APPENDIX E

RIO VALENCIANO DAM PROJECT: SITE GEOLOGY AND GEOLOGIC STRUCTURE ANALYSIS –DR. JAMES JOYCE-

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Rio Valenciano Dam Project
Site Geology and Geologic Structure Analysis

Prepared for the CSA Group
on behalf of
The Puerto Rico Aqueduct and Sewer Authority

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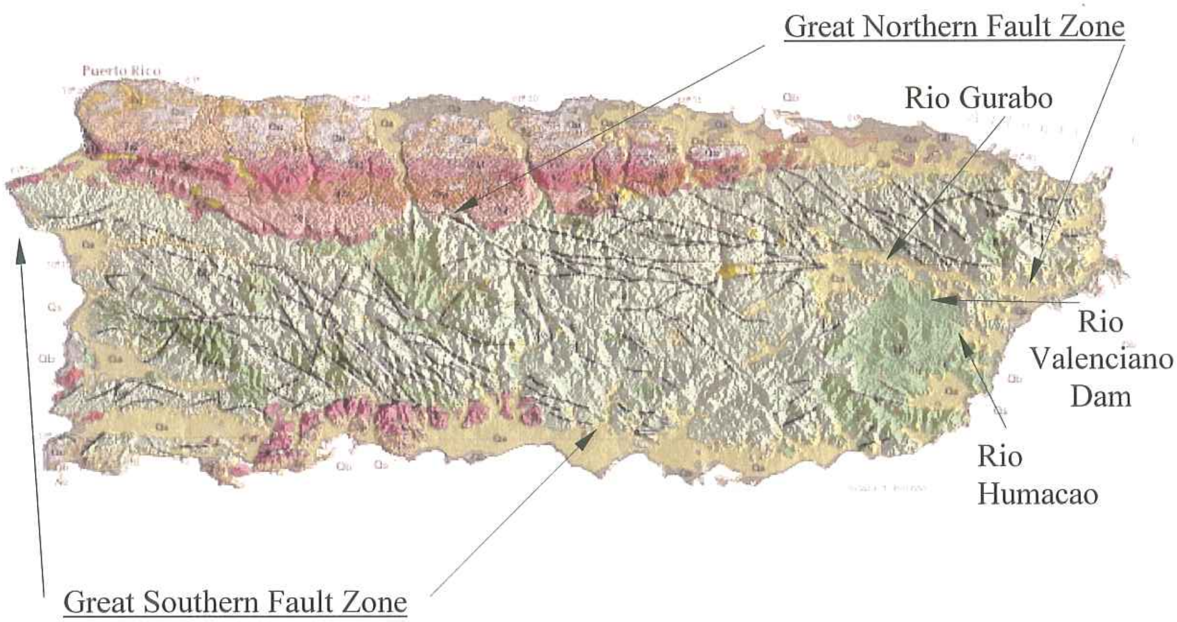


Geology of Puerto Rico

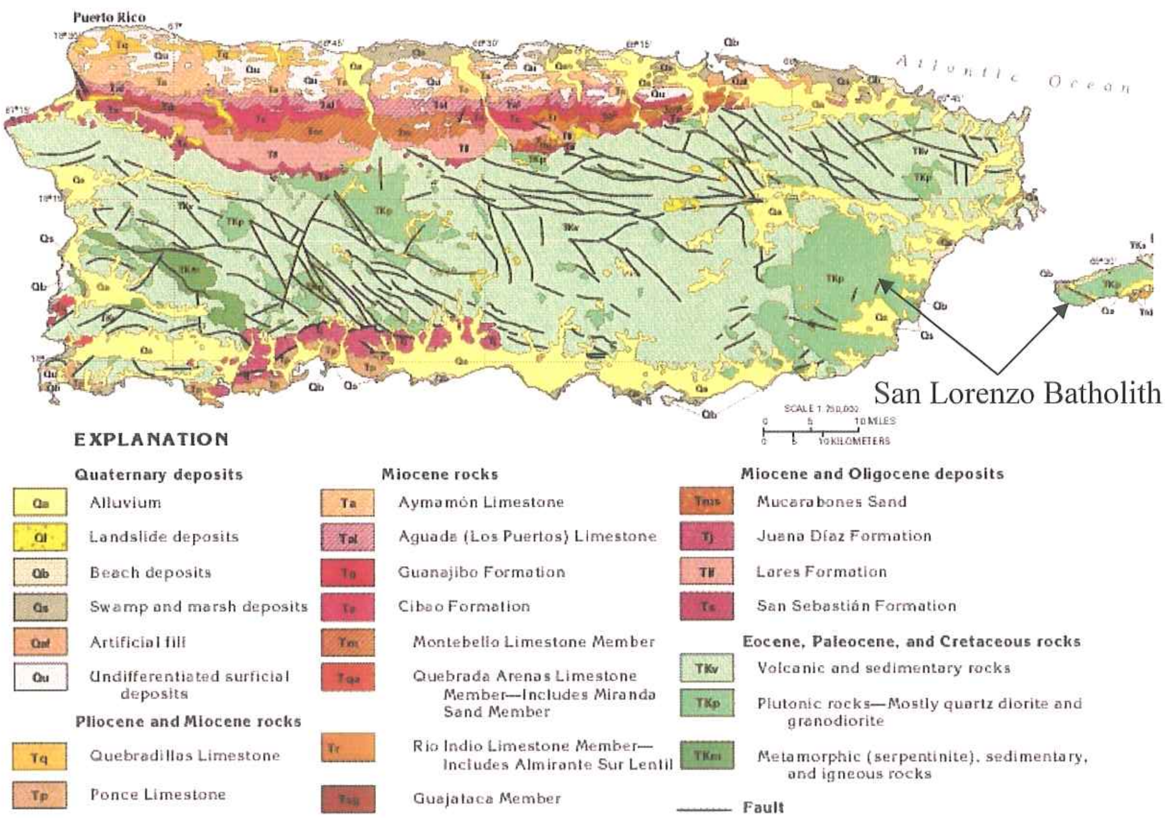


Figure 1 Raised relief and geologic map of Puerto Rico from USGS Groundwater Atlas of the United States (Miller et al, 1997) and the USGS raised relief map.

Introduction

The site of the proposed dam on the Rio Valenciano lies about 3 km south of the city of Juncos and about 4.5 km from its confluence with the Rio Gurabo in the Gurabo valley. The drainage basin of the river covers most of the central and eastern portion of the San Lorenzo Batholith (Figures 1–2). The batholith is an extensive area of coarse-grained granite like rock that covers most of the eastern portion of Puerto Rico. It extends from Caguas on the west to Humacao on the east and from Juncos on the north nearly to Patillas on the south. It likely extends eastward from Humacao as far as the island of Vieques. The batholith is bound on the north and northeast by a belt of hydrothermally altered volcanic rocks that follow along the Cerro Mula Fault and the other faults that comprise the Great Northern Puerto Rico Fault Zone (Figure 1-2). The fault zone is characterized by a pronounced, parallel, linear valley that extends from the east coast to just west of Caguas. The Rio Valenciano crosses the hydrothermally altered rock as it confluences with the Rio Gurabo at the southern margin of that valley (Figure 2). The Gurabo valley is characterized by raised fluvial and alluvial fan terraces especially along its margins (Figure 2). The Cerro Mula Fault is considered have undergone considerable left lateral displacement (north side west – south side east) between 100 and 75 million years ago. Subsequent displacements along faults in the Great Northern Puerto Rico Fault Zone likely continued up to about 35 million years ago. The pronounced geomorphic expression (principally parallel river valleys) of the fault zone and other faults in eastern Puerto Rico raises the question of recent or active displacements along these faults. The Rio Valenciano is characterized by extend straight stretches and sharp angular bends indicative of either joint or fault control over river flow. The northwest trend of the southern portion of the river valley is essentially parallel to and aligned with the extension of the fault mapped in the Rio Humacao (Figure 2). At the drainage divide between the two rivers there is another drainage alignment the trends off to the west-northwest into the Rio Grande de Loiza valley towards Caguas (Figure 2b). There are relatively few shallow crustal earthquakes that occur in the eastern portion of the island. Only two events occurred Gurabo valley along the western trace of the Cerro Mula Fault. A few events also occurred along the southeastern end of the Cerro Mula Fault. Five seismic events have occurred along the Rio Valenciano and two of these events occurred only about a kilometer east of the dam site. A few events also occurred along the Rio Humacao valley and in the hills just to the south of the valley. The remainder of the events fall in the hills between the Cerro Mula Fault and the Rio Valenciano-Humacao valleys. A 7.4 km deep, felt, magnitude 3.4, earthquake occurred on January 2, 2007 close to the Rio Grande de Loiza valley on the boundary between the Caguas and Juncos quadrangles Figure 4. This event was followed by several more shallow earthquakes in that area, one along Rio Valenciano, one along Rio Humacao and three south of it. Notably all these events are aligned NW. Recent GPS studies by Jansma and Mattioli (2005) suggest up to a few mm/yr of NE to ENE extension may occur between the northeast and northwest ends of the island (Figure 5). This differential movement is likely accommodated by reactivation of favorably oriented older bedrock faults. Assessment of active faulting in the dam site region is the focus of the earthquake hazard components of the overall study. The study herein focuses on the geologic structure of the dam site.

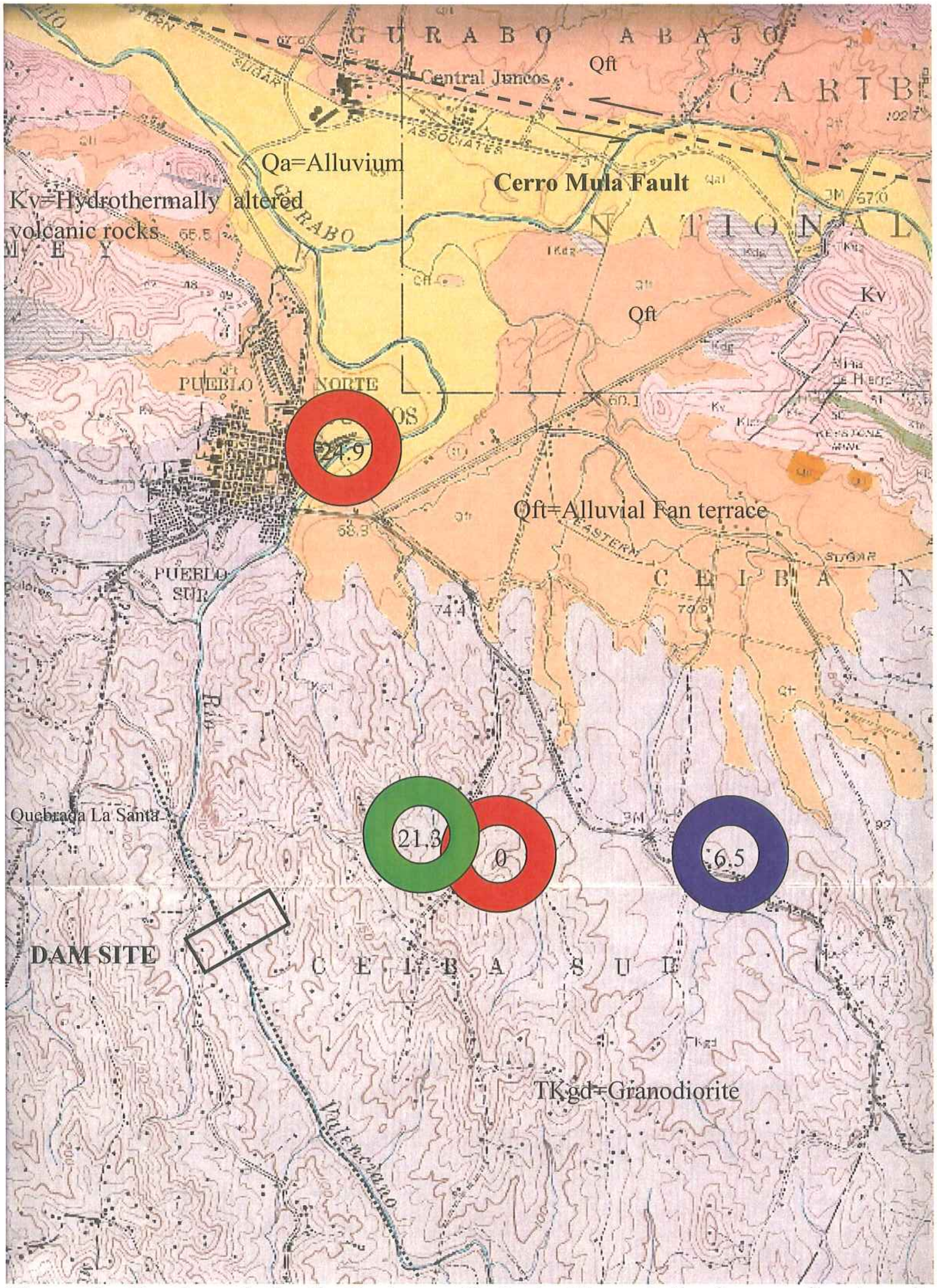


Figure 2a Portion of the Preliminary Geologic Map of the Juncos Quadrangle (Broedel, 1961). The dashed line is the extension of the Rio Humacao fault. Circles are earthquake epicenters with depths. Magnitudes; 1-2 = blue; 2-3 green; 3-4 red.

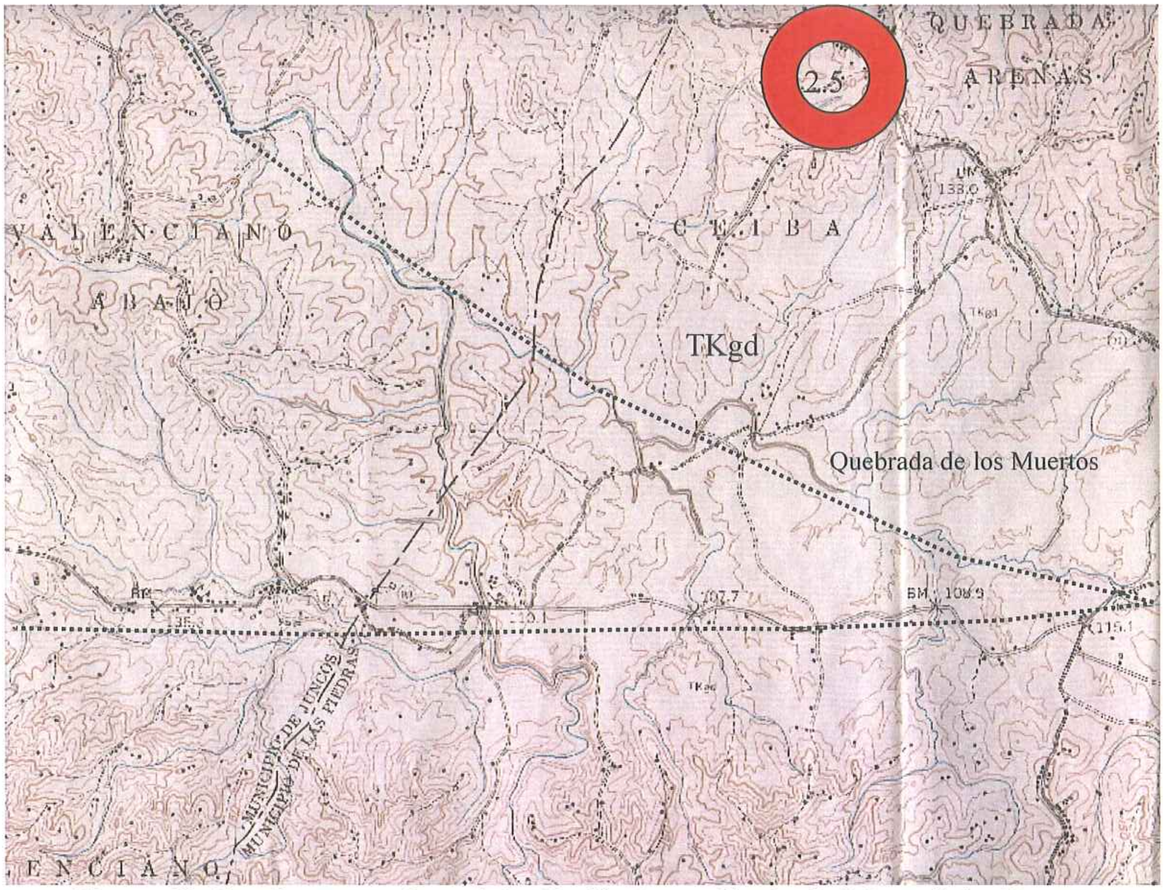


Figure 2b Southern portion of the Preliminary Geologic Map of the Juncos Quadrangle (Broedel, 1961) along Rio Valenciano. Symbols same as 2a.

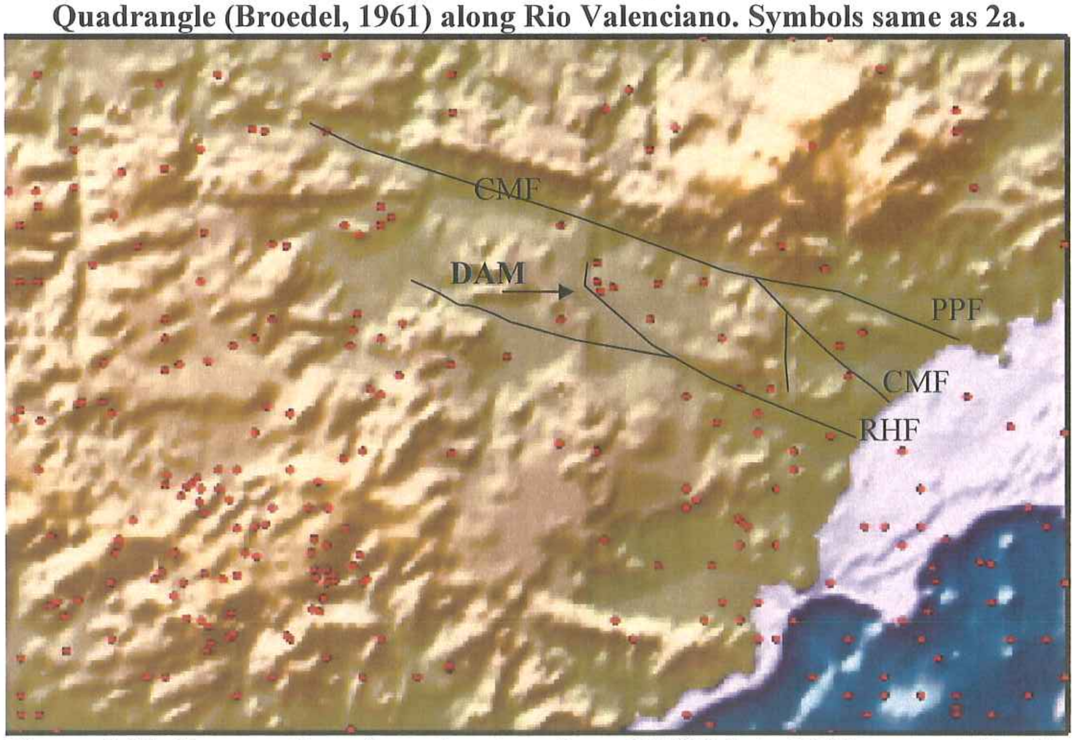
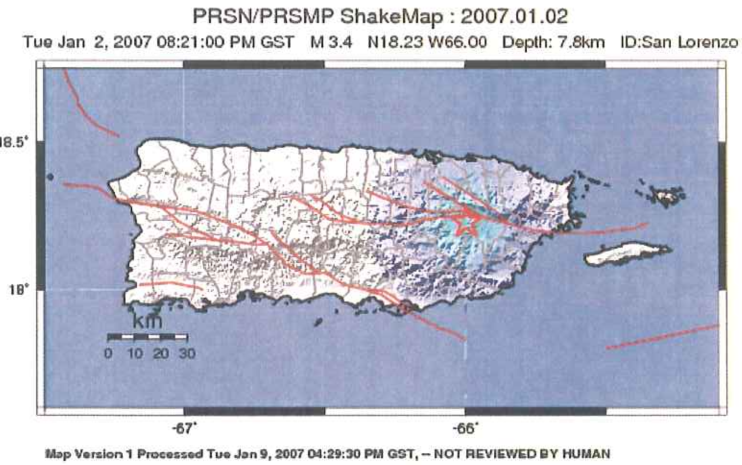


Figure 3 Shallow earthquake epicenters from PRSN data 1995-present. Faults: HF = Rio Humacao Fault, CMF = Cerro Mula Fault, PPF = Peña Pobre Fault.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 4 Shakemap intensity estimate for recent local earthquake by PRSN.

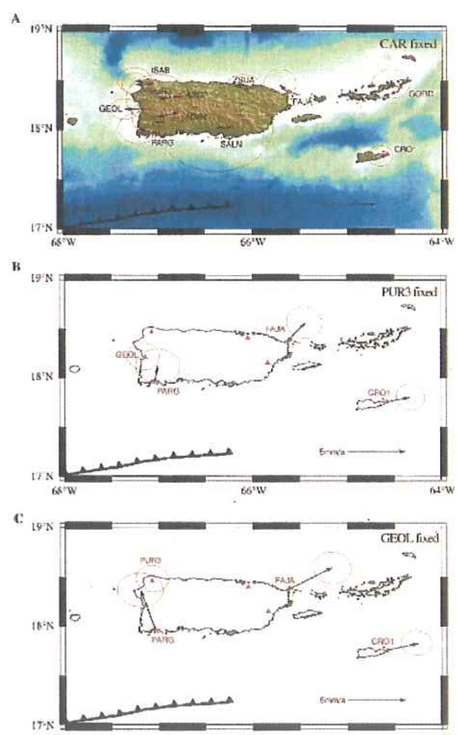


Figure 5. (A) Velocities relative to Caribbean reference frame. Confidence ellipses are 1σ. Heavy black line with triangles offshore south of Puerto Rico represents the Muertos trough. (B) Velocities relative to fixed GEOL. For magnitude of changes along baselines, see Table 2. (C) Velocities relative to fixed PUR3. Table 2 lists velocities and 1σ for sites. Note that calculated 1σ errors were determined by propagating errors from the ITRF2000 time series component errors and likely are overestimates; therefore, error ellipses shown have been scaled to 0.5 1σ.

Figure 5 Jansma and Mattioli (2005) Figure 5 showing GPS estimates of relative motion between Puerto Rico stations and the Caribbean Plate and within the island.

Site Geology

The site lies in the north central portion of the San Lorenzo Batholith. Previous studies have established that the batholith is mainly composed of granodiorite that was mostly emplaced about 70-80 million years ago (M'Gonigle, 1978, Cox et al, 1977). Field exposures in the site area and cores drilled along the dam centerline were all composed of granodiorite. The exposed granodiorite rocks are composed of 30-60% white feldspar (mainly plagioclase), 20-50% clear quartz, 20-30% black hornblende and 0-5% pink feldspar (orthoclase). Metamorphosed mafic xenoliths are common in larger exposures and were identified in the Black and Veatch cores. The xenoliths range in size considerably but are usually between 5-20 cm in diameter. Some of the xenoliths have been epidotized where the granodiorite is cut by epidote veins (Photo 1). A few thin, pink feldspar rich aplite dikes were also observed in the exposures with concentrated epidote veins (Photo 1). The granodiorite is also cut by both orthogonal and conjugate joint sets.

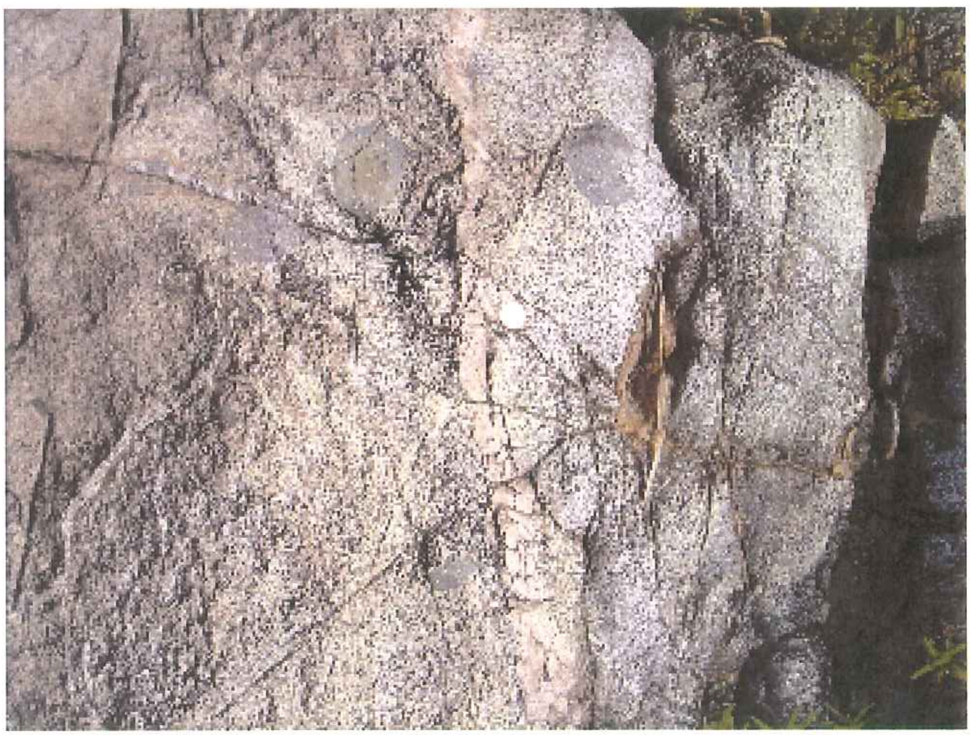


Photo 1 Granodiorite with xenoliths and cross cutting aplite dike and joints.

The infiltration of water along the joints has promoted deep chemical, granular weathering and the production residual grus and saprolitic sand soil. Preferential water infiltration along the dominant orthogonal joints has resulted in spheroidal weathering and the production of corestones boulders that characterize the hillside exposures of the granodiorite (Photo 2). Because of the high percentage of quartz in the rock the residual soils are extremely high in sand content. The sand soils are highly erodable and this results in the river being overcharged with sand (Photo 3). The extremely high sand bed

Photo 2 Spheroidal weathering: corestone surrounded by grus and sand residuum.

load of river poses a significant problem to maintaining the reservoir capacity of the dam. At present the periodic extraction of the bed load sand from the river channel is required

Photo 3 Bed load sand trapped behind the small holding dam below the dam site.

to maintain the capacity of the small holding dam at the intake plant downstream of the proposed dam site. A mitigation plan for this sedimentation problem must be considered.

Black and Veatch Joint Analysis

Granodiorite is a very homogeneous, strong to very strong rock that is largely impermeable. Therefore the in-situ rock strength and permeability of granodiorite are controlled by the occurrence of joints. For this reason a detailed study of joints and permeability were undertaken in the previous study of the dam site by Black and Veatch. The Black and Veatch joint analysis consisted of core description and outcrop descriptions with attitude measurements. The strike and dip of joints measured around the dam site area were complied on a stereograph in Figure 5 of their 2000 report to the Infrastructure Finance Authority. Based on the contoured distribution of the measured joint poles they concluded that the granodiorite at the dam site was dominated by 4 joint sets. Joint sets 1 and 2 were both vertical to sub-vertical and trended N14E and N8W respectively. The report commented that these two sets might actually be the same set with an average north trend. Measurements made during the present investigation support this idea. The third dominant set was also characterized as vertical to sub-vertical, trending N80E and largely perpendicular to joint set 1-2. The present study largely confirms this as a dominant joint set but with an average strike of E-W. A fourth dominant joint set was determined to have an average strike of N56W with average dip of 85° SW. The importance of this set could not be confirmed by the present study. In fact, no joints even similar to this attitude were measured in the present investigation. This discrepancy between the two data sets is inexplicable. It is possible that the N56W joint set only occurs locally and in exposures not included in the present study. The report also noted the occurrence of a low angle joint set but cited difficulty in measuring these joints had precluded their measurement and inclusion in the orientation data on their stereograph. Spacing between joints in the dominant sets observed in outcrops was described as between 0.3-1.0 meters and for the subsidiary sets as between 2-3 meters.

Joints were also carefully described in the Black and Veatch boring-core logs. The logs described joint angle and conditions including planarity, roughness, openness, and infilling. Rock Quality Designation (RQD) percentages were determined for each core run. No recovery zones were interpreted in the report as washed out weathered rock or residuum between corestones. The core descriptions annotated with some present interpretations are summarized below:

BV-1-102.5

13.2-25.5 (8.3') Corestone, moderately. wide-wide, (70-90°, 10°, 80°)(10-30°), Planar, slightly rough to rough RQD-100%

25.5-28.1 (2.6') NR residuum

28.1-33.2 (5.1') Corestone, RQD-71%

33.2-33.9 (0.7') NR residuum

33.9-44.0 (>10') Corestone/granodiorite, very wide, (0-20°, 30°, 70-80°), Planar, slightly rough to rough RQD-100%

BV-2-124.8

5.0-25.0 (20') Granodiorite, wide-very wide, (50-80°), (40-50°)/4, Planar, smooth, RQD-83,100,94,98,100%

25.0-45.0 (20') Granodiorite, wide-very wide, (0-10°, **40-50°**/2, 60-70°)
Planar, smooth to slightly rough, RQD-100%

45.0-60.0 (15') Granodiorite, wide-very wide, (10-30°)
Wavy, slightly rough, RQD-100-91-100% 53.0 brown water

BV-4-83.1

35.2-38.4 (3.2') highly weathered Granodiorite RQD-15%

38.4-39.0 (0.6) NR residuum

40.0-45.0 (5') moderately weathered Granodiorite -, (50-60°/2,70°)
Planar, smooth, narrow, RQD -51%

45.0-64.1 (19.1') Granodiorite, wide-very wide, (40°/2, 40-50°,70-80°,80-90°)
Planar, smooth to rough, narrow to very narrow, RQD-100%

BV-5-77.7

14.0-18.7, (14.7') weathered Corestone,-, (0-20°/2, 40-50°)
Planar, slightly rough, narrow, clay and sand filled,RQD-0%

16.7-19.0, (2.3') NR residuum

19.0-32.8, (13.8') Corestone,-,(75°,<u>70°</u>,0-20°), (30°,*15°,60°*), (30-50°,*90°*,50-70°)
Planar (1wavy), slightly rough, very narrow, <u>1 narrow clay filled</u>, *3 tight quartz filled,* RQD- 82%, 95%

32.8-36.1, (3.3'), NR residuum

36.1-43.3, (7.2'), Corestone,-, (80°, 20-30°), Irregular, Planar, very rough, slightly rough, very narrow, RQD-31%, 64%

43.3-44.65 (1.35') NR Residuum or sub-horizontal joints

44.65-52.4 (7.75') Corestone/granodiorite, (*15°,*10-20°, 50°), (80°, 50°), Planar, slightly rough-rough, very narrow, *narrow quartz, green mineral filled,* RQD-70%, -%

52.4-54.0 (1.6'), NR Sub-horizontal joint/core end

54.0-60.5 (6.5') Granodiorite/corestone, (*70-90°*, 10°), *Wavy, rough, narrow, quartz and green mineral filled,* Planar, rough, RQD-93%

60.5-60.75 (0.25') NR Sub-horizontal joint-weathered below

60.75-64.0 (3.75') Moderately to slightly weathered granodiorite, (0-90°), Planar, smooth, RQD-34%

64.0-69.0 (5.0') Granodiorite/corestone, (35°, 45°), Planar, rough, slightly rough, RQD-100%

69.0-70.0 (1.0) moderately weathered Granodiorite, (sub-horizontal joint?)

70.0-73.0 (2.0) Granodiorite, (0-90°), Planar, slightly rough, RQD-80%

73.0-74.0 (1.0) Highly to extremely to slightly weathered granodiorite, (sub-horizontal joint?)

BV-7-80.2

14.1-15.0 (1.0') Corestone

15.0-17.0 (2.0') NR residuum

17.0-20.0 (3.0') Corestone, highly fractured, (<u>10-30°,70°</u>, 15°,80°), Planar, slightly rough/2, rough/2, <u>narrow clay filled</u>, very narrow.

20.0-23.1 (3.1') NR residuum

23.1-25.0 (2.9') Highly weathered and fractured granodiorite

25.0-27.5 (2.5') Moderately weathered granodiorite

27.5-30.0 (2.5') Slightly weathered granodiorite, RQD-66%
30.0-46.3 (16.3') Granodiorite, (60°/2,30°, 75°), Planar, slightly rough, rough, (70°), (0-10°, 70°, *20°*), (60°), Planar, *planar-irregular*, slightly rough, *rough-very rough*, narrow Fe-clay, RQD-100%/2, 96%
40.0-42.0 (2.0') Andesite dike
46.3-50.0 (3.7) Unrecovered core

BV-8-102.23

13.35-15.0 (1.65') Corestone, -, (60-90°)
15.0-16.65 (1.65') NR residuum
16.65-24.65 (8.0') Corestone, -, (90°/2, 0-70°, 0-30°) (50-60°) Planar, smooth to slightly rough RQD-50%
24.65-25.00 (0.35') NR residuum
25.0-27.0 (2.0') Corestone, -, (50-60°), Planar, smooth
27.0-28.0 (2.0') NR residuum
28.0-29.0 (1.0') Corestone
29.0-30.7 (1.7') NR residuum
30.7-63.0) (32.3') Granodiorite -, (60-70°/40-50°/2, 0-40°, 10-20°) Planar-wavy, Smooth-slightly rough, RQD-56-46-100/2-92-80-100-88
48.5-50.0 (1.5'), RQD-20, sub-horizontal joints?

In general most of the joints were described as planar, slightly rough with very narrow openings (<0.05"). A few joints in the upper portions of the cores had narrow openings (0.05-0.1") and clay infilling. A few joints were filled and healed with quartz. 20% of the joints were inclined 0-20°;34% were inclined 0-40°; 29% were inclined 30°-60°; 22% were inclined 50°-70°: 32% were inclined 70°-90°. Joint angle data from cores are obviously biased against the vertical joints. Field observations and measurements in the previous and present study have established that the dominant joint patterns are inclined 85°-90° and sub-horizontal. The remainder of the moderately to steeply inclined joint sets are subsidiary but obviously important. Although the core descriptions of joint conditions are quite good they are limited because of their size in fully describing planarity, roughness and continuity as well as the spacing of vertical joints. Other than a general statement on opening and spacing no field observations regarding joint conditions were included in the report. The present study has specifically undertaken the task of joint measurement and condition description with a special focus on the low angle joints.

Joint Orientation and Condition Analysis

The present joint analysis collected data from the river bank and channel exposures from the around dam site to 1 kilometer downstream (north) and along a rocky, southwest flowing river stretch about 2 kilometers upstream (south)(Figure 7). Joint data also came from road cuts along PR 919 from 0.5 to 1.5 kilometers south of the site (Figure 7). The summary of the measured joint set pole orientations are shown on the stereogram in Figure 6. The vast majority of the measured joints fall into one of three nearly orthogonal dominant joint sets. Joint Set 1 trends N-NNE and is vertical to steeply inclined W-NW. Joint Set 2 tends E-ENE and is vertical to steeply inclined S-SSE. Joint Set 3 is sub-horizontal and inclined northward about 10°-20°. The dense concentration of

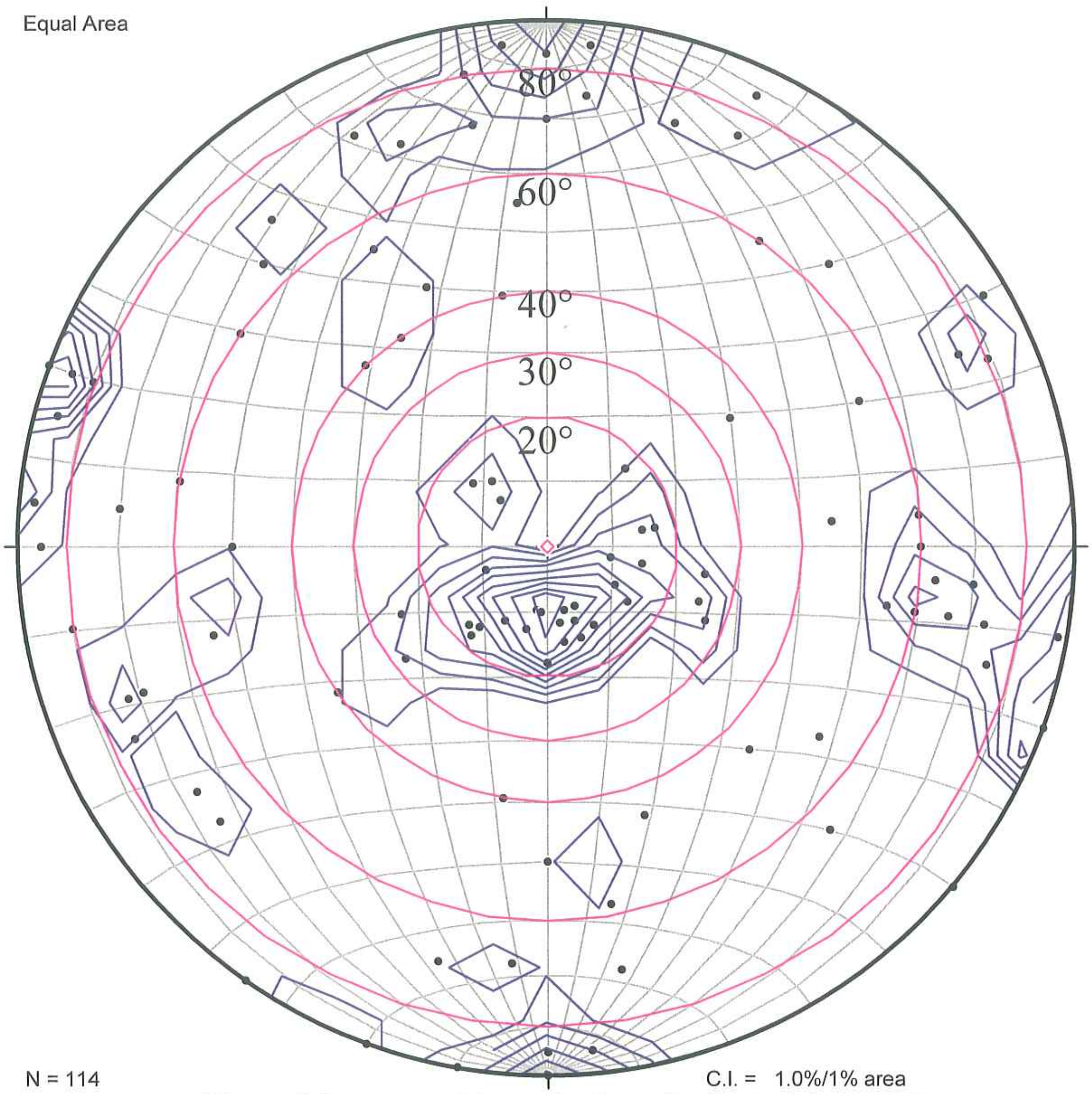


Figure 6 Stereographic projection of poles to joint set planes.

sub-horizontal joint poles is largely due to multiple measurements at one or two localities. The contoured pole densities do not represent a true statistical analysis as sampling was not statistical. The contour data does however, delineate well the dominant and subsidiary joint sets that were observed in the field area (Photos 1-2, 4-6, 7-10). The dominant orthogonal joint sets 1-3 define the boundaries of spheroidal weathering corestones throughout the observation area. The massive corestones are often cut by inclined, conjugate joints. When seen in extended outcrops the 2 vertical sets are generally continuous with spacing of 1-5 meters and sometimes greater. Intervals between the continuous joins are sometimes characterized by discontinuous and semi-continuous parallel joints with spacing about 0.5-1.0 meters lending a thicker and thinner "bedded" appearance to the massive igneous rock. Joints in surface exposures tend to be open from 2mm to 2cm (*moderately wide to wide*) and some are filled with clayey soil or grus residuum. Their surfaces tend to be planar and rough to slightly rough.

The sub-horizontal joint set 3 differs markedly in character from the vertical sets. The sub-horizontal set tends to be semi-continuous on the order of 5-15 meters or greater, wavy to anastomotic with slightly rough to irregular surfaces (Photos 4-5-6). The sub-

Photo 4 Sub-horizontal sheeting and orthogonal joints in PR 919 road cut at site #4.

Photo 5 Sub-horizontal and steeply inclined joints on the riverbank at site #10.

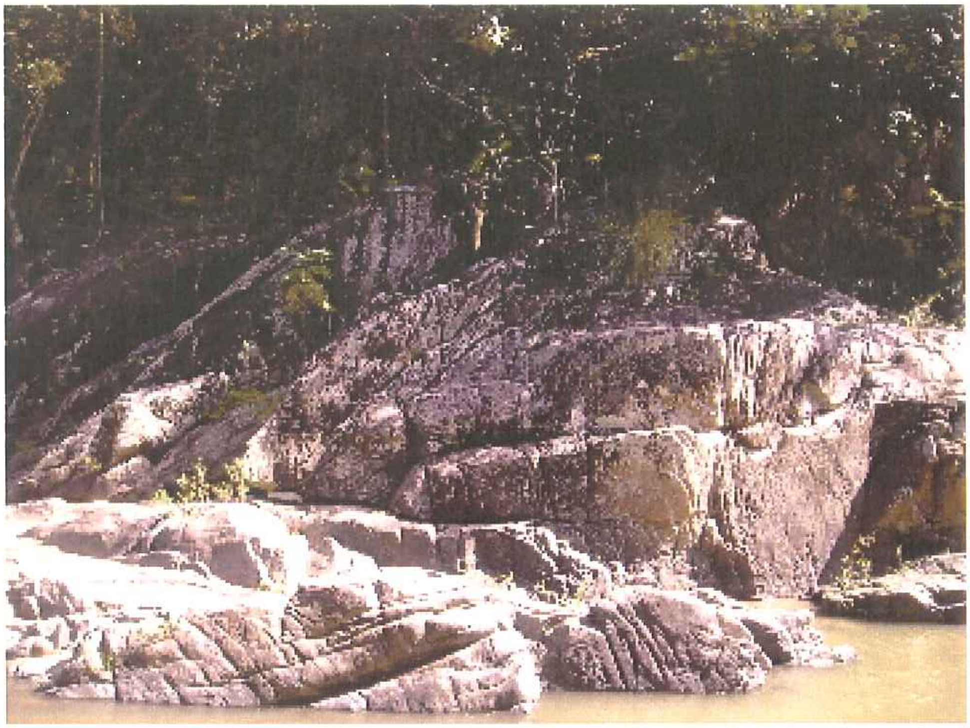


Photo 6 Sub-horizontal and inclined joints on adjacent river bank at site #10.

horizontal joints are open wide to very wide (2-5 cm) and sometimes filled with clayey soil or sandy residuum. Spacing of the semi-continuous joints is 1-10 meters. Intervals between the semi-continuous joints are characterized by discontinuous joints with spacing from 2cm to 1.0 m. The occurrence and continuity of the sub-horizontal joint sets at the dam site is of particular importance. The Black and Veatch cores along the dam centerline were analyzed to that affect. Semi-continuous sub-horizontal joints and corestone boundaries were recognized in the cores as no recovery zones that were underlain by weathered rock. Sub-horizontal joints were also recognized from the core descriptions with angles between 0-20°. Core borings BV-1 and BV-8 are about 200 meters apart and at the same elevation 102 meters on opposite ends of the dam centerline. Both borings encountered corestone boundaries at elevations of 98 – 94 – 93 – 91-2 meters. BV-8 probably encountered another boundary or sub-horizontal joint at elevation 86.3-85.8 meters. Boring BV-7 was located on the west side of the centerline at an elevation of 90.2 meters. Corestone boundaries – sub-horizontal joints were encountered at elevations of 85.5 – 84.6 – 83.2. Sub-horizontal joints were noted in the core at elevations of 77.1 and 76.1. Unfortunately no core descriptions that cover the same intermediate elevation interval as BV-7 were provided for the east side of the centerline on the opposite side of the river. Therefore continuity of the joints across the river channel at these elevations cannot be assessed.

Boring BV-5 is located near the west bank of the river at an elevation of 77.7 meters. Corestone boundaries were encountered at elevations of 73.1 – 72.2 – 65.9 – 63.5 – 60.2 meters. Sub-horizontal joints were recognized at elevations of 57.8 – 55.1 – 53.7. Boring BV-4 was located along the dam centerline on the east side of the river 50 meters east of BV-5 and at an elevation of 83.1 meters. The boring encountered 35 feet of weathered granodiorite residuum down to an elevation of 71.5 meters which is about 1.5 meters below the riverbed. The boring continued through highly to moderately weathered granodiorite down to an elevation of 69 meters. No recovery intervals that may be sub-horizontal joints occurred between 70.5 and 70.0 meters. There is no record of sub-horizontal joints or core losses below an elevation of 69 meters down to the end of the core at 62.1 meters. The corestone boundaries and sub-horizontal joints recorded at elevations of 65.9 and 63.5 meters in BV-5 apparently are not continuous below the riverbed as far as BV-4. It should be noted however that 1-3 meter corestones with sub-horizontal joints and boundaries were observed along the eastern banks of the river near the location of the centerline (Figure 7, 1-2) whereas the western bank near the centerline location is composed of granodiorite residuum with a few small corestones. The sub-horizontal joints are believed to be formed by unloading and when closely spaced appear like sheeting (Photo 4). The general northward inclination may be due to the post Miocene northward tilting of the island. As the sub-horizontal joints probably formed by unloading there is some concern that deeper excavation during construction of the dam could lead to propagation and extension of these joints below the dam foundation surface.

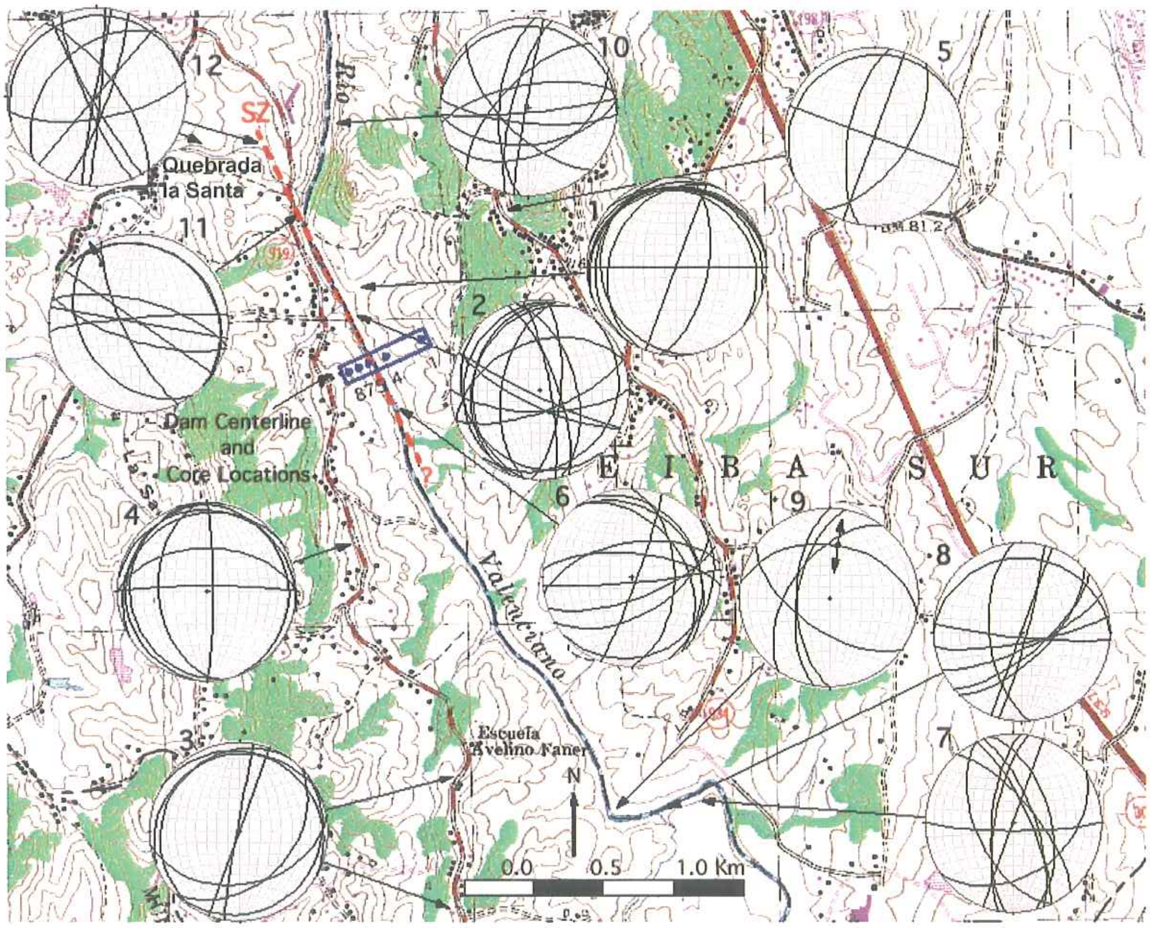


Figure 7 Topographic map showing the locations of the dam centerline, Black and Veatch cores and present study sites with stereographic plots of joint measurements.

Important subsidiary joint sets are moderately to steeply inclined and trend NNW, NE, and EW. These joint sets tend to be concentrated in fracture zones marked by closely spaced dominant and subsidiary joints. The subsidiary joints tend to be conjugate about the N-S and E-W trending dominant joint sets. The NNW trending joint set clearly controls the orientation of the Rio Valenciano valley and channel at the dam site, 0.5 km downstream and nearly 2 km upstream (Figure 7). Fracture zones with closely spaced dominant and subsidiary joints commonly contain quartz-epidote, or thin aplite dikes. Most of the observed veins trended E-W and were steeply to moderately inclined. A few of these veins showed evidence of dip parallel shear. Some NW – NE trending conjugate veining was observed at Sites 7-8 (Figure 7). Although these conjugate veins cut across xenoliths no evidence of shear displacement of the xenoliths was observed. Likewise, no shear displacement was observed where xenoliths were cut by any other joints. Epidote fiber slickenside slip striations were observed on a NNW trending steeply inclined joint face in a fracture zone about 500 meters downstream from the dam site. The fracture zones therefore, may actually represent fault zones or zones of greater extension. The intensity of jointing in the fracture zones promotes the infiltration of water and more complete and homogeneous weathering, thus thwarting the spheroidal weathering that is so common throughout the area. The fracture zones are more deeply weathered with thick residual soil covers and more subject to erosion. Notably, boring BV-4 penetrated 35 feet of residual soil and completely weathered rock before encountering fresh rock.

Fracture-Fault Zone Analysis

The second part of the geologic structure analysis was focused on the recognition of bedrock fault zones in the river valley that may approach or even pass under the dam site. The impact of these fault zones on the dam could be two fold. Reactivation of these fault zones could produce earthquakes that cause strong ground motion or even displacements at the dam site. If these bedrock fault zones pass under the dam site they could be zones of structural weakness and higher permeability that could affect the stability of the dam. Although the 1961 Preliminary Geologic Map of the Juncos Quadrangle (Broedel, 1961) does not show any faults in the area, the Metallogenic Map of Puerto Rico (Cox and Briggs, 1973) shows a NW trending fault extending from Humacao along the Rio Humacao into the upper portions of the Rio Valenciano. The Geologic Map of the Humacao Quadrangle (M'Gonigle, 1978) shows the fault in the Rio Humacao as inferred with the south side of the fault displaced upward (Figure 8). The parallel mylonite shear foliations shown in the granodiorite along the river valley were presumably the evidence for the inferred fault and displacement. A sub-parallel mylonite zone is mapped just south of the Rio Humacao. Slickenside measurements along the mylonite zone suggested reverse and left lateral displacement along the fault zone. The parallelism and continuity of the upper Rio Humacao and Rio Valenciano - Quebrada de los Muertos river valleys combined with the straight NNW trending 2.5 kilometer stretch of the Rio Valenciano suggests that the fault in the Rio Humacao may extend northward below the Rio Valenciano and the proposed dam site (Figure 2). Besides the straight NNW trending channel other evidences for a bedrock fault below the river at dam site were cited by Black and Veatch in their report as: a 13 foot long fault gouge recorded in a Corps of Engineers' core located about 500 meters downstream from the dam; a sheared or hydrothermally altered dike in a river exposure about 100 meters down stream of the site; a suspected sheared or hydrothermally altered dike in the core of boring BSJ-13.

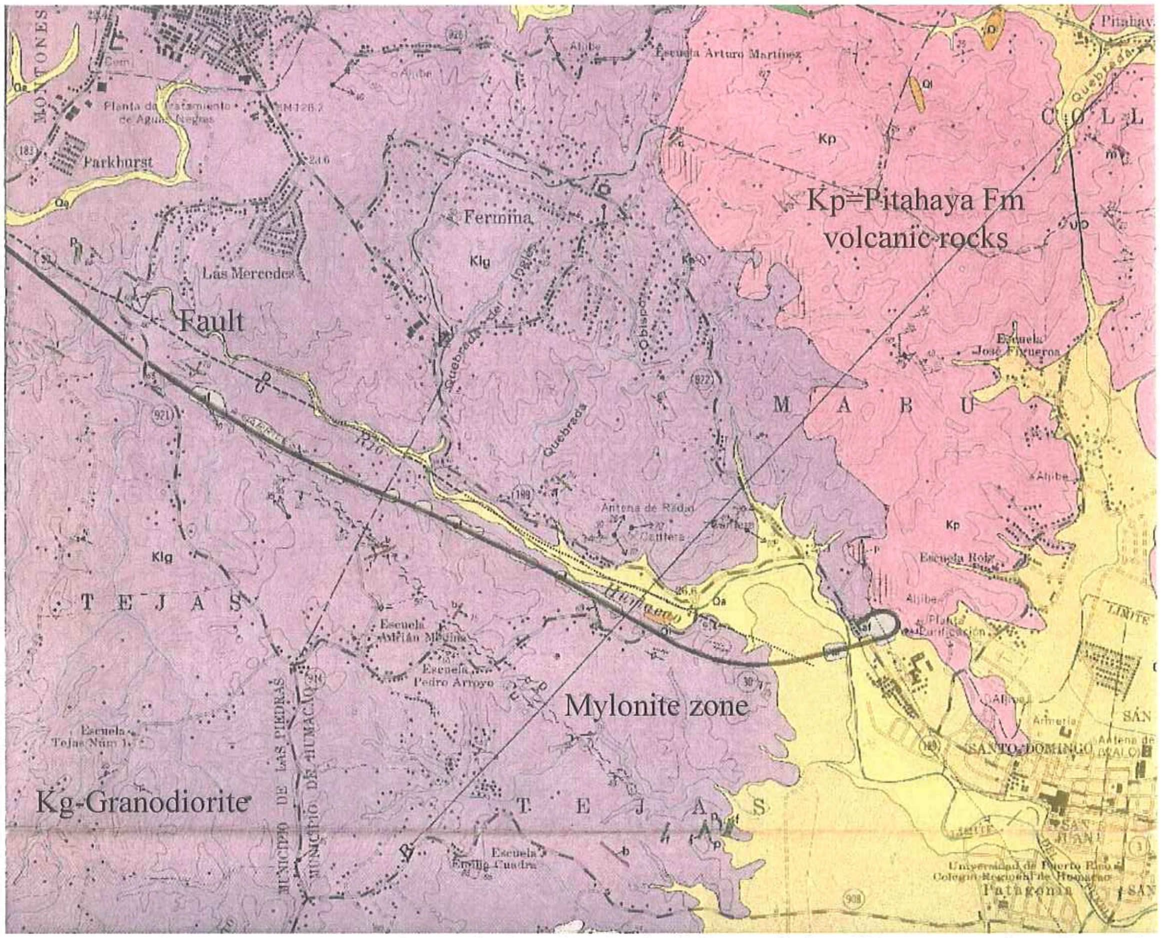


Figure 8 Rio Humacao portion of the Geologic Map of the Humacao Quadrangle (M'Gonigle, 1978) showing the mylonite zone and the inferred fault in the river.

Rock exposures in and along the river channel were inspected for evidence of bedrock faults. Special attention was paid to two stretches of the river where rock was extensively exposed within the channel. The river flows WSW over rock along a 370 meter stretch between two right angle bends about 2 km downstream and southeast of the site (Figure 7, #7-8-9). The bend in the river marks the change in the river course from NW to NNW. If the fault from the Rio Humacao extends northwestward along the Rio Valenciano it should cut across the rock exposures in the WSW flowing stretch (Figure 2b). The locations of the joint measurements in this stretch are shown in Figure 7 along with stereographs numbered 7-8-9. NNW trending steeply inclined joints define a dominant cross channel joint set at the eastern end of the stretch (Figure 7, #7). No evidence of shear was seen on the joint faces nor were there fracture zones developed. Numerous joints cut across xenoliths but no displacements were observed. A well developed fracture zone was observed at the western end of the stretch (Figure 7, #9). The fracture zone was defined by closely spaced N trending steeply inclined joints (Photo 7). Spacing between the joints range between 2-10 cm up to 25 cm within a 3-4 meter thick zone. The dihedral angles between conjugate fractures formed in the fracture zone suggest E-W extension and N-S compression. The only slip striations observed were on a perpendicular northward inclined epidote vein-joint. The slip striations were parallel to the dip but to degraded to determine sense of motion (Figure 7, #9). A small exposure of intensely fractured rock was observed in the river channel just downstream of the western bend (Figure 7, #9). The exposure was characterized by bluish veins that contain pyrophyllite. Overall no evidence was found to indicate that this stretch of the river is traversed by either NW or NNW trending faults, shear zones or mylonite zones.

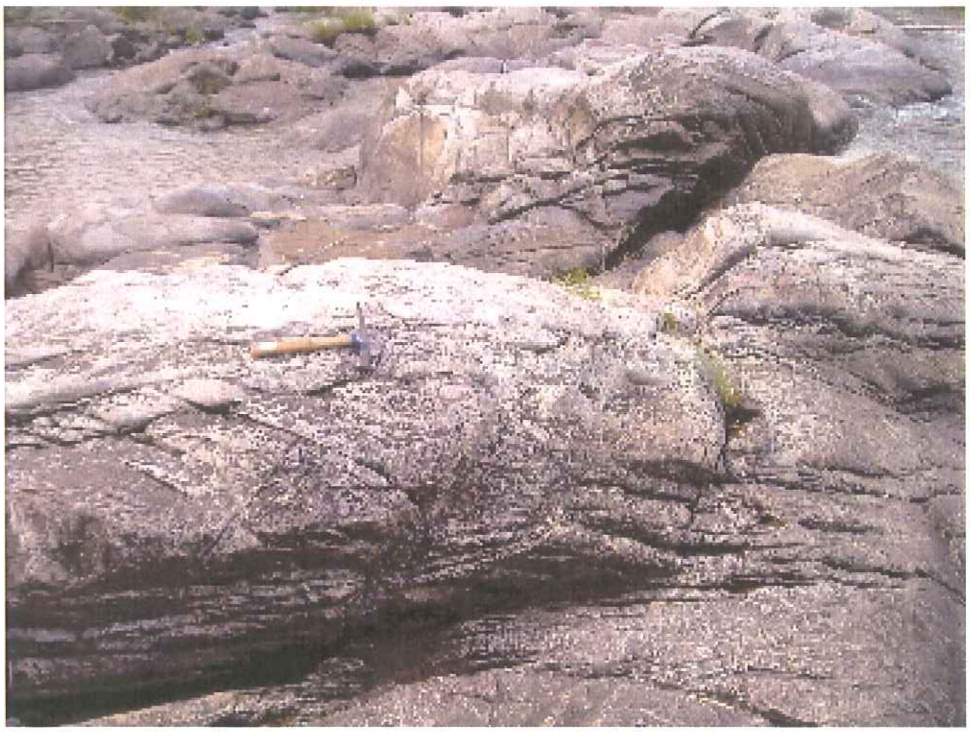


Photo 7 N-S trending fracture zone with conjugate joints at western river bend site 9

The other stretch of river with extensive rock exposure lies about 800 meters downstream of the dam site and about 200 meters from where the river changes course from NNW to N (Figure 7, #10). The rock exposure stretches over about 200 meters where the river is confined to flow within a very narrow, 1-2 meter wide straight channel between two N trending continuous joints (Photos 8-9). The rock exposures are dominated by moderately spaced, continuous, N-NNE and WNW-ENE trending, steeply inclined joint sets as shown in the stereograph #10 on Figure 7. None of the observed joints showed evidence of shear and fracture zones were not developed. Dihedral angles between measured conjugate fractures suggest E-W extension with N-S compression. The observations suggest that the north trending stretch that carries the Rio Valenciano to the city of Juncos is not parallel to a fault but follows north trending extensional joint system instead.

About 500 meters downstream from the dam site the river abruptly changes course towards the north and is joined by Quebrada la Santa from the west (Figure 7). A few small exposures of highly fractured rock occur along the west side of the channel (Photo 10) and in recent excavations at the mouth of the quebrada. The highly fractured rock exposures along the channel are dominated by NNW and WNW trending steeply inclined and NW trending shallow to moderately inclined joints (Figure 7 #11). Joint spacing ranges from 10-50 cm for continuous joints down to 2-5 cm for discontinuous

Photo 8 Rio Valenciano flowing along and within north trending continuous joints.

Photo 9 Rio Valenciano flowing along and within north trending continuous joints

joints. An exposed NNW trending joint face shows slickenside striations in epidote and iron oxide with a rake of 25° (Figure 7, #11 Photo 11). Releasing steps in the slickenside surface suggests an oblique right lateral displacement along the fault with a small normal

Photo 10 Fracture shear zone 500 meters downstream form the dam site.

Photo 11 Slickensides on NNW trending shear plane arrow shows slip direction.

component. That is, the west side of the fault is moving to the north-northwest and down whereas the east side of the fault is moving to the south-southeast and up. The measured strike of the shear plane and parallel joint set is exactly parallel and aligned with the river channel (Figure 7). It is likely that these exposures are then representative of the structural conditions of the rock below the river channel at the dam site. Extending this fracture-shear zone parallel to the strike of the shear plane places it along a NNW trending stretch of the Quebrada la Santa, the quebrada that flows into the river just north of the fracture-shear zone exposures Figure 7. Although the main channel of the quebrada bends off to the west at the end of this stretch, an extensive and topographically pronounced NNW trending drainage gulley confluences the quebrada at that point (Figure 7). A relatively flat exposure of intensely fractured and sheared rock occurs on the inside of the bend at the confluence point (Photo 12). Notably, the east side of the channel at the bend is confined by a vertical NNW trending joint face in massive granodiorite. The fracture-shear zone is dominated by continuous a NNE trending joint-fracture set with a more closely spaced discontinuous NE trending fracture within the NNE joint intervals (Photo 12). The NE discontinuous joints tend to curve counterclockwise into the continuous NNE joints at their terminations. Intersection of the two fractures produces rhomboid to elliptical rock phacoids. The counter clockwise rotation and orientation of the phacoids are compatible with NNE left lateral shear (Photo 12). Despite being aligned with the right lateral shear-fracture zone observed in the river

Photo 12 NE-NNE left lateral shear fractures in shear zone at quebrada bend.

and probably enclosed between NNW trending joints, the sense and direction of shear in the quebrada bend exposure is strikingly different. There are two possibilities for compatibility between the two shear zone observations. The NNE left lateral shear may be a conjugate-antithetic shear system developed in the NNW right lateral shear zone. The other compatible possibility is that the NNE fractures are extensional and intervening NW fractures are left lateral Reidal shears developed within the right lateral shear zone. There is no geomorphic evidence to suggest the alternative that a separate NNE trending shear-fracture zone intersects the NNW right lateral shear zone at the quebrada bend.

The exposure of the river parallel fracture-shear zone discussed above occurs 500 meters downstream from the dam site. This is the same distance stated in the Black and Veatch report (2000) for the Army Corps of Engineers' core site where a 13 foot long fault gouge was reported. Although no true fault gouge was observed in the exposures of the NNW fracture-shear zone, the shear zone exposed at the quebrada bend may appear as a gouge zone when sampled in a boring or a core. No information on this Corps of Engineers core was provided for the present study so this possibility cannot be assessed. Nevertheless, the present observations are compatible with the occurrence of the gouge zone and support the Black and Veatch assertion that a NNW fracture-shear zone may underlie the river channel at dam site. Field observations suggest that the fracture-shear zone is relatively narrow on the order of 2-5 meters perhaps up to 10-15 meters. Previously drilled borings and cores all lie along the riverbanks and therefore do not provide any information about this shear zone nor its hydraulic conductivity. The best solution to this problem would be to place 3 or 4 additional borings and cores in the riverbed along the centerline of the dam. This will allow for assessment of the occurrence of the fracture-shear zone and its impact on the dam as well as provide important information on whether the sub-horizontal joints interpreted from the BV-5 core continue below the river channel. The fact that the local seismic events are aligned with the river and the NNW trend of the fracture-shear zone (Figures 2-3) suggests a potential for reactivation of faulting that requires further investigation.

Conclusions

1. The proposed dam site lies along a remarkably straight NNW trending stretch of the Rio Valenciano that marks the continuation of a pronounced river valley lineament that is parallel to a mapped fault in the Rio Humacao valley. Although local crustal seismicity is relatively sparse the epicenters are close to and aligned with NW-NNW trending Valenciano and Humacao river valleys.

2. The proposed dam site and the Rio Valenciano valley are underlain by massive and strong granodiorite. The granodiorite is characterized by deep granular chemical and spheroidal weathering. The resultant granodiorite residuum extends from 15-40 feet below the surface and spheroidal weathering extends as deep as 75 feet below the surface. Soils produced from the granodiorite residuum are essentially sand. Erosion of these sand soils overcharges the river and poses a significant threat to the longevity of the reservoir capacity.

3. The granodiorite is broken up by and spheroidal weathering produced by the intersection of three regionally dominant joint sets; two vertical sets that trend N to NNE and WNW to ENE and one sub-horizontal set that is generally inclined 10-20° northward. The sub-horizontal joints are continuous for distances of 5-15 meters or

possibly much greater and pose the greatest concern for the foundation stability of the dam. Joint surfaces in exposures are commonly wavy, rough to irregular and wide open.

4. An important subsidiary joint pattern trends NNW and controls the direction of the river channel and valley at the dam site and 2 km upstream. A NNW trending right lateral fracture-shear zone emerges from the river channel about 500 meters downstream where the channel abruptly bends to the NNE and N. The fracture-shear zone continues off to the NNW along the Quebrada de la Santa and into a tributary gulley. It is probable that this fracture-shear zone extends SSE downstream below the river channel and the dam site but this has yet to be established.

Recommendations

1. Continued monitoring and definition of the crustal seismic activity in and around the Rio Grande de Loiza, Rio Valenciano and Rio Humacao river valleys. Pursuit and procurement of GPS data to determine estimated movements between the Fajardo, Humacao and Rio Piedras continuous sites.

2. Perforation of 3-4 borings and cores in the river channel along the dam centerline to precisely define the geologic structure below the river bed, in order to determine both the existence and character of the fracture shear zone and the continuity of the sub-horizontal joints below the river.

3. Continued mapping and analysis of bedrock structures in the dam site area, rivers valleys associated with faults or earthquakes and outcrops of previously mapped faults.

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