenciano Dam: 1. Fault Evaluation-Phase Two – Williams Associates

APPENDIX H Geologic Evaluation Studies for the Rio Valenciano Dam: 2. Liquefaction Study – Phase One- M. Tuttle & Associates

APPENDIX I Preliminary Report, Seismic Design Parameters, Proposed Rio Valenciano Dam and Reservoir – Swaisgood Consulting

SEISMIC HAZARD ANALYSIS
RIO VALENCIANO DAM SITE
JUNCOS, PUERTO RICO

January 7, 2008

EXECUTIVE SUMMARY

This report presents the results of an 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. Recent seismo-tectonic studies, however, have raised concern about this conventional wisdom prompting this investigation as an extension of a seismic hazard evaluation performed by Black & Veatch in 2000.

The purpose of this investigation was to determine if there are any regional or local faults capable of producing ground shaking or surface rupture at the proposed 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, evaluation of exposures of mapped faults within the GNPRFZ, interpretation of neotectonic geomorphology along the GNPRFZ from aerial photography, LIDAR laser terrain mapping imagery, and field investigations, trenching across potential Quaternary fault features, and evaluation of scenario earthquakes for local and regional faults and their likelihood to induce liquefaction in Late Quaternary (last 40,000 years) sand layers in the alluvial sediments of the nearby Blanco, Humacao, Gurabo, Valenciano, and Grande de Loíza rivers followed by field checking to identify past liquefaction events.

The proposed 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 the sound rock is mantled by a residual sandy soil that grades into saprolite and eventually weathered granodiorite. 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 as part of site geotechnical studies currently under way.

Field, trenching, and geomorphic data compiled during this assessment confirm the presence of a steeply-dipping geologic fault below the Río Valenciano at the dam site. The NNW-trending Río Valenciano Fault extends about 1 kilometer north of the dam site and an undetermined distance to the south. Structural and geomorphic observations indicate the fault is an old feature that is not active at present.

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. Following detailed field assessment, trenches were excavated across several of these. No evidence of Quaternary fault activity was found.

An evaluation of the liquefaction potential of Quaternary alluvial sand deposits within the Río Blanco, Río Gurabo, and Río Grande de Loíza floodplains concluded that widespread liquefaction would occur during major earthquake events originating on the Muertos Trough and the Puerto Rico Trench subduction zone or on the nearby faults of the GNPRFZ. However, no evidence of past liquefaction has been found during field checking that will be concluded in conjunction with the geotechnical studies that are currently under way.

The studies conducted for this assessment indicate no significant local fault activity within the GNPRFZ during late Quaternary time (last 40,000 years). Preliminary seismic design parameters have been calculated for the proposed dam site 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 proposed site producing a peak ground acceleration (PGA) of 0.46g at the site. A seismic coefficient of 0.27g is recommended for the stability and stress analyses of the dam. The PGA for the operating basis earthquake (OBE) is 0.13g.

SEISMIC HAZARD ANALYSIS
RIO VALENCIANO DAM SITE
JUNCOS, PUERTO RICO

Project No. 3557-06
January 7, 2008

1.0 INTRODUCTION

This report presents the results of an 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. Río Valenciano drains a portion of the Sierra de Cayey foothills on the south margin of the Río Gurabo valley between Gurabo and Juncos (Figure 1). The dam site is located approximately 3 to 5 kilometers (2 to 3 miles) south of the Great Northern Puerto Rico Fault Zone (GNPRFZ), a system of northwest to west-northwest trending high angle faults that roughly parallels the north margin of the valley. The purpose of this investigation was twofold: first, 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; and second, to provide seismic parameters and ground motion records for engineering design of the project. 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 information about the tectonic setting and earthquake activity of Puerto Rico and the surrounding region published after the B&V report was released.

The Río Valenciano Dam seismic hazard studies included: a detailed assessment of the bedrock geology of the dam site and surrounding area with emphasis on structural features associated with tectonic faulting; interpretation of neotectonic geomorphology from aerial photography, LIDAR imagery, and field investigation leading to trenching across suspected fault traces; 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. The area of study encompassed the

lowland and hilly margins of the valley that extends from Caguas to the east coast of Puerto Rico between Naguabo and Humacao, an area of approximately 200 km^2 that includes all or portions of the Gurabo, Blanco, Grande de Loíza, and Humacao rivers and the Río Valenciano drainage.

The work was performed by a team of local and stateside geoscientists that included:

- 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 and neotectonic interpretation of aerial photography;
- 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.

The evaluation was requested by CSA Group (CSA) who is under contract with the Puerto Rico Aqueduct and Sewer Authority (PRASA), the Project Owner, to prepare an Environmental Impact Statement (EIS) for the project and complete the design of the dam and appurtenant structures.

2.0 TECTONIC SETTING

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 2). 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 2). 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 produced as Caribbean crust is subducted beneath the PR-VI block forms the south boundary of the 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 rotates 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). Additional information on the tectonic setting of the PR-VI block is contained in the June 2000 B&V seismic hazard report

(Black & Veatch, 2000a) included in Appendix A as well as in the neotectonics report prepared for this seismic hazard analysis and discussed later in this report.

Field studies by the USGS have produced detailed geologic maps (1:20,000 scale) of most of the island that identify numerous geologic faults, including two major, west-northwest trending fault zones (Figure 3) dominated by left-lateral displacements: the GNPRFZ and the Great Southern Puerto Rico Fault Zone (GSPRFZ). 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. None of the USGS faults has been seen to offset Quaternary (last 2 million years) sediment so they are generally considered to be inactive. The GNPRFZ disappears under the Oligocene-Miocene carbonate belt west of Caguas and San Juan suggesting an even longer period of inactivity. Within the study area, the GNPRFZ faults locally offset Cretaceous bedrock units that outcrop near the valley margins, but the mapped fault traces disappear under Quaternary alluvial sediment of the river valleys and the coastal deposits of the Naguabo-Humacao area along most of their lengths. This absence of evidence of recent faulting combined with the scattered pattern of on-land microseismic activity supported the notion that recent tectonic deformation within the PR-VI block has been restricted to the submarine block margins and nearby offshore areas.

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 4), a large, late Cretaceous plutonic body that outcrops throughout an area of about 400 square kilometers (Figure 2) between the municipalities of Caguas, 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 Valenciano enters a long, relatively straight valley oriented north-northwest that continues for a distance of about 2.2 kilometers (Figure 4). It then curves to the northeast into another relatively straight stretch that continues trending north for a distance of about 800 meters before entering a shorter northeast-trending reach that leads into the Río Gurabo floodplain. The proposed Río Valenciano Dam site is located within the longer, north-northwest trending reach.

Geologic faults and other structural features (such as joints or inclined contacts between different rock types) are frequently zones of enhanced rock permeability. Rocks in and along fault zones then tend to weather and erode faster than intact rock nearby. This 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 4). Nevertheless, the linearity and length of the river segments, particularly the north-northwest trending reach within which the dam site is located, are suggestive of some type of underlying structural control.

In a geotechnical report for the dam site (Black & Veatch, 2000b), B&V cite the linearity of the river and observations of shear deformation at several locations nearby to postulate the existence of a fault below the river extending north and south of the site, and conclude it is inactive based on the absence of evidence of recent activity within the GNPRFZ (the B&V geotechnical report is included herein as Appendix B). More recent paleoseismicity studies, however, have discovered 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 paleoliquefaction features in north-central Puerto Rico suggestive of a strong local earthquake about 2800 years ago (Tuttle et al., 2005), raising concerns that other onshore faults may be seismically active. Additionally, recent

Global Positioning System (GPS) measurements (Jansma and Mattioli, 2005) indicate the island is being stretched in an east-west direction by 3 ± 2 millimeters per year. 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 that represent zones of crustal weakness. These data raised concerns about previous conclusions regarding the inactivity of the GNPRFZ prompting this expansion of the B&V study.

3.0 FIELDS OF STUDY AND TECHNICAL FINDINGS

The seismic hazard evaluation comprised four complementary and cooperative studies. Dr. Joyce evaluated the geology of the dam site and surrounding areas related to the GNPRFZ compiling a wealth of information on rock deformation features in the study area. Williams Associates studied the tectonic geomorphology of the area between Caguas and the Humacao-Naguabo coast identifying several topographic features that may have been produced by faulting; these were subsequently trenched to search for evidence of recent faulting. Tuttle Associates analyzed the liquefaction potential of alluvial and coastal sediments in the vicinity of the GNPRFZ and searched for earthquake-induced liquefaction features in the area. At the same time, Swaisgood Consulting developed seismic parameters for dam design. The following sections summarize these activities and their respective findings.

3.1- Background and Previous Work

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. 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.

The first study of the geology and geotechnical characteristics of the dam site and nearby areas 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 the boring logs lack information on the engineering character of the rock. 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) 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.

B&V also compiled information about rock fracturing[1]. Fractures in rock 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, and its 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.

B&V recorded a number of fracture orientation measurements. They noted that high-angle joint sets with average strikes oriented roughly north-south and east-west and low angle joints of unspecified orientation are common in the area, and that secondary or subsidiary joints of variable orientation and steep to moderate dips are abundant locally. B&V also posited the existence of a fault below the Valenciano River passing under the dam site, as noted above. The Juncos quadrangle geologic map (Figure 4) does not show any faults within the Río Valenciano valley. This map, however, was published as a preliminary map and shows few geologic structures. 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. B&V concluded

[1] The B&V report refers to rock mass discontinuities. These 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 and fractures such as joints and faults that are the most common discontinuities in massive rocks such as granodiorite (the difference between joints and faults is that joints do not exhibit any measurable relative motion between the opposing rock faces whereas faults do). The USACE report mentions the primary joint orientations observed but does not provide any actual measurement data.

the Valenciano and Humacao faults were part of the inactive GNPRFZ and suggested the two faults may be connected.

3.2- Bedrock Fault Structural Analysis

The goal of the bedrock fault structural analysis was to evaluate the geologic structures in the area of the Valenciano dam site and nearby sections of the GNPRFZ to gain a better understanding of recent tectonic activity in the area. For this, Dr. Joyce conducted a comprehensive fracture survey of the Río Valenciano channel for a distance of about 2.5 kilometers upstream (south) and 700 meters downstream (north) of the dam site, several Valenciano tributary drainages, and rock exposures along route PR-919 and in a commercial quarry on route PR-928 (both west of the river). He also studied exposures of the GNPRFZ faults and observed several of the trenches excavated across potential fault features, including two trenches excavated by the USGS along the mapped trace of the Cerro Mula Fault, one of the prominent features of the GNPRFZ. Finally, he compiled information on microseismic activity in the area and assessed its relation to surface geologic structures. His findings were documented in two reports included herein as Appendices E and F.

Figure 5 shows stereographic plots of the measured joints. The data highlight the prominence of the high angle joint sets observed in the previous studies and 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 possibly attributable 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.

The study also confirms the control of structural features over the plan view form of the Río Valenciano. For example, the north-south trend of a roughly 800-meter stretch of Río Valenciano that begins approximately 500 meters north of the dam follows the prominent north-south high angle joint set reported by all site investigators. More significantly, deformation features observed on some of the fractures confirm the presence of a high angle fault, named the Río Valenciano Fault, below the river bed at the dam site. The physical characteristics of the fault below the dam site are currently under investigation by means of angled borings as part of an ongoing geotechnical study being carried out to finalize dam design. The Río Valenciano Fault extends from south of the dam site trending NNW past Quebrada La Santa (Figure 5) and into a similarly oriented secondary drainage where it appears to die out approximately 900 meters north of the dam site. Its southernmost limit is unknown. It is not exposed in the extensive rock outcrops present along the west-southwest trending river reach approximately 2 kilometers south of the dam site (Figures 4 and 5), an observation that argues against any connection between the Valenciano and Humacao faults.

Field observations support the contention that the Río Valenciano Fault is no longer active. Deformation features and associated mineralization present in the rock indicate the deformation occurred at depth before the fault was exposed by erosion. Two trenches were excavated across the trace of the fault, one into relatively young river terrace deposits about 200 meters south of the dam site, the other into older alluvial sediment on the crest of a hill approximately 800 meters to the north. In each case, the alluvial sediment was unaffected by the underlying fault.

Similarly, no evidence of recent motion was observed in the trenches excavated over suspected fault features within the GNPRFZ, including the two USGS trenches (the trenches excavated as part of the neotectonic component of this study are discussed in the following section). Joyce also studied outcrops along the traces of the Peña Pobre, Cerro Mula, and Humacao faults. As with the Río Valenciano Fault, the strain features observed are consistent with deep-seated deformation that occurred millions of years ago. He noted

that the low level of microseismicity associated with these faults supports this conclusion. Interestingly, he noted inconsistencies between the sense of motion shown by some deformation features and the left-lateral displacement indicated for the faults on the USGS maps.

3.3- Neotectonics Study

The purpose of the neotectonics study was to evaluate if branches of the GNPRFZ within the study area "have been active during the past 35,000 years and specifically to evaluate whether potentially active faults exist in the vicinity of the proposed dam itself" and, if evidence of recent activity was found, "to estimate maximum magnitude earthquakes and their source locations to be used in the development of seismic design parameters and ground motion records for the Río Valenciano Dam"[2]. The study was performed by Williams Associates with assistance from M. Tuttle Associates; their report can be found in Appendix G.

The first phase of the study focused on the identification of geomorphic features that could have been produced by Quaternary faulting and locating the surface trace of the causative faults. It included 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[3] imagery. This resulted in the identification of a variety of features such as linear ridges, valleys, and alluvial stream segments, aligned bends in streams, and aligned terrace risers that could have formed by Quaternary faulting, often near the traces of mapped bedrock faults. The study area was then field checked, focusing on possible fault-related features previously

[2] Citations are from the Williams Associates report (Appendix G).
[3] 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.

identified. No conclusive evidence of recent faulting was found but a number of potential fault sites were identified for more detailed exploration by trenching.

The second phase of the investigation consisted of the excavation of trenches across the suspected fault traces. Six sites with Quaternary sediment were selected for trenching, two on the Río Valenciano, three near the trace of the Peña Pobre Fault in the Río Blanco sector of Naguabo, and one on the trace of the Cerro Mula Fault in Gurabo (Figure 6). The Río Valenciano sites were selected based on the coincidence of bedrock shears and topographic lineaments. The Peña Pobre and Cerro Mula locations were chosen for coincidence of previously mapped faults and prominent topographic lineaments.

The sites are described in the Williams Associates report that includes detailed photographic logs of each trench (Appendix G). The southern Río Valenciano trench exposed sheared granodiorite below recent sandy deposits (carbon dated as not older than AD 1680) that showed no indication of having been faulted. The northern Río Valenciano trench excavated older alluvium derived from the granodiorite. The alluvium consists of well stratified soil that exhibit no fault disruption. Although bedrock was not reached, the location of the trench between exposures where the granodiorite exhibits shear deformation supports the notion that the Río Valenciano Fault has not been active during the Quaternary. The Peña Pobre and Cerro Mula trenches penetrated through the surface alluvium into the underlying bedrock. The entire exposed sequence is unfaulted.

The Williams Associated field and trenching investigations did not detect any Holocene (last 12,000 years) fault activity. On a broader scale, no pattern of offset ridges or stream features was observed along the mountain fronts that border the valleys in the study area or within the Río Valenciano drainage, where a number of topographic lineaments are seen to cross the main river channel (and the Río Valenciano Fault trace). Williams Associates concludes these observations point to an absence of significant fault activity within this portion of the GNPRFZ during late Quaternary time (last 40,000 years).

3.4- 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 be 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 spatial 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), thereby providing an independent assessment of the source and maximum magnitude of earthquakes likely to impact the area. 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 is being undertaken by M. Tuttle & Associates with assistance from K. Dyer-Williams; copy of the M. Tuttle & Associates paleoliquefaction report for the first phase of the evaluation is included in Appendix H. The first phase of the investigation focused on two tasks. One 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[4]) 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.

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 H). The results reveal that widespread liquefaction would occur during ground shaking from a great (**M**8.25) earthquake on the Muertos Trough or the Puerto Rico Trench, or from a large to very large (**M**6.8-7.3) earthquake occurring on one of the local faults in the GNPRFZ.

The second task consisted of 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

[4] 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.

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 definitive evidence of liquefaction was observed.

Phase two of the paleoliquefaction study will entail field reconnaissance to locate and analyze earthquake-induced liquefaction features along selected reaches of Río Blanco, Río Grande de Loíza, Río Gurabo, and Río Humacao. Phase 2 work will be completed in conjunction with the geotechnical studies of the dam site that are currently under way.

3.5- Seismic Design Parameters

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 use for dam design. Swaisgood Consulting performed a determination of seismic design parameters using procedures 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 I.

The analysis considered distant seismic sources associated with the major offshore fault zones that surround the PR-VI crustal block (Figure 1 in Appendix I); no local seismic sources will be evaluated based on the results of the investigations reported herein. 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 7 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 8 reproduced from the Swaisgood Consulting report. The report recommends a PGA of 0.13g be used as the Valenciano Dam OBE.

4.0 CONCLUSIONS

This evaluation of seismic hazard for the Río Valenciano Dam site encompasses studies of the geology and structure, neotectonic geomorphology, and paleoseismicity of the dam site and nearby areas. The investigation has been characterized by extensive collaboration and exchange of information and ideas between the various specialists involved in the project. Conclusions derived from these studies are provided below. Direct quotations from the consultant reports are used 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. Soil borings drilled for previous site studies and the current geotechnical investigation indicate the thickness of the residuum within the footprint of the proposed dam varies in the range of 1.5 to 43 feet. B&V have recommended that the residuum be removed so that the dam structure bears on sound rock, a recommendation we agree with in so far as is economically feasible. Deeper weathered rock sections may be improved by grouting, the injection of suitable mixtures of cement and water (and other additives deemed necessary) for the purpose of strengthening the rock mass and reducing its permeability.

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 of the geotechnical studies currently underway 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. Information compiled during this study confirms the existence of a fault below the Río Valenciano at the dam site. The NNW-trending Río Valenciano Fault extends about 1 km. north of the dam site before dying out in a secondary drainage tributary to Quebrada La Santa. Its southernmost extent is uncertain; it does not appear to cross a prominent WSW-trending Río Valenciano segment located about 1.8 km. south of the dam site so it is assumed to die out somewhere in the NNW-trending intervening reach. The geologic structure and geomorphic

evidence compiled for this study indicate the fault is an old feature that is not presently active.

4. A regional geomorphic evaluation of known and possible fault features by Williams Associates (Appendix F) located and analyzed topographic lineaments, deflected streams, and aligned river segments consistent with Late Quaternary faulting on the mapped faults in the GNPRFZ in the area between Naguabo-Humacao and the west margin of Caguas. These were subsequently field checked and several of the suggestive fault features were trenched. No evidence of recent faulting was found. Furthermore, no pattern of tectonic displacement of valleys and other range front features was observed, leading Williams Associates to conclude there has been no significant activity within the GNPRFZ during late Quaternary time (last 40,000 years).
5. M. Tuttle & Associates (Appendix G) is conducting a paleoliquefaction study of the study area. An analysis of the liquefaction potential of Quaternary sand deposits within the Río Blanco, Río Gurabo, and Río Grande de Loiza alluvial valleys indicates that great (**M**8.25) earthquakes produced by the Muertos trough or the Puerto Rico Trench subduction zone or large to very large (**M**6.8-7.3) earthquakes generated by faults in the GNPRFZ would likely induce widespread liquefaction in the area. Nevertheless, field investigations performed to date have found no evidence of past liquefaction. The sum of the studies completed for this Fault Hazard Analysis demonstrates a lack of recent surface fault activity in the study area. It does not, however, preclude activity on crustal faults that do not break the ground surface (blind faults), and provides incomplete data on the seismic history of the area. The final phase of the paleoliquefaction analysis, which entails detailed field reconnaissance and will be performed as part of the geotechnical studies currently under way, will provide a more complete history of seismicity in the area.

6. Swaisgood Consulting (Appendix H) has determined preliminary seismic design parameters for the Río Valenciano Dam. The Maximum Design Earthquake (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 peak ground acceleration (PGA) of 0.46g at the dam site. The PGA for the Operating Basis Earthquake (OBE) is 0.13g. A seismic coefficient of 0.27g is recommended for the stability and stress analyses of the dam and for the evaluation of rock wedge sliding stability.

5.0 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. 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.

Respectfully submitted,

LUIS O. GARCIA & ASSOCIATES
GEO CIM, INC.

Alejandro E. Soto, PG
Associate

REFERENCES

Black and Veatch Puerto Rico, 2000a, *Seismic Hazard Study, Rio Valenciano Reservoir, Preliminary Report*, June 29, 2000; 25 p.

Black and Veatch Puerto Rico, 2000b, *Rio Valenciano Reservoir Geotechnical Report*; June 30, 2000; 15p.

Broedel, C.H., 1961; *Preliminary Geologic Map Showing Iron and Copper Prospects in the Juncos Quadrangle, Puerto Rico*; U.S. Geological Survey Miscellaneous Geologic Investigations Map I-326; 1:20,000.

Buck, Seifert, and Jost, 1971; *Memorandum on Design of Proposed Dam and Reservoir on the Rio Valenciano*; July 16, 1971; 17p.

Cox, D.P. and Briggs, R.P., 1973; *Metallogenic Map of Puerto Rico*; U.S. Geol. Survey Misc. Geologic Investigation Map I-721; 1:240,000.

Geomatrix, 1988; *Geological-Seismological Evaluation to Assess Potential Earthquake Ground Motions for the Portugues Dam, Puerto Rico*; Draft Report; Department of the Army, Jacksonville District, Corps of Engineers, Jacksonville, Florida, 89 p.

Golder Associates, 1994; *Site Specific Seismic Hazzard Assessment, Design of North Expansion for Industrial Cell No. 1, BFI Ponce Landfill, Ponce, Puerto Rico*; Report submitted to BFI of Ponce, Inc., Ponce Puerto Rico; 9p.

Jansma, P.E. and Mattioli, G.S., 2005; *GPS results from Puerto Rico and the Virgin Islands: Constraints on tectonic setting and rates of active faulting*; in Mann, P., ed., Active Tectonics and Seismic Hazards of Puerto Rico, the Virgin Islands, and Offshore Areas; Geological Society of America Special Paper 385; p.13–30.

McCann, W.R., 1985; *On the earthquake hazard of Puerto Rico and the Virgin Islands*; Bull. Seismological Soc. America, v.75, n,1; pp.251-262.

M'Gonigle, J.W., 1978; *Geologic Map of the Humacao Quadrangle, Puerto Rico*; U.S. Geological Survey Misc. Investigation Series Map I-1070; 1:20,000.

Pease, M.H., 1968; *Geologic Map of the Aguas Buenas Quadrangle, Puerto Rico*; U.S. Geological Survey Misc. Investigation Map I-479; 1:20,000.

Prentice, C. S., and P. Mann, 2005, *Paleoseismic study of the South Lajas fault: First documentation of an onshore Holocene fault in Puerto Rico*, in Mann, P., ed., Active

Tectonics and Seismic Hazards of Puerto Rico, the Virgin Islands, and Offshore Areas: Geological Society of America Special Paper 385, p. 215-222.

Seed, H.B. and Idriss, I.M., 1971; *Simplified procedure for evaluating soil liquefaction potential*; Journal of the Geotechnical Engr. Div., ASCE; v. 97, n. 9; p. 1249-1273.

Seiders, V.M., 1971; *Geologic Map of the Gurabo Quadrangle, Puerto Rico*; U.S. Geological Survey Misc. Investigation Map I-657; 1:20,000.

Tuttle, M. P., 2001; *The use of liquefaction features in paleoseismology: Lessons learned in the New Madrid seismic zone, central United States*; Journal of Seismology, v. 5, p. 361-380.

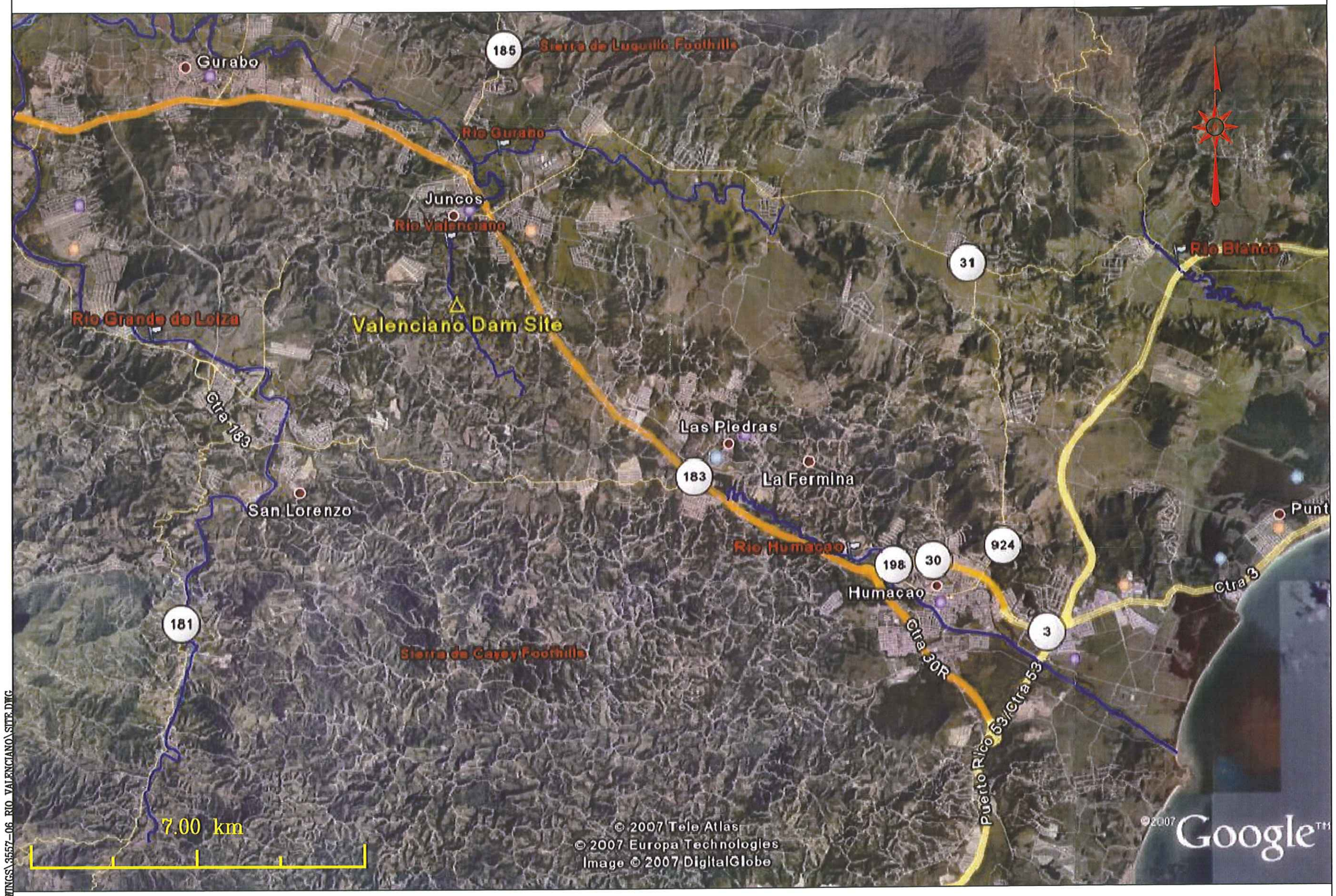
Tuttle, M. P., K. Dyer-Williams, E.S. Schweig, C.S. Prentice, J.C. Moya, and K.B. Tucker, 2005; *Liquefaction induced by historic and prehistoric earthquakes in western Puerto Rico*; in Mann, P., ed., Active Tectonics and Seismic Hazards of Puerto Rico, the Virgin Islands, and Offshore Areas: Geological Society of America Special Paper 385, p. 263-276.

URS Corporation, 2004; *Deterministic and Probabilistic Seismic Hazard Analyses for Portugues Dam, Puerto Rico*; Technical Report for the U.S. Army Corps of Engineers, p. 1-1 to 8-6.

U.S. Army Corps of Engineers, undated; *Rio Valenciano Study, Foundation and Materials, Technical Appendix B*; 17p.

U.S. Geological Survey, 2001; *Earthquakes and Tsunamis in Puerto Rico and the U.S. Virgin Islands*; USGS Fact Sheet FS-141-00, April 2001; 2p.

Youd, T. L., and Idriss, I.M., 2001; *Liquefaction resistance of soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils*; Journal of Geotechnical and Geoenvironmental Engineering, v. 127, n. 10, p. 297-313.



N:\AUTOCAD\DRAWINGS\3557-06 RIO VALENCIANO\SITE.DWG

GeoCim	LUIS O. GARCIA & ASSOCIATES GEOTECHNICAL ENGINEERING CONSULTANTS AMELIA DISTRIBUTION CENTER LOT. 26 A EMMA ST. GUAYNABO, PUERTO RICO 00968-8007	GOOGLE EARTH IMAGE SHOWING THE LOCATION OF THE PROPOSED RÍO VALENCIANO DAM AND PROMINENT PHYSIOGRAPHIC/CULTURAL FEATURES OF THE STUDY AREA	VALENCIANO DAM JUNCOS, P.R.			DRW. BY: F. ARIAS
			DATE: 01/03/08	JOB NO: 3557-07	CKD. BY: AS	SCALE: N.T.S.	FIGURE NO: 1

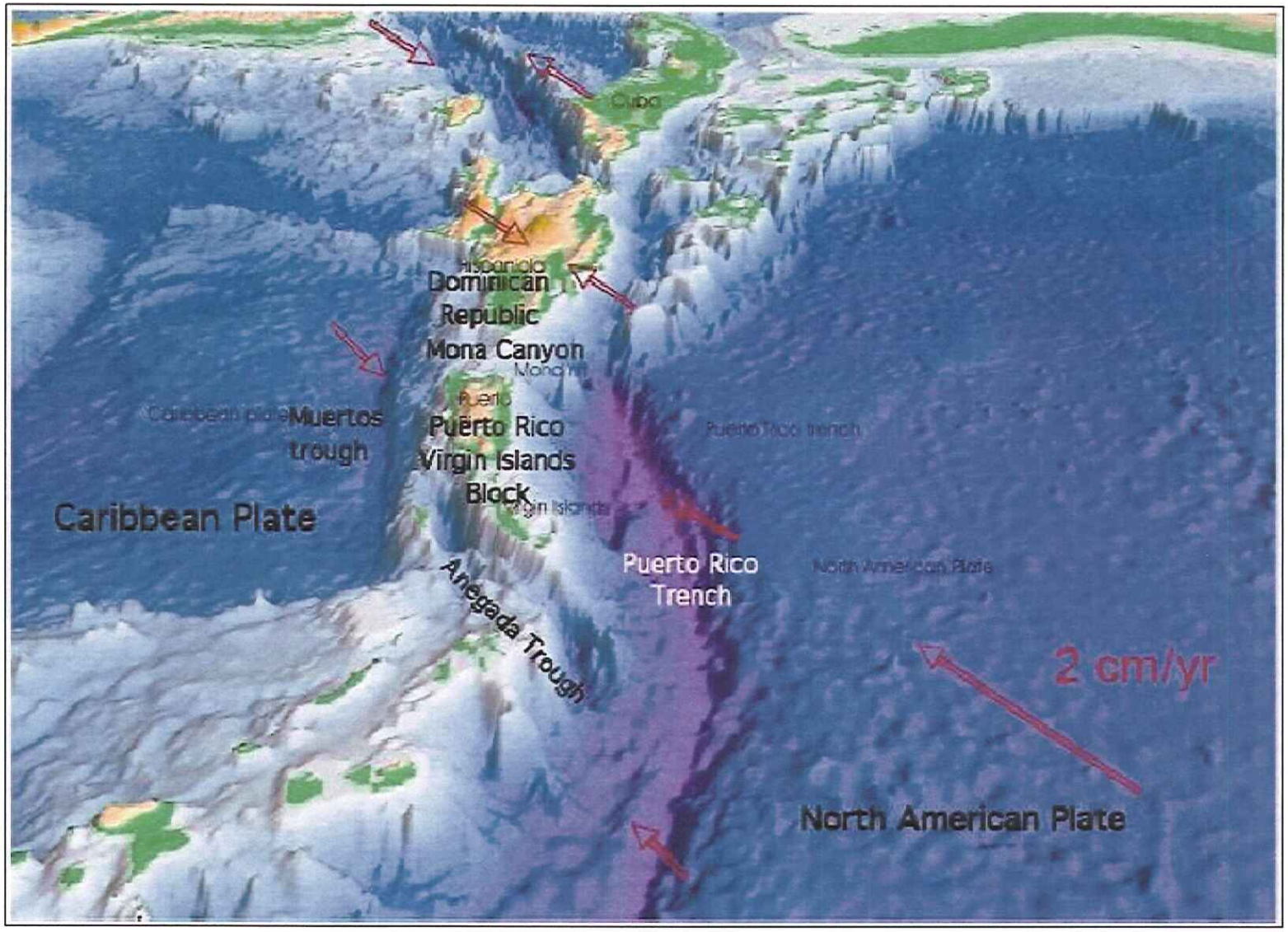
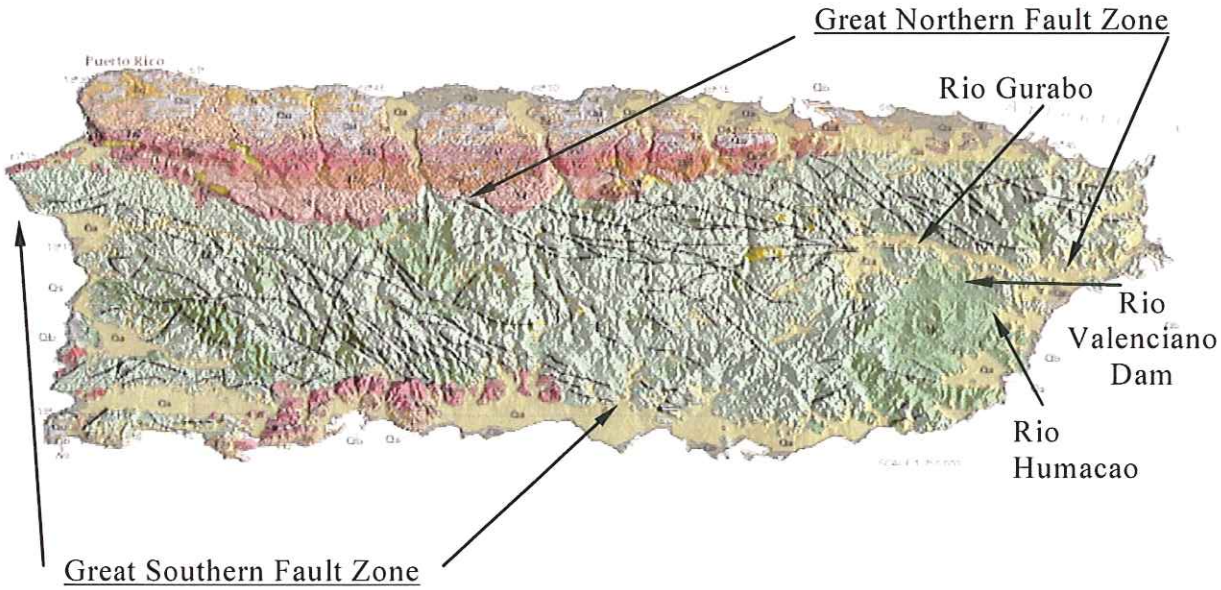


Fig 2: Morphology of the PR-VI block. Prominent topographic-tectonic features are indicated. Arrows denote relative plate motions.

GeoCim LUIS O. GARCIA & ASSOCIATES	SEISMIC HAZARD ANALYSIS					
	RIO VALENCIANO DAM SITE, JUNCOS, P.R.					
	DRW. BY: L. Rivera	CKD. BY: A.S.	SCALE: .	DATE: 01/04/08	JOB. NO: 3557-06	FIGURE NO: 2



Geology of Puerto Rico

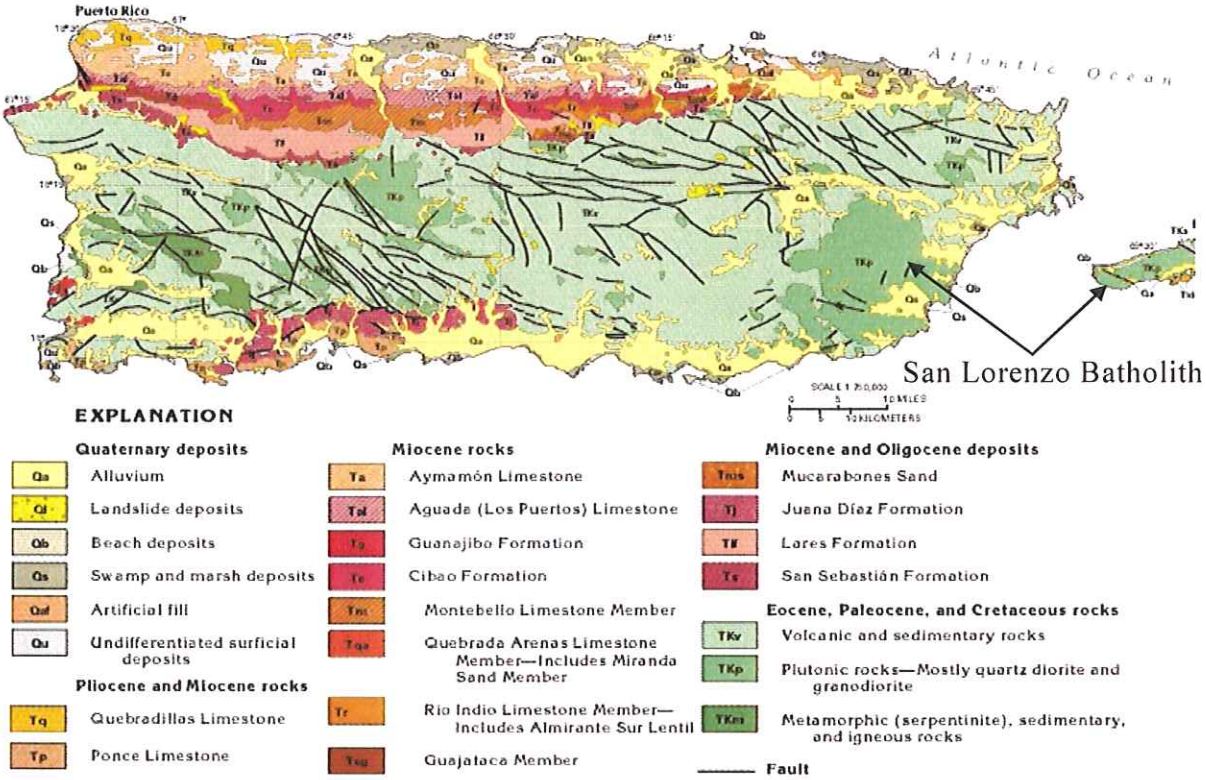


Figure 3: Raised relief and geologic maps of Puerto Rico; reproduced from Joyce (Appendix E)

Giovanni I:\Autocad\Drawings\355/ rlovalenciano\MARCOS

GeoCim LUIS O. GARCIA & ASSOCIATES	SEISMIC HAZARD ANALYSIS					
	RIO VALENCIANO DAM SITE, JUNCOS, P.R.					
	DRW. BY: L. Rivera	CKD. BY: A.S.	SCALE: .	DATE: 1/04/08	JOB. NO: 3357-06	FIGURE NO: 3