APPENDIX G

GEOLOGIC EVALUATION STUDIES FOR THE RIO VALENCIANO DAM: 1. FAULT EVALUATION-PHASE TWO –WILLIAMS ASSOCIATES-

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CSA Group Architects and Engineers
Mercantil Plaza, Mezzanine Suite
San Juan, Puerto Rico 00918
Attention: Teresita Colom-Vega, PE

7 January 2008

Subject: Final Report: Paleoseismic Evaluation of the Northern Puerto Rico Fault Zone

Dear Ms. Vega:

For Williams Associates I am pleased to present this (DRAFT) final report documenting a paleoseismic investigation of the Northern Puerto Rico Fault Zone (NPRFZ) of eastern Puerto Rico. Following our statement of work under CSA Contract Number CI-2006-061-B PMC, this investigation included: (1) review of previous studies; (2) interpretation of historical and modern aerial photographs; (3) acquisition, processing and interpretation of regional Lidar data; (4) field inspection and evaluation of suspect fault features identified from studies and remotely sensed data; and (5) subsurface exploration of principal (suspected) fault features to search for direct evidence of activity or non-activity. This report partially satisfies the terms of the above contract.

The purpose of this investigation is to independently assess the seismic potential of the Northern Puerto Rico Fault Zone through exploratory trenching and geomorphic analysis to provide an objective basis for inclusion or exclusion of the zone as a seismic source in seismic hazard assessment and design parameters for the Valenciano Dam. The analysis, interpretations, and findings are derived from a large geologic and paleoseismic investigation of the Northern Puerto Rico Fault (NPRFZ). The study was designed and carried out to discover any evidence of activity of the NPRFZ during the late prehistoric period, i.e. the past 35,000 years. The enclosed study focuses on the larger valleys and bounding uplands of eastern Puerto Rico including the valleys of Rio Loiza, Rio Gurabo, Rio Valenciano, Rio Humacao, and Rio Blanco. Study of all of the major valley areas associated with the NPRFZ ensured a thorough and objective basis for detection of fault activity. No evidence of significant Recent activity (up to about 10,000 years) or late Quaternary activity (10,000 to 40,000 years) of the NPRFZ was detected in these investigations.

The findings presented here are sufficient and complete for the purposes of supporting the planning phase of the Valenciano project. Some data review, updates and elaboration are in progress, but these will not alter the central conclusions of this report. These final materials will be incorporated in a final review version of the report and will be the final product of this project. We expect to provide this final draft in about four weeks.

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Williams Associates is fully committed to serve CSA on the use of the data contained herein. Please do not hesitate to contact us if there are any questions regarding this submittal.

Respectfully,

WILLIAMS ASSOCIATES

Patrick L. Williams, PhD
Senior Geologist and Project Manager

GEOLOGICAL EVALUATION STUDIES FOR THE RIO VALENCIANO DAM

1. Fault Evaluation-Phase Two

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EXECUTIVE SUMMARY

During the period December 2006 to October 2007 a focused evaluation of the Northern Puerto Rico Fault Zone (NPRFZ) was conducted for the purpose of developing data for a seismic hazard evaluation for the Valenciano EIS. Detailed studies were made utilizing: a) published and unpublished sources of geological mapping and geological research, particularly published geological mapping, map compilations and studies of faulting and fault motions in the region of Puerto Rico (Figure 1); b) very high quality and high quality sets of high resolution Lidar data extending east from Caguas were acquired independently in collaboration with PRASA and USGS and used to evaluate previously mapped branches and to develop new interpretations of the NPRFZ in the study area; c) high quality historical aerial photography, dated 1936-1937 (and benefiting from very low vegetation cover) were loaned to us by CSA; d) our own extensive field inspection and evaluation of suspect fault features; e) and most importantly a series of 6 trenched exposures for subsurface investigations at sites selected either for coincidence of previously mapped bedrock faults and prominent topographic lineaments (Naguabo and Gurabo areas) or for coincidence of bedrock shears and topographic lineaments within the immediate vicinity of the dam site.

All suspect features identified with remotely sensed data were evaluated in the field, and those that remained of interest after inspection were investigated by means of subsurface exploration (trenching). During the sum of the landform interpretation, field study, and trenching phase, no significant Holocene activity (i.e. offsets of valley deposits during past 10,000 years) was detected across any part of the NPRFZ.

Despite the presence of several prominent linear range-fronts bounding valleys between Caguas and the Naguabo/Humacao coastal area, no organized pattern of offset of range-front features was detected. The lack of any pattern of offset of ridge spurs and stream valleys (where they cross suspect faults) indicates the absence of significant activity of the NPRFZ in late Quaternary time, i.e. about 10,000 to 40,000 years.

Introduction

This Phase-Two Fault Evaluation is based on our understanding of the requirements for a Seismic Hazard Analysis (SHA) for completion of the EIS for the Rio Valenciano Dam. The purpose of the fault evaluation is to evaluate whether branches of the Northern Puerto Rico fault zone (NPRFZ), 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 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 Rio Valenciano dam. This study incorporates and extends activities of the Phase-One Fault Evaluation, specifically: (1) review of previous studies; (2) interpretation of historical and modern aerial photographs; (3) acquisition, processing and interpretation of regional Lidar data; (4) field inspection and evaluation of suspect fault features identified from studies and remotely sensed data; (5) subsurface investigation of principal (suspected) fault features to search for direct evidence of activity or non-activity.

Scope and project schedule

The second phase of this investigation is defined to include the following tasks: a) field evaluation of potential excavation sites; b) program of subsurface excavation; c) data assembly; d) report preparation. The excavation or "trenching" phase was conducted during two 3-week periods in March and October of 2007.

Our original schedule for completion in Spring of 2007 was modified by various logistical and access issues. These were resolved and field work was completed in October 2007. During November and December effort was focused on assembly of photomosaic trench diagrams. During December 2007 and January 2008 data assembly, final interpretation and reporting were conducted.

Approach

The principal bedrock faults and fault zones delineate zones of crustal weakness, and are thereby the most likely locations for reactivation or continuing fault activity (Figure 1). Our approach to detection of late Quaternary and Holocene activity of the NPRFZ has been to focus

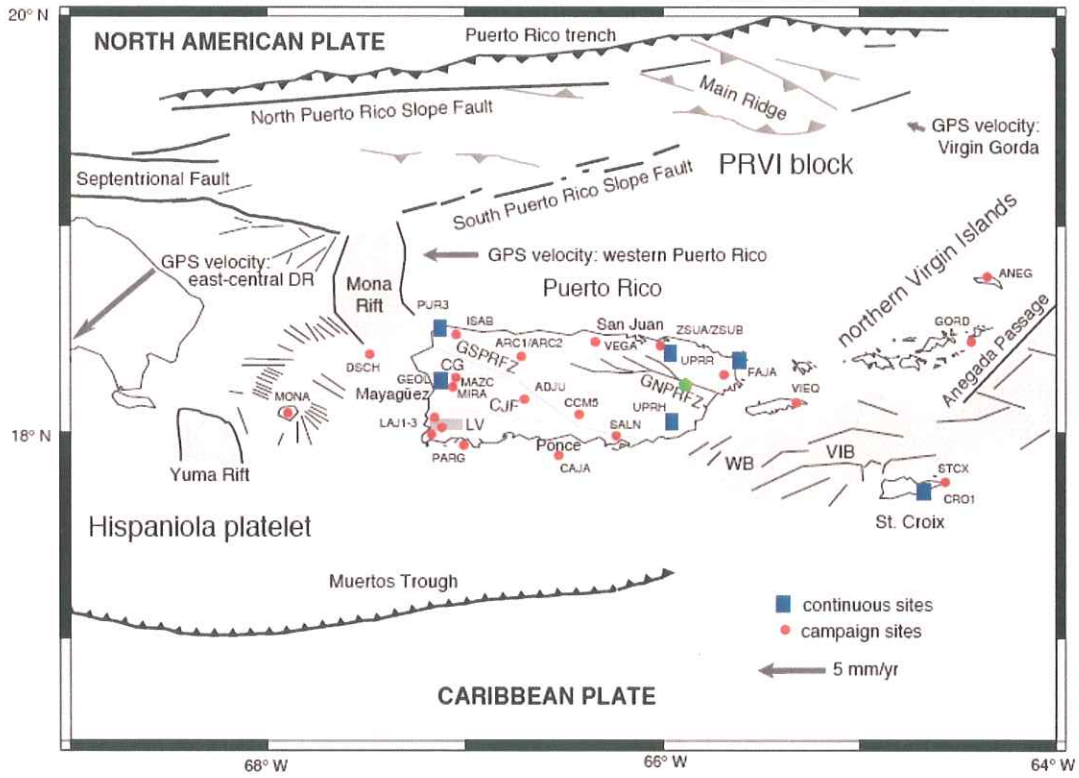

Figure 1 (From Jansma and Mattioli, NEHRP report, 2005). Regional geography and major faults. Proposed Valenciano Dam is located at green dot near the top of "F" in GNPRFZ. Blue squares are locations of continuous GPS stations placed to measure differential motion across faults within the Puerto Rico - Virgin Islands block (PRVI). Red dots are benchmark monuments that have been occupied temporarily in "campaign" surveys.

on the most prominent bedrock fault intersections with valley deposits, and the projection of those fault trends within Quaternary and Recent valley deposits, particularly river terraces and alluvial fans. We reviewed all USGS maps, USGS DEM (digital elevation model), and Google Earth imagery in the region to identify those areas characterized by sedimentary cover, i.e. larger valley areas.

We searched for evidence of active faulting within sediments of the most prominent linear valleys and along linear valley margins. We also searched for mid valley active fault features in valleys with prominent bedrock faults projecting into the mid valley area. The area of study extends from the east coast of Puerto Rico between Naguabo and Humacao, to the western extent of the Gurabo-Loiza valleys near Caguas (Figure 2).

Figure 2. General extent of study area is between dashed yellow lines. Primary bedrock faults of study area derived from USGS quadrangle mapping are colored blue. Prominent lineaments (candidate faults) interpreted in this study from landform features viewed in published digital elevation models and Lidar data compiled in this study are denoted by red lines. Candidate active fault features selected for investigation in Phase 2 are colored pink. Yellow stars denote Phase 2 trench sites. Yellow boxes outline maps of a candidate study area detailed in planning maps (Phase 1 report Appendix 1). Black boxes are stereo air photos interpreting possible fault features (Phase 1 report Appendix 2). White boxes are Lidar images in areas selected for Phase 2 study (Phase 1 report Appendix 3).

We note that the geometry of the NPRFZ is distributed and complex (Figures 2, 3), and detection of possible active featured required a broad reconnaissance investigation. Some strands of the NPRFZ are more prominent, particularly those associated with extensive linear valleys or separating contrasting and apparently substantially displaced bedrock units. Potential active fault landform features associated with the most prominent faults were closely inspected with the aid of remotely sensed data acquired during the Phase 1 investigations (Figure 2). All

areas with landform features suggestive of active faulting were inspected in the field. Particular focus was placed on determination whether of possible offsets of ridge spurs and tributary valleys were associated with patterns of disturbance of valley deposits such as channel offsets, fault line ridges and scarps.

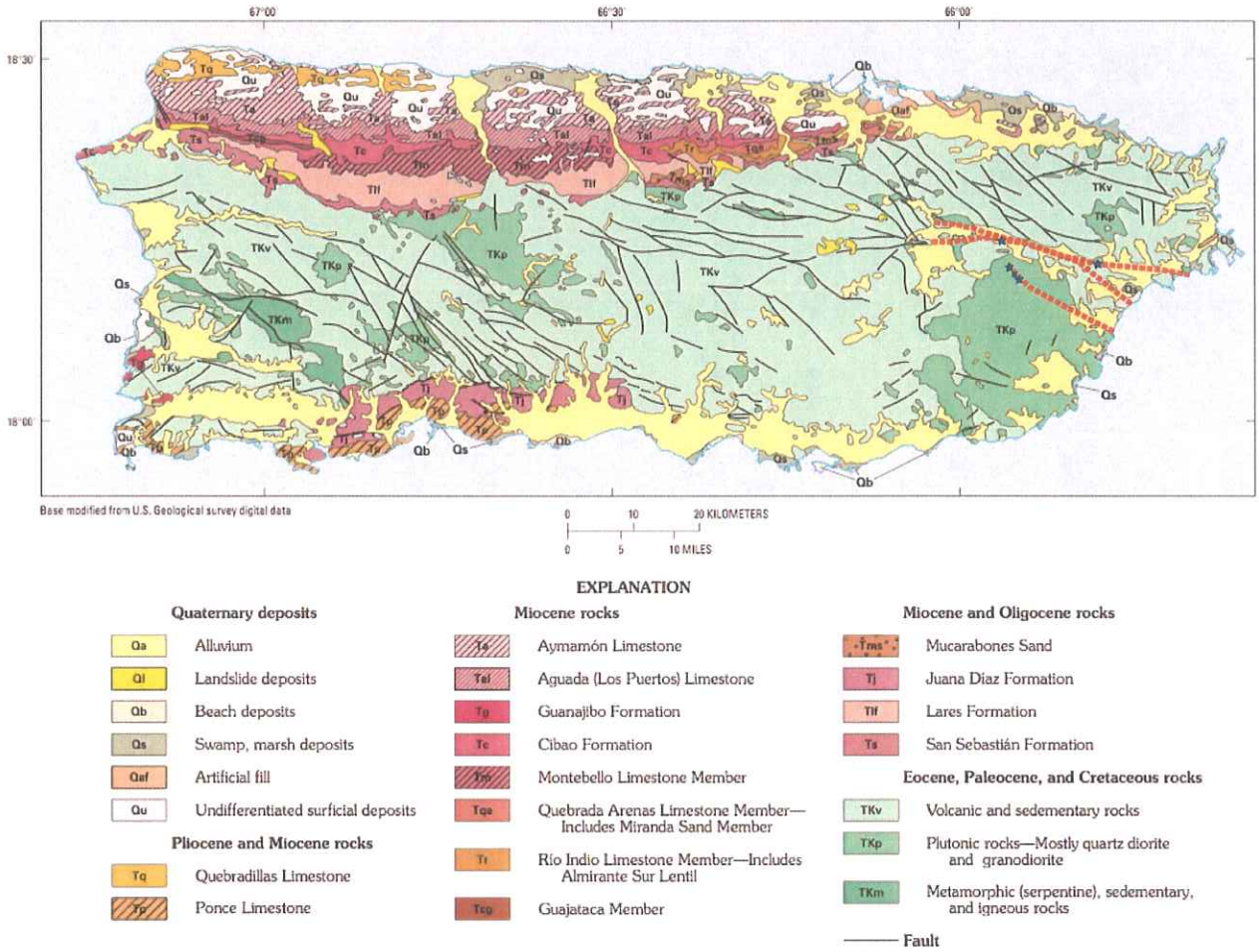

FIGURE 3.—Geology of Puerto Rico (modified from Briggs and Ackers, 1965; Monroe, 1980; and R.D. Krushensky, written commun., 1993).

Figure 3. (Modified from Renken et al, 2002). Geological map of Puerto Rico shows major fault patterns and geological units of the Island. Dashed red pattern to the east is our compilation of the primary "valley faults" of the NPRFZ, the Cerro Mula and Pena Pobre faults. Also shown crossing into TKp is the Valenciano - Humacao shear zone mapped by Dr. James Joyce (this study). Locations of trench sites are shown by blue stars. Dam site shown by blue rectangle. These locations are illustrated in greater detail below. Note that the Cerro Mula fault projects into a "fan" of faults extending WNW across northern Puerto Rico. We note the lack of any distinctive offset of the upper Tertiary cretaceous belt by the NPRFZ.

Geologic and Tectonic Setting

Previous studies. Our Valenciano Dam fault evaluation was initiated with compilation and review of primary geological and geotechnical data pertaining to the Rio Valenciano site and the NPRFZ, particularly the prior studies of Black & Veatch (2001).

The work detailed in this report greatly expands on those studies with primary investigation of geomorphology and fault patterns across the entire During the review phase we have endeavored to obtain the most relevant materials for evaluation of fault hazards at the proposed dam site, particularly materials that were generated subsequent to the Black and Veatch investigation. The reviewed materials are compiled in the *References* section below. Because of the essential absence of local field studies, we placed the most importance on contextual evidence of fault activity, particularly geodetic and plate tectonic indicators. Additional high quality contextual evidence comes from bedrock mapping by the U.S. Geological Survey (Figure 3).

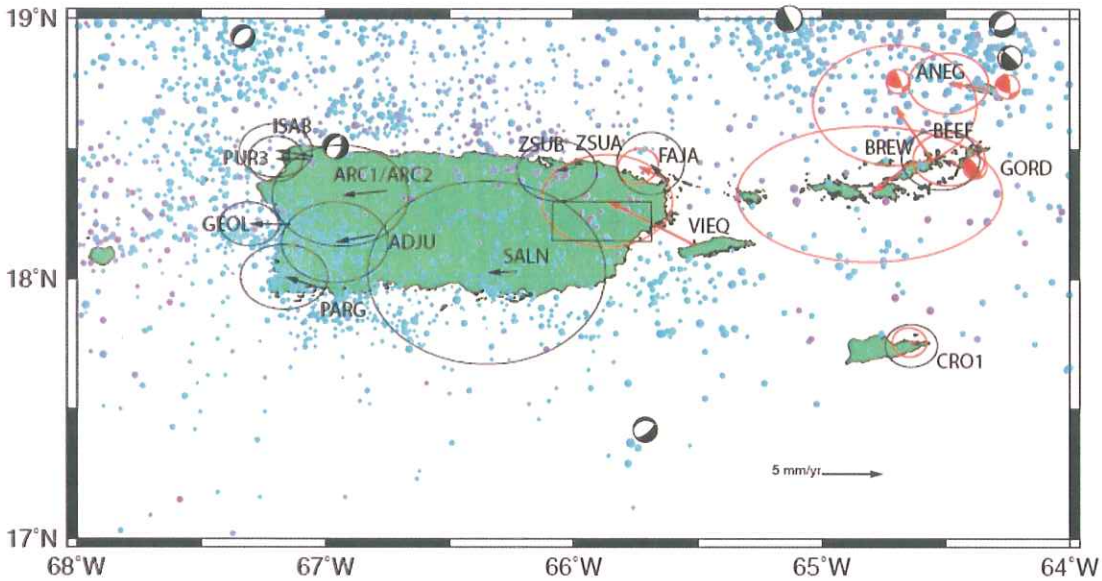

Figure 4. (From Jansma and Mattioli, NEHRP report, 2005 shows GPS results to the end of 2005). Map of Puerto Rico and Virgin Islands. Study area in rectangle. Epicenters (blue dots) and GPS-derived. Mann and others (2005A) suggest that the geometry of the NPRFZ is consistent with right-lateral motion, but that is not supported by GPS evidence to this date. At face value these data indicate a small east-west extension across Puerto Rico. Ellipses show uncertainly in GPS vector solution. Velocity scaled to arrow at lower right. Note that motions are relative to St. Croix. Comparing FAJA and ZSUB to the best western Puerto Rico vectors, PUR3, GEOL, and PARG indicates 1-2 mm/yr (extensional) motion between these locations.

Geodetic studies. GPS velocity studies are a primary tool for providing fundamental constraint of potential fault motion. GPS data are collected over a period of several years to detect differential motion across regions of interest. Investigation of deformation across the region of the NPRFZ by means of GPS are by no means conclusive, but as time passes the resolution of those analyses will improve. The reason for current uncertainty in GPS solutions are: (1) slow strain rates, (2) short periods of investigation and (3) problems with instrumentation and site stability (Figure 4) (Jansma and Mattioli, 2005). Despite these problems, the GPS studies are permissive of small (i.e. 1 to 3 mm/yr) differential motion across the NPRFZ, probably east-west extension. The GPS data, and the complex plate tectonic context of Puerto Rico (Figure 1) have motivated continuing investigation of seismicity and active faulting on the Island.

Geological maps and digital imagery. The very preliminary GPS data discussed above, and recent reinterpretation of island tectonics in recent publications (e.g. Mann, 2005C) have resulted in the questioning of extensive prior geological mapping, that is, that major deformation of the island of Puerto Rico ended in middle to late Tertiary time, several million years before present. The strongest evidence for the earlier consensus is the truncation of numerous Cretaceous/early Tertiary faults against mid Tertiary intrusive bodies. Key examples are the many faults and folds truncated by N80W-trending diabase dikes in the Gurabo quadrangle (Seiders 1971a, b) and the Rio Blanco stock (Eocene?) of the southern Luquillo Mountains (Seiders 1971c). We also note the lack of disruption of the major geological contact between the upper Tertiary limestone belt and Tertiary/Cretaceous volcanic rocks in northern Puerto Rico (Figure 3). This also indicates that the onshore faults of eastern and northern Puerto Rico have little post late Tertiary and post Tertiary activity. Evidence of Quaternary fault activity has not been developed for either the more strongly through-going SPRFZ (Rodriguez-Martinez, 2007) or the NPRFZ (this study). Renken et al. (2002) shows that branches of the SPRFZ do not appear to displace any late quaternary terrestrial deposits of the Ponce to Salinas coastal plain, although we note that offsets have been observed in shallow marine beds of unknown age (probably Quaternary) offshore of this area (Mann et al., 2005B).

Aerial photography. An extremely useful acquisition for this project is historical aerial photography. A full island photo set was recorded in 1936-1937. The quality of the photos is threefold. With a few exceptions (from film damage) the images are extremely clear and detailed, the landscape is essentially bare, with most valley areas under cultivation and mountain areas deforested, and cultural landscape modification of valleys and valley margins, particularly in the Caguas- is profoundly less than modern. Readers are referred to Table 1 and Appendix 2 of the Phase 1 Geological Evaluation Report for the Valenciano Dam.

Lidar survey. The highlight of the Phase 1 study has been the acquisition, processing, and preliminary review of Lidar imagery. The power of these data to address questions and controversies of fault activity is clear. The Lidar data have been examined through the study area for prominent fault features, and to further evaluate features seen in photography and in the field. The power of these data is evident. The single drawback of the Lidar data is the extent of modification in areas for development. The pairing of Lidar and good historical photography provides the Valenciano project with powerful tools for fault evaluation in the region. Readers are referred to Appendix 3 of the Phase 1 Geological Evaluation Report for the Valenciano Dam. Lidar data are used in trench site location maps (Figures 7, 8, and 9).

Seismicity. We note that while multiple geological evidence and GPS data point to low activity or inactivity of the NPRFZ, some amount of shallow seismic activity is present in the study area. Certainly some stresses must be imposed on the island by the motions of surrounding faults (e.g. Figures 1, 6). This is evidenced by a significant number of seismic events in the area (Clinton et al. 2006). We note however that relative to the southwest portion of Puerto Rico, most of the island is relatively quiet (Figure 6). It is possible that the many closely-spaced faults of the southwest portion of the island (Figure 3) cause deformation to focus in that area.

Figure 5. Principal area of study and locations of trench investigations conducted for investigation of the Northern Puerto Rico Fault Zone. The most prominent bedrock faults, colored blue, are derived from several sources of USGS quadrangle mapping. Heavy red lines denote primary topographic lineaments that are related to the mapped faults and thus were selected for additional study. The location of the Valenciano Dam site is noted by a yellow rectangle. Yellow stars denote the locations of the four sites where 6 paleoseismic trenches were excavated.

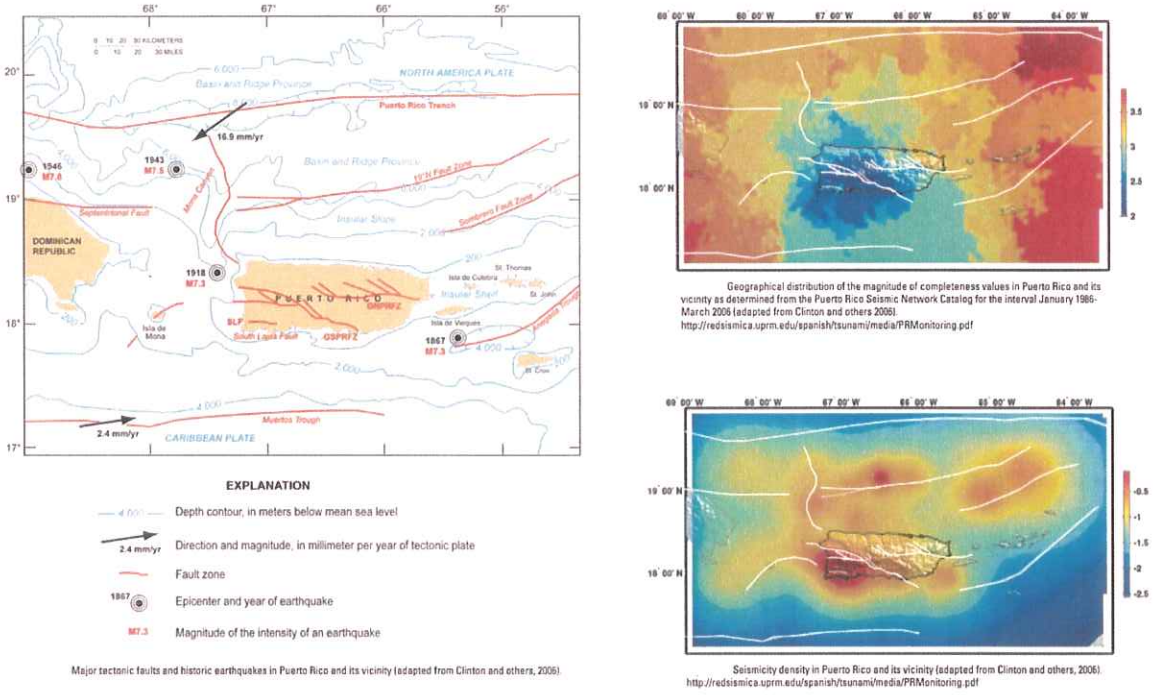

Figure 6. Adapted from Clinton et al. (2006) and Rodriguez-Martinez (2007) shows suspected active regional faults - (a); Puerto Rico Seismic Network magnitude detection threshold 1986-2006 (ranges from M2 to M3.7) (b); and seismic density (earthquakes per km^2) - (c); Note that during the instrumental period the island is divided between an area of significantly lower seismic rates in the northeast relative to the southwest.

Field Investigations

In order to evaluate our preliminary interpretations of possible active fault feature, we undertook two weeks of field work during Phase 1, and more than 2 weeks of field work during phase 2. Site mapping was conducted in the Rio Blanco, Gurabo, Humacao, Loiza, and Valenciano Valleys. While definitive evidence of active faulting has not been developed, we have evaluated multiple sites with suspect fault features. Firstly near the town of Rio Blanco where a set of right-deflected streams are contained within a body of coarse alluvium, and thus do not appear to be controlled by bedrock joint patterns, secondly near the Loiza-Gurabo River confluence, where a prominent, and apparently youthful lineament extends from Rte 52 to the eastern edge of Caguas, and thirdly near Humacao, where the fault controlled Humacao gorge transitions to a pristine terrace with candidate fault features just SW of the city. More equivocal features have been identified and field checked in the eastern Rio Blanco Valley, and the central and eastern Gurabo Valley.

Trenching phase. In all cases the selection of trench sites was challenged by extensive land modification for commercial and residential development and agriculture. Even with these challenges, good sites were located for investigation. In the end we all the sites we excavated were identified as high priority candidate fault sites during Phase 1 of this study. At Rio Blanco we were impressed by the justaposition of several lineaments subparallel to the mapped Pena Pobre fault. We observed that incision in the area provides surfaces of differing age, and older fan surfaces and terraces could record Quaternary faulting, while valley deposits may record Holocene faulting. Direct investigation of Valenciano Valley was not initially contemplated. Our thinking evolved as new facts were developed supporting the existence of a Valenciano - Humacao shear zone. It was clear that we needed to attempt to find ways to detect or preclude faulting within the Valenciano Valley itself. We were fortunate to develop two successful sites close to the damsite. In the initial site we exposed an ancient, low displacement shear fabric in grandiorite. In the second Valenciano site we mapped a 20-m-width of unfaulted terrace deposits capping the projection of the shear zone in Quebrada de Santa. Accessing sites in the Gurabo Valley turned out to be challenging. The Gurabo site gave us a second good quality test for faulting at a site where plausible geomorphic evidence of the NPRFZ is occurs. The lack of any evidence of faulting in the trench indicates that the geomorphic lineament does not express activity of the NPRFZ.

Rio Blanco Trenches - Naguabo

Investigation of the "eastern" NPRFZ fault focused early on the Rio Blanco area. Here the "bedrock" trace of the Pena Pobre fault crosses or passes close to several large and small scale geomorphic features that define linear trends or are similar to features associated with of active faulting such as fault line valleys and ridges. In particular a number of geomorphic lineaments were identified in the area of the drainage divide between the towns of Pena Pobre and Rio Blanco (Figure 7). The most prominent and "youthful" of these features crosses from upland into valley deposits of a tributary of the Rio Blanco River, and was identified in Phase 1 as a primary target for investigation of the Pena Pobre fault. Two of the valley lineaments were investigated in Two trenches in young flood plain deposits (channel and overbank deposits).

The details of these trenches: "Rio Blanco 1" and "Rio Blanco 2" are presented in Plates 1 and 2. Unfortunately the terrace deposits exposed in trenches Rio Blanco 1 and 2 are almost certainly too young to be meaningful indicators of fauling.

The most intriguing feature of the Rio Blanco area is a candidate fault line ride and fault-linee valley investigated in Trench "Rio Blanco 3 (Plates 3, 4)." At this location a linear ridge deflects three drainages that flow parallel to the 150 meter-long ridge (Figure 7). The clear absence of faulting in Rio Blanco Trench 3 precludes that the linear ridge feature was produced by fault action. We still do not entirely understand the origin of the ridge.

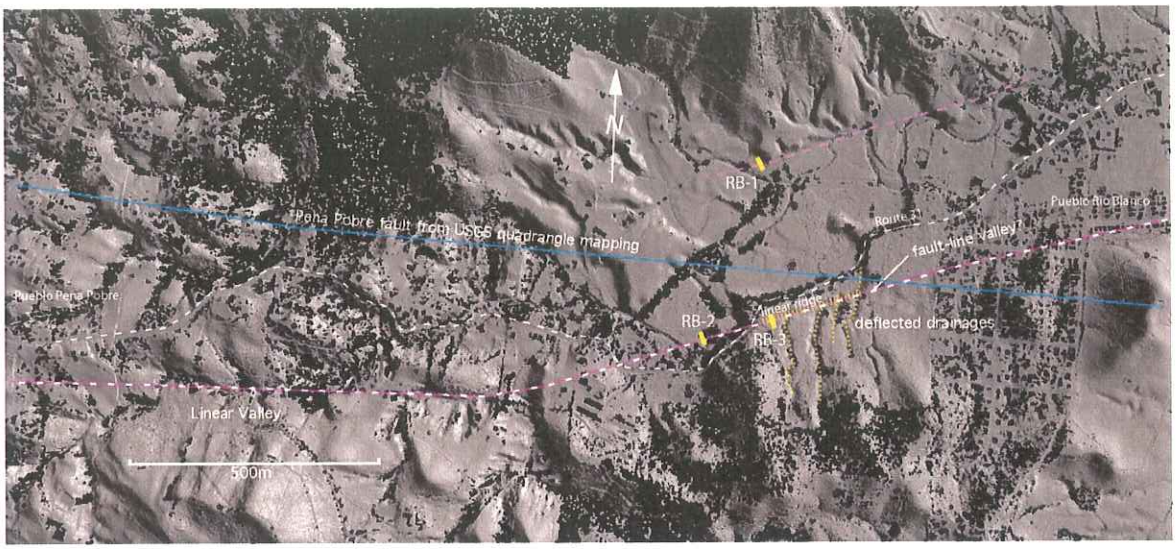

Figure 7. Lidar view of area from Pena Pobre to Rio Blanco (source USGS). North is up. Width of image 2.9 km. Locations of trenches Rio Blanco 1 (Plate 1), Rio Blanco 2 (Plate 2), and Rio Blanco 3 (Plate 3), are shown in yellow bars. Deflection of several streams by linear ridge west of Rio Blanco was suggestive of faulting or bedrock control. Upper thickness of ridge is exposed along Rte 31, and is comprised of old alluvium. This feature projects to linear valleys to west and younger terrace surfaces immediately to east and west. Trend of features are proximate to but ~20° oblique to Pena Pobre bedrock fault as mapped. Topographic lineaments of RB-1 and RB-2 are terrace risers. Linear valley of RB-3 may be modified, originating either a as a road, or a power-line right-of way. No evidence of bedrock or fault control was discovered.

Valenciano Trenches - Juncos

In order to evaluate shearing mapped in the Valenciano Valley by Dr. James Joyce (this study), trench sites were located to utilize areas where the very-linear trend of the valley projected onto terrace areas. Valenciano Trench 1 (Plate 5) is located south of the proposed Valenciano dam site (Figure 7). This trench exposed young terrace deposits and clay-banded grandiorite. The terrace deposits are very young, the upper beds contain fence materials (barbwire). Material from the basal bed has been carbon dated as modern, and no older than AD 1680 [Beta Analytic sample # 2007235740]. The clay-banded grandiorite indicates some amount of deformation (shear), as predicted, along the trend of the Valenciano Valley. Geometry of the bands indicates downslope creep in the upper deeply weathered layers of the bedrock. Cross cutting relationships and lack of a true fault "gouge zone" exclude more than a few meters total displacement across the exposed shears of Trench 1 since mid Tertiary time.

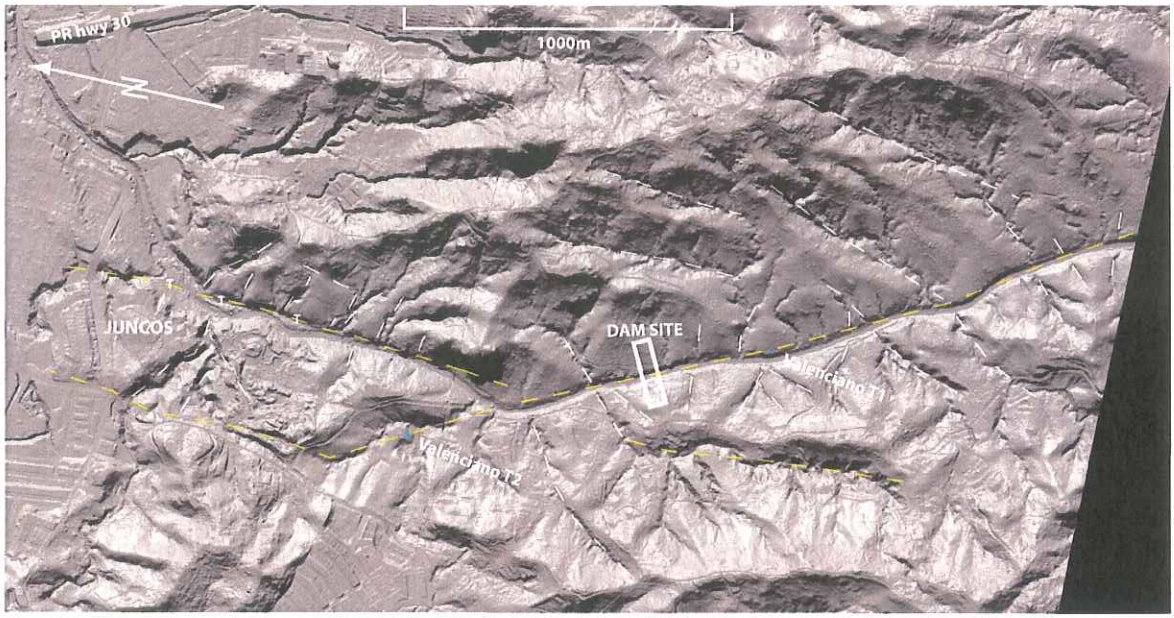

Figure 8. Lidar view of lower Valenciano Valley showing strong linear trends of the area.). Thin white dashes are lineaments, presumably controlled by regional joint patterns. Thin yellow dashes are interpretations of a throughgoing lineament associated with the primary Valenciano drainage system. The Valenciano trend extends up Quebrada la Santa to the left. Terrace deposits at Valenciano T2 (plate 5) in the Quebrada are not disrupted in the area of the excavation which spans reasonable projections of the Humacao - Valenciano shear zone into the Quebrada. The age of the Quebrada deposits was not determined directly, but based on paleoenvironment and position, they are estimated to be mid Holocene age (5,000 years).

The second Valenciano site is located to northwest of the damsite in the projection of the Valenciano Valley trend into Quebrada de Santa (Figure 7). Laterally extensive terrace deposits mapped in the trench excavation at Valenciano T2 (plate 6) are not disrupted by faulting. The 20-meter-long excavation spans reasonable projections of the Humacao - Valenciano shear zone in the Quebrada as mapped by Dr. James Joyce. The age of the Quebrada deposits has not been directly determined. On the basis of paleo-environment and position, the terrace beds are estimated to be of mid Holocene age (ca. 5,000 years).

Further evidence of inactivity of the Humacao - Valenciano shear zone is interpreted from the several joint sets that are evident in the geometry of drainage patterns illustrated in Figure 6. The linearity and continuity of several of these lineaments across the primary through-going drainage of the valley is a strongly suggests the absence of substantial displacement across the Valenciano - Humacao shear zone.

The sum of the data set developed from mapping and trench excavations located close to the proposed Valenciano damsite clearly indicate inactivity of the Humacao - Valenciano shear zone.

Gurabo Trenches - Gurabo Valley

The Gurabo "Golf Course Site" was selected for investigation on the basis of the interpretation of air photos during Phase 1 of these studies. In that analysis faulting was indicated here by a linear hill front situated parallel to the trend of the Cerro Mula fault (Figures 5, 9). A suggestive left stream deflection also supports the interpreted fault location (Figure 9). The fortuitous survival of a small panel of the original linear hillfront was trenched to evaluate any evidence of ancient or modern faulting. Despite good exposures of a natural erosional surface on volcanic bedrock and continuous colluvial deposits across the interpreted projection of the Cerro Mula fault. Neither of these were found. The site contains some interesting geology. Very hard boulders form a debris layer over the top of bedrock recording deep erosion and downslope transport at the site. Above the boulder lag mostly fine-grained colluvial processes have dominated. These units are consistent with the morphology and geology of he site, and represent natural deposits of unknown age.

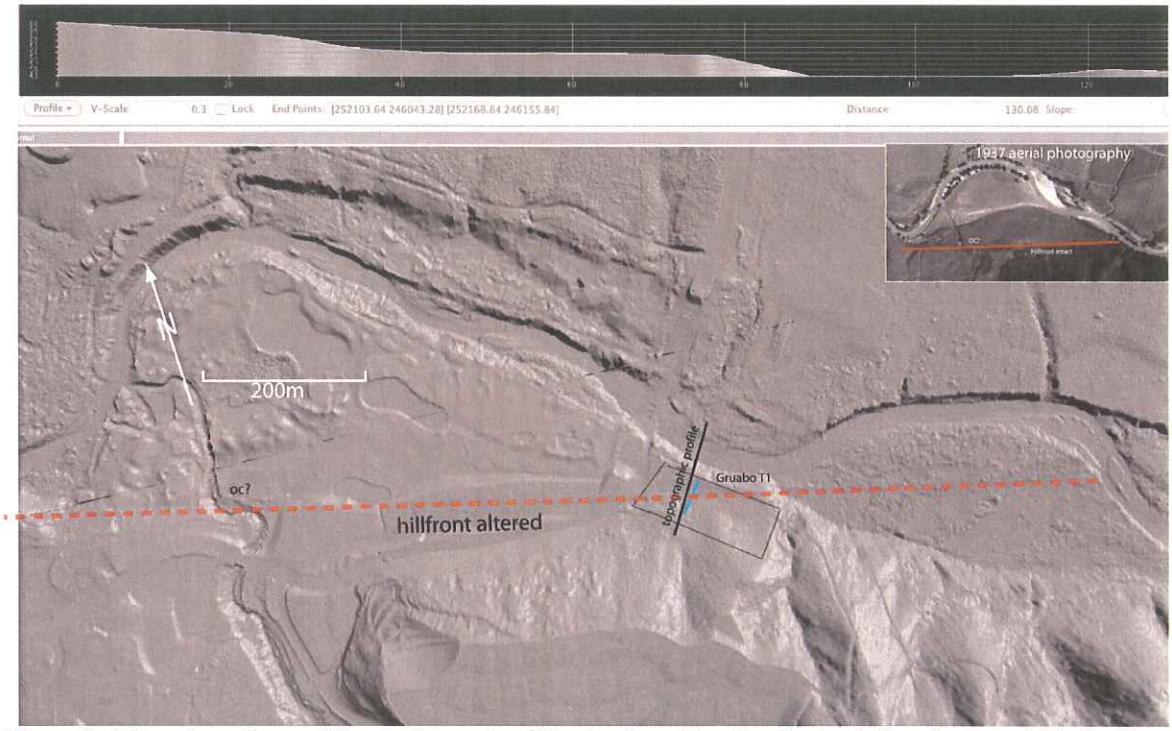

Figure 9. Lidar view of area of the south margin of the Gurabo valley showing basis for selection of this "golf course" site for trench exploration. Prencipal features noted in Phase 1 are the linear hillfront and stream deflection. Note the loss of hillfront due to grading. A surviving complete panel of the linear hillfront was trenched in order to evaluate any evidence of the presence or absence of ancient or modern faulting.

Conclusion

During the period December 2006 to October 2007 a focused evaluation of the Northern Puerto Rico Fault Zone (NPRFZ) was conducted for the purpose of developing data for a seismic hazard evaluation for the Valenciano EIS. Detailed studies were made utilizing: a) published sources of geological mapping and contextual information, particularly published USGS quadrangle mapping and other map compilations; b) very high quality and high quality

sets of high resolution Lidar data extending east from Caguas were acquired independently by PRASA and USGS and used to evaluate previously mapped branches and to develop new interpretations of the NPRFZ in the study area; c) high quality historical aerial photography, dated 1936-1937 (and benefiting from very low vegetation cover) were loaned to us by CSA; d) our own extensive field inspection and evaluation of suspect fault features; e) and most importantly from a series of 6 trenched exposures for subsurface investigations at sites selected either for coincidence of previously mapped bedrock faults and prominent topographic lineaments (Naguabo and Gurabo areas) or for coincidence of bedrock shears and topographic lineaments within the immediate vicinity of the dam site.

All suspect features identified with remotely sensed data were evaluated in the field, and those that remained of interest after inspection were investigated by means of subsurface exploration (trenching). During the sum of the landform interpretation, field study, and trenching phase, no significant Holocene activity (i.e. offsets of valley deposits during past 10,000 years) was detected across any part of the NPRFZ.

Despite the presence of several prominent linear range-fronts bounding valleys between Caguas and Naguabo/Humacao, no organized pattern of offset of range-front features was detected. The lack of any pattern of offset of ridge spurs and stream valleys (where they cross suspect faults) indicates the absence of significant activity of the NPRFZ in late Quaternary time, i.e. about 10,000 to 40,000 years.

Acknowledgements

Important assistance with this study has been provided by many staff at CSAGroup. Particular kudos goes to Maher Lugo, Teresita Vega and Matt Moses. Field work was conducted with the participation of Coral Roig-Silva, Dany Pase, Maher Lugo, Cheryl Stelte, Dr. James Joyce, Dr. Tish Tuttle, and Dr. Teresa Ramirez. Outstanding mentoring and practical support for this project was provided by Dr. Alex Soto.

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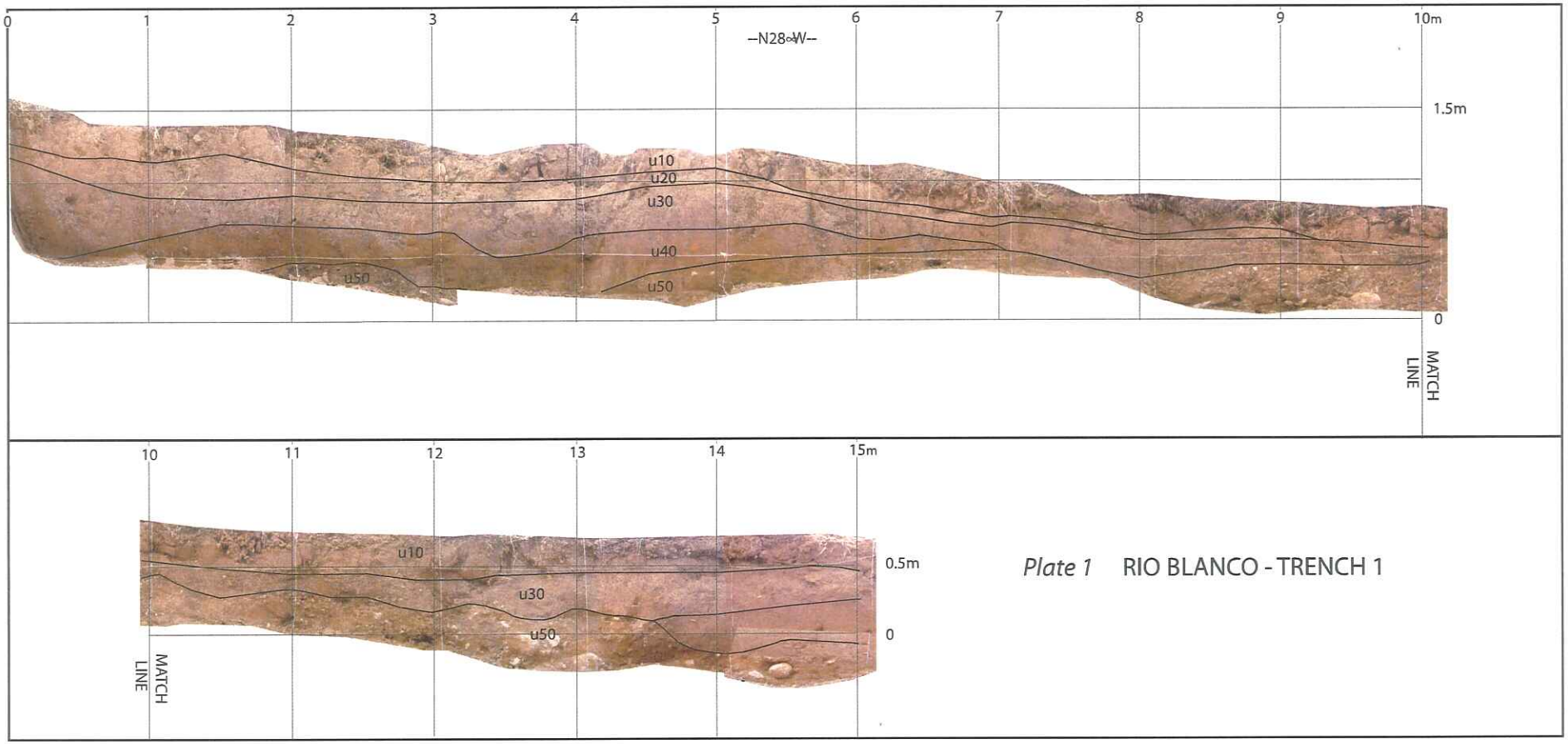

Plate 1 RIO BLANCO - TRENCH 1

Unit 10 Massive, disturbed unit, dark brown(10YR 4/3) silt, contains glass and pieces of brick. <modern overbank deposit trampled by cattle>.

Unit 20 Massive grayish brown (10YR 5/2) sandy silt, crumb structure, few (redeposited?) manganese nodules, oxidize patches yellow brown (10YR 5/6). <weak soil developed on overbank deposit>.

Unit 30 Massive grayish brown (10YR 5/2) sandy silt, weak subangular blocky peds, many 1cm manganese nodules; manganese nodule yellowish red (5YR 4/6). <soil developed on overbank deposit>.

Unit 40 Massive strong brown (7.5YR 4/6) clayy silt with black manganese nodules <overbank deposit>.

Unit 50 weakly cross-bedded yellowish brown (10YR 5/6) sandy gravel with cobbles and boulders; most cobbles are grayish brown (10YR 5/2); poorly sorted sand, gravel, pebbles, and cobbles. <channel deposit>.

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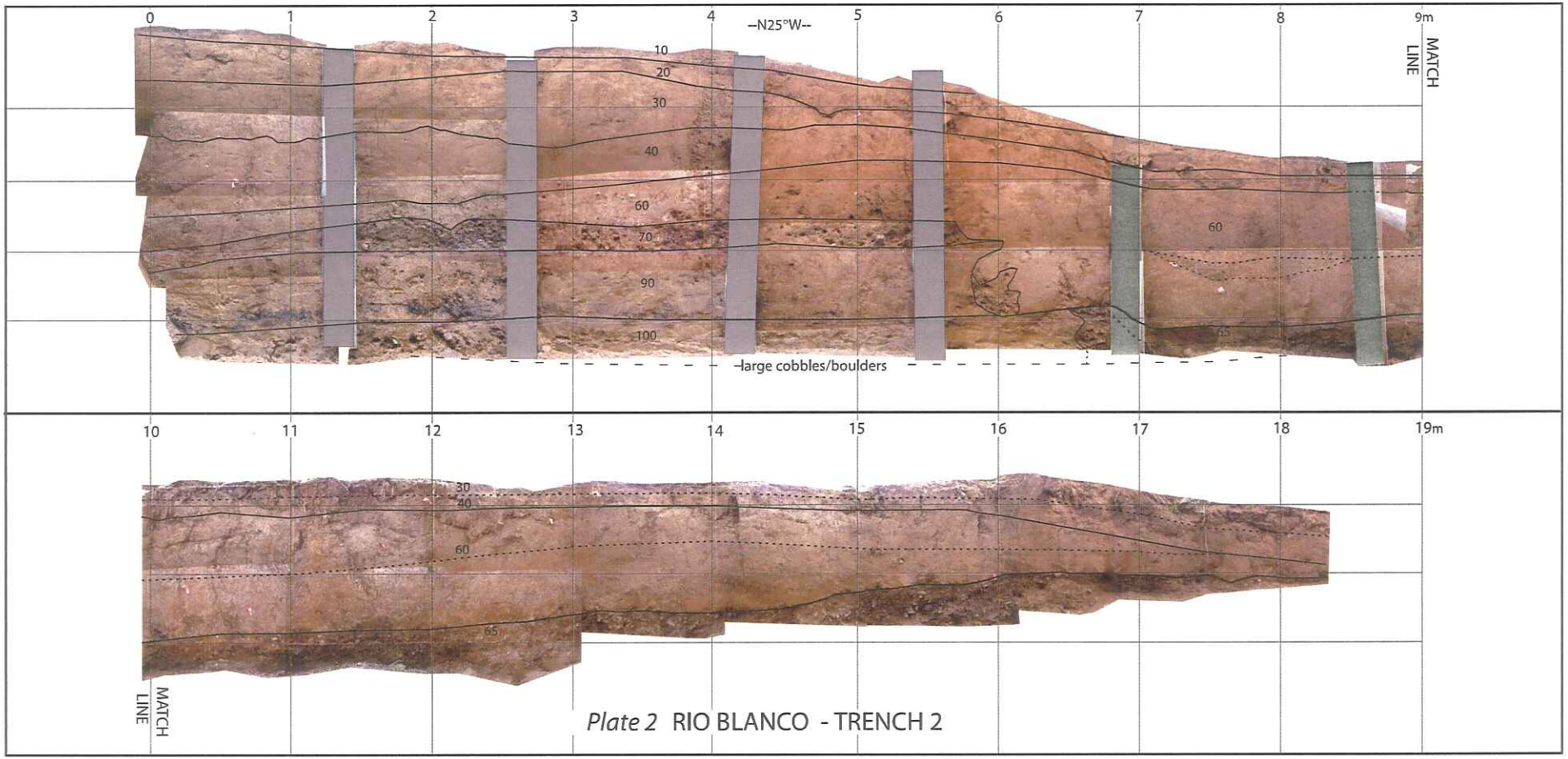

Plate 2 RIO BLANCO - TRENCH 2

unit 10 Massive brown (7.5YR 4/4), juvenile soil developed on sandy silt. 100% worm cast texture. Soft, loose. <soil developed on overbank deposit>.

unit 20 Massive to bedded reddish brown (5YR 4/4) sandy silt. Many root casts, roots. Discontinuous pebble line at base. Hard friable. <overbank deposit>.

unit 30 Weakly bedded medium brown to reddish brown (5YR 5/4), fines upward from sandy silt- abundant coarse sand to fine sandy silt. Moderately well sorted. Discontinuous mixing from bioturbation (discontinuous zones of worm casts). Hard, slightly cemented. <overbank deposit>.

unit 40 Weakly bedded greyish brown (5YR 4/2) w/reddish brown nodules, fines-up from coarse sandy to fine sandy silt, clay coatings on broken surfaces, discontinuous worm casts, incipient pd structure, hard moderately compact. <overbank deposit>.

unit 60 Weakly bedded sandy pebble gravel to pebble sand with discontinuous zones of fine to coarse sand, well sorted gravel locally present. Continuous manganese coatings (esp in gravels), zones of oxidixed sand and pebble sand. Oxidized zones are med reddish brown (5YR 5/4), sand zones are soft, loose near bottom contact. Upper part of unit is hard, moderately compact (clay cement infiltrating from unit above), No soil development. <channel deposit>.

unit 65 Fining-up unit of pebble cobble gravel to pebble granule sand. Dark reddish brown (5YR 3/4), moderate manganese coating of sand and pebbles <channel deposit>

unit 70 Massive to weakly bedded dark reddish brown (5YR 3/4) gravel with discontinuous zones of pebble small cobble gravel and sandy silt. <channel deposit>

unit 90 Weakly bedded fine to coarse pebble sand, dark reddish brown (5YR 3/4) with black mottles. Zones of well developed manganese coating on sand and pebbles. Few pebbles to 4 cm, soft loose, some cohesion due to silt coatings. No soil development. <overbank deposit / channel deposit>.

unit 100 Weakly bedded, greyish brown (5YR 4/2) very soft silty, fine to coarse sand, few large pebbles to small cobbles (6-10cm), mottles and zones of heavy oxidation. Motles (dark reddish brown and medium grayish brown), minor zones of manganese coating. <overbank deposit / channel deposit>.

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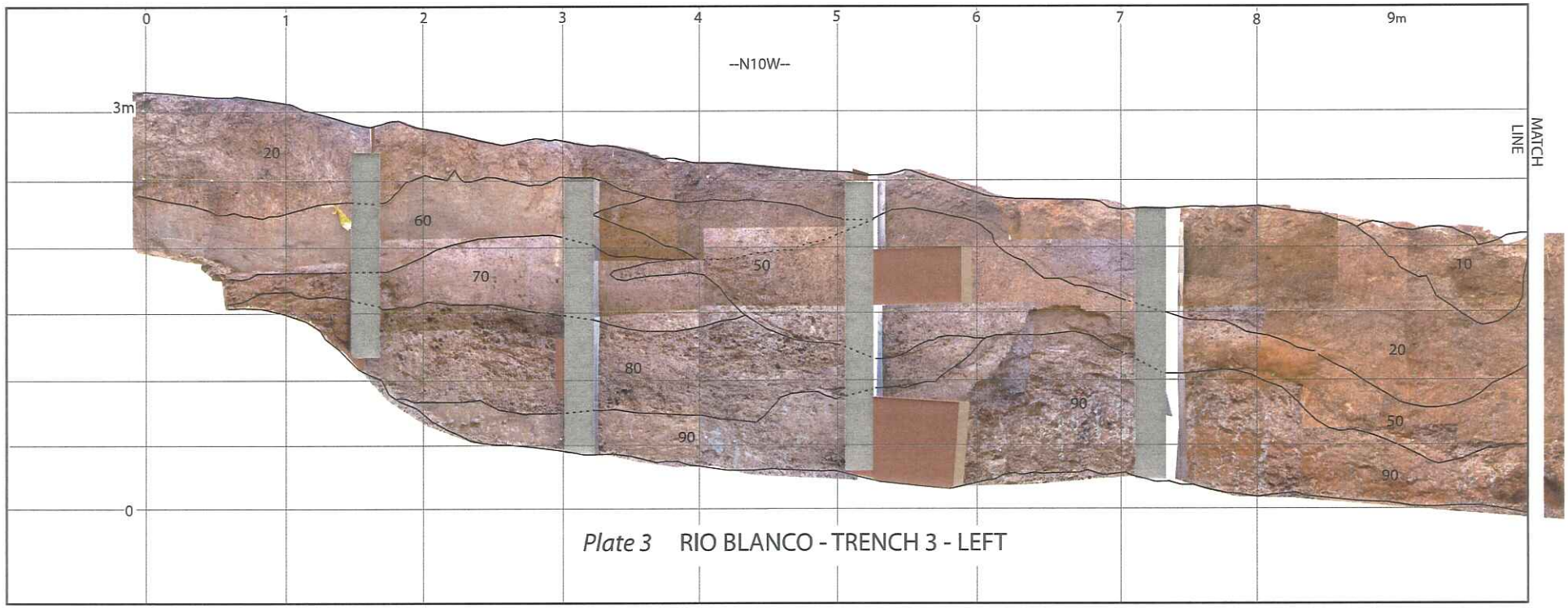

Plate 3 RIO BLANCO - TRENCH 3 - LEFT

unit 10 Massive, mixed, many different clast types. < fill>

unit 20 Massive, dark reddish brown (5YR 3/5) sandy pebble granule silt, soft to firm moist, very friable, pebbles subangular to subrounded, granular texture, weak clay coatings, root casts, many pores. <modern organic soil "A" horizon developed on debris flow>.

unit 50 Massive yellowish red (5YR 4/6) and light reddish brown (5YR 6/4) pebbly sandy clayey silt, subangular and subrounded pebbles, many manganese models up to 5x10 cm, stone line at base of unit, granular structure to weak angular blocky structure, weak clay coatings, few pores, moderately plastic, soft to slightly firm moist. <weak subsoil developed on overbank deposit / channel deposit>.

unit 60 Massive yellowish red (5YR 4/6) and pinkish gray (5YR 6/2) silty sandy pebble clay, moderately firm, responds to moderate pressure, slightly plastic, root fills "granular" continuous clay coatings, many small and large pores dense med firm, clayey silt with sand and granular, color as in RB1N: Up to 40% gray colors. <weak subsoil developed on overbank deposit / channel deposit>.

unit 70 Massive yellowish red (5YR 4.5/6); 90% red/brown; clayey sandy green silt; very firm, slightly plastic, granular texture weak clay coatings; similar to unit 50 with more pebbles and granules, less gray color. <weak subsoil developed on overbank deposit>.

unit 80 Massive reddish brown (5YR 6/4) to yellowish red (5YR 4/6), clayy silty sandy pebble cobble gravel, granular, soft, many pebbles, angular, debris (?) well-graded clay to cobble, subrounded to angular gravel, massive gravel, 50% pebbles and cobbles, cobbles at base are subrounded and up to 20 centimeters in long axis, grain-size clay to cobble. <debris flow depost>.

unit 90 Massive yellowish red (5YR 4/6, 5YR 5/8), and medium light gray (5YR 6/1) mottles, mixture from clay to pebble, pebbles 2-15 mm, manganese in zones to 20 mm, many clay-filled root casts, weathered volcanic agglomerate clay with many root zones defined by reduced color and branching vertical structure, works to clayey texture, very firm to firm. <volcanic sapprolite>.

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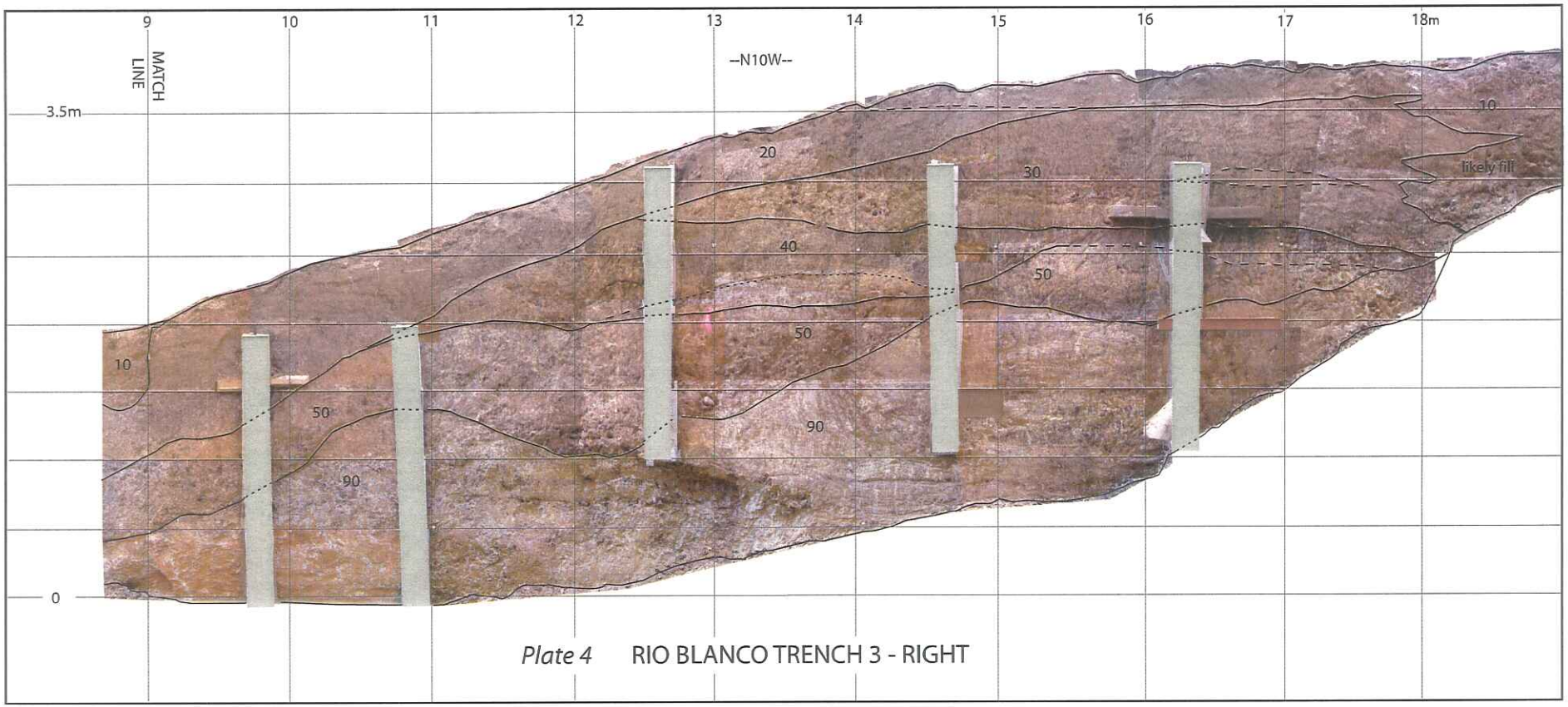

Plate 4 RIO BLANCO TRENCH 3 - RIGHT

unit 10 Massive mixed, many different clast types. < fill>.

unit 20 Massive dark reddish brown (5YR 3/5) sandy pebble granule silt, soft to firm moist, very friable, pebbles subangular to subrounded, granular texture, weak clay coatings, root casts, many pores. <modern organic soil "A" horizon developed on debris flow>.

unit 30 Massive yellowish red (5YR 4/6) fine sandy silt, hard brittle, 50% manganese mottled angular blocky structure, continuous clay coatings, large pores, few small pores, strong pilly structure. <subsoil developed on overbank deposit / channel deposit >.

unit 40 Weakly bedded to massive reddish brown (5YR 4/4) very fine sandy silt, stone line at base, manganese nodules to 1 cm, weak ped structure, discontinuous clay coating, small pilly structure, firm, dense, responds to firm pressure moist. <weak subsoil developed on overbank deposit / channel deposit>.

unit 50 Massive yellowish red (5YR 4/6) and light reddish brown (5YR 6/4) pebbly sandy clayey silt, subangular and subrounded pebbles, many manganese models up to 5x10 cm, stone line at base of unit, granular structure to weak angular blocky structure, weak clay coatings, few pores, moderately plastic, soft to slightly firm moist. <weak subsoil developed on overbank deposit / channel deposit>.

unit 90 Massive yellowish red (5YR 4/6, 5YR 5/8) mixture from clay to pebble, pebbles 2-15 mm, and medium light gray (5YR 6/1) mottles, manganese in zones to 20 mm, many clay-filled root casts, weathered volcanic agglomerate clay with many root zones defined by reduced color and branching vertical structure, works to clayey texture, very firm to firm. <volcanic sapprolite>.

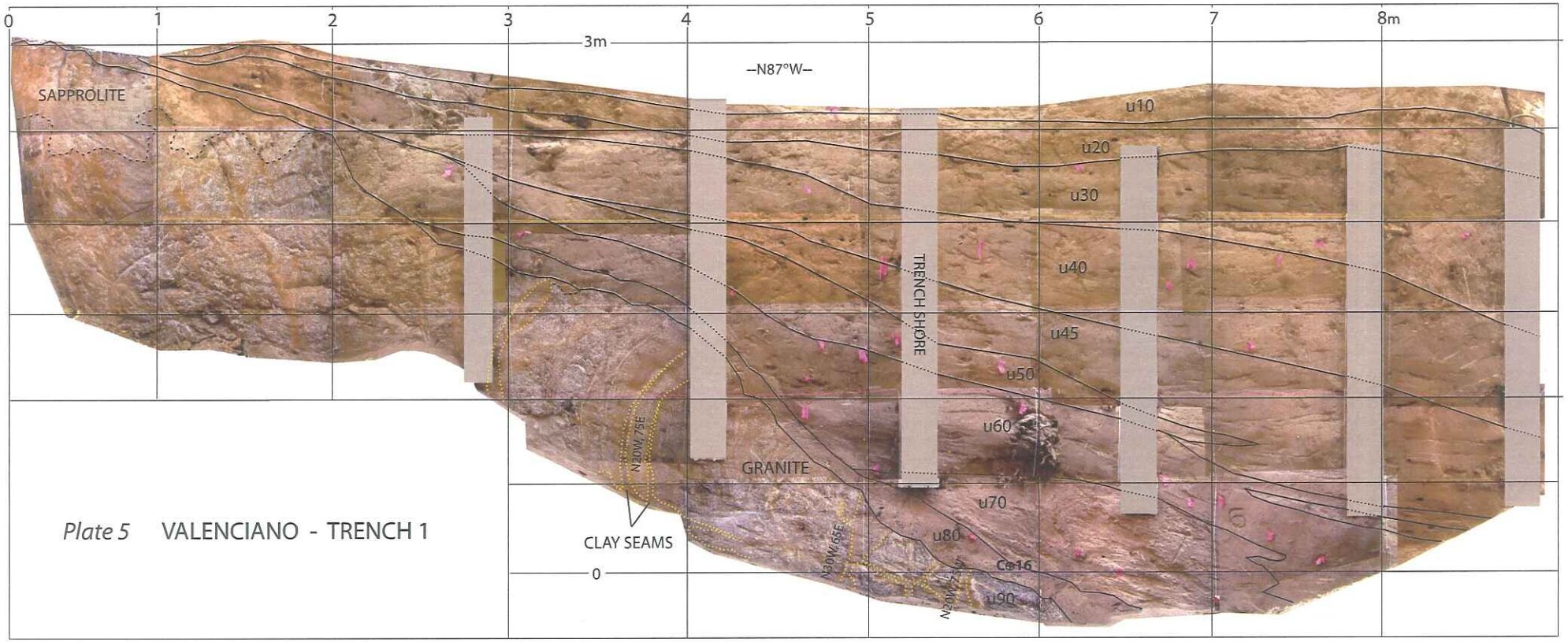

Plate 5 VALENCIANO - TRENCH 1

Unit 10 Weakly bedded light brown (7.5YR 6/4) silty very fine sand and sandy silt, many roots, many redeposited angular silt clasts, bedded sand. <mixed overbank/flood deposit>.

Unit 20 Similar to above, grayish brown (7.5YR 6/4), interbedded medium sand, sandy silt, silt is comprised of angular silt clasts and beds of sand. <overbank/flood deposit>.

Unit 30 Massive grayish brown (10YR 5/2) silty sand, sandy silt, angular silt clasts up to 90% of unit, lower 20cm comprised of semi continuous interbeds of medium sand and silt, 4cm sand bed at base; **barbwire located at mid level of unit at meter 10.25**. <overbank/flood deposit>.

Unit 40 Similar to above, grayish brown (10YR 5/2), sandy silt beds up to 13cm thick, interbeds of silty sand up to 7cm thick, silt beds are continuous, some bioturbation, sand beds are discontinuous, some mixing, common charcoal. <overbank/flood deposit>.

Unit 45 Massive medium grayish brown (5YR 5/3) very fine sandy silt to very fine sand, slight soil development; firm, friable crumb texture (might be from worm clasts or redeposition of older silts), no clay coatings or ped development, charcoal present; **barbwire located at top of unit at meter 10.5**. <overbank/flood deposit>.

Unit 50 Similar to above, silty fine to coarse sand, massive with suggestion of fining upward, medium reddish brown (5YR 5/3), few burrows, slight soil development at the top, no clay coating or ped development, organic accumulation and a root zone, common charcoal. <overbank/flood deposit>.

Unit 60 Massive reddish brown (5YR 5/3) coarse sand; bottom 40cm contains bedded onlapping silts and abundant charcoal at STA 6m large root cast or wood debris contains abundant charcoal. <overbank/flood deposit>.

Unit 70 Massive grayish brown (10YR 5/2) medium to coarse sand, with minor clay and silt, abundant roots, charcoal fragments, dark angular fragments may be hornblend or manganese, abundant charcoal at top contact, hard, dense, friable, no clay coating only slight ped development. <overbank/flood deposit>.

Unit 80 Massive medium gray brown very fine sandy silt to very fine sand, hard, dry, friable, roots, no clay coating, no peds. <overbank/flood deposit>.

Unit 90 Yellowish red (5YR 5/6) and reddish yellow (5YR 6/6), weathered granite, soft, common clay filled seams, felsic, granular quartz angular, felspar weathers to white powder, many joints, many clay lined joints (0.5 to 1cm thick) high and low angle, many altitudes, displacement indicators (cross joints) suggest up to 5cm offset of clay-filled shear zones. <bedrock>

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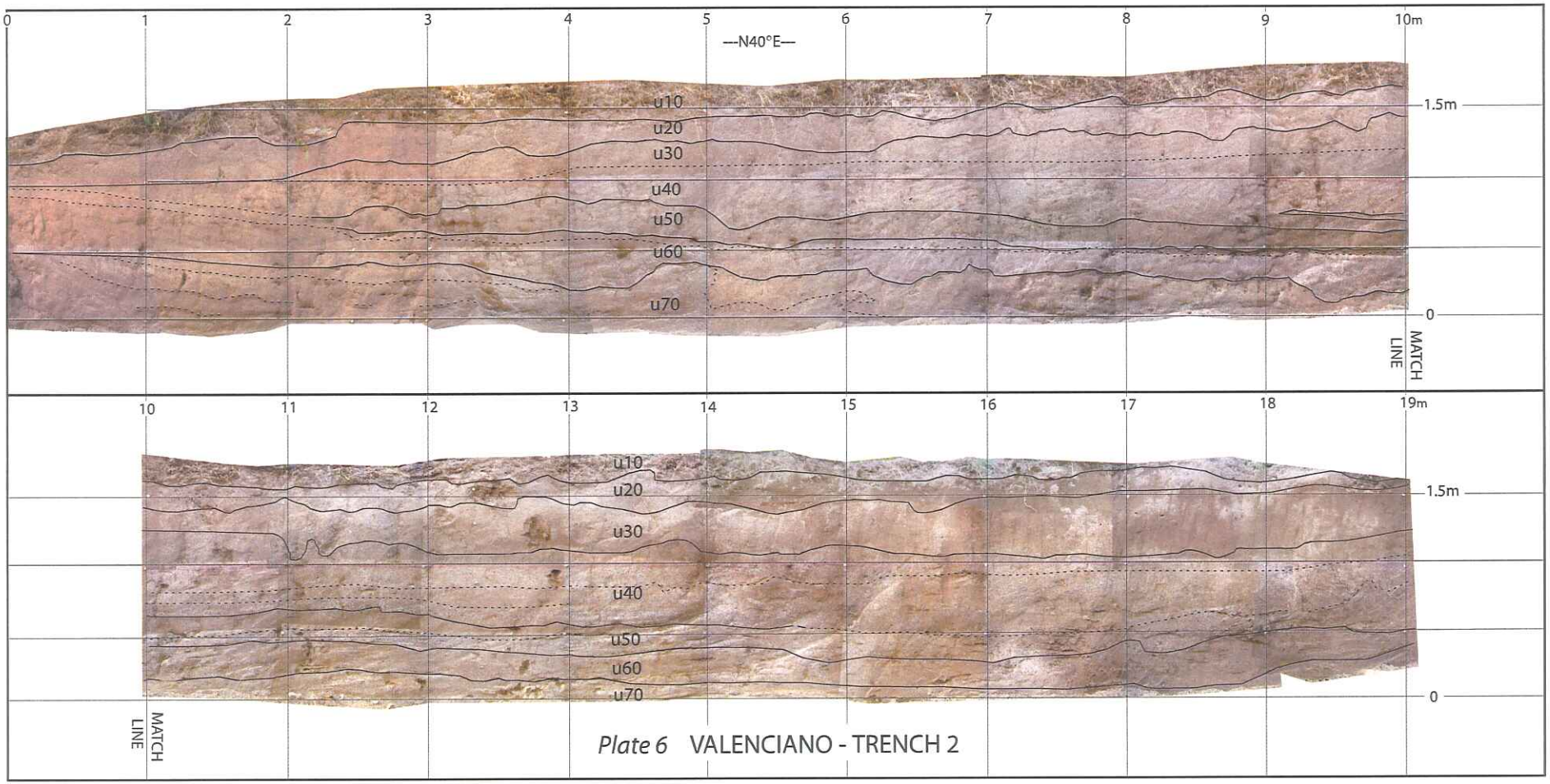

Plate 6 VALENCIANO - TRENCH 2

Unit 10 Massive reddish brown (5YR 5/3); loose silt to sand, few pebbles up to 1 cm; prominent pores up to 1 mm, few worm cast, granular texture, concrete debris in shallow pit at 2m. < soil developed on disturbed overbank deposit>

Unit 20 Massive reddish brown (5YR 4/4) silt to granule sand, less than 5% pebbles; hard, brittle, cohesive, many pores, many roots, clay coatings faint to none, texture is granular. <bioturbated overbank deposit>.

Unit 30 Weakly bedded yellowish red (5YR 4/6) silty granule sand, few rounded pebbles, many angular grus, weak clay coatings in root casts, weak peds, many black managanese nodules or clasts, hard, moderately brittle, cohesive <overbank deposit>

Unit 40 Weakly bedded yellowish red (5YR 4/4) silty granule sand and clayey silts; cohesive; <overbank deposit>

Unit 50 Weakly bedded reddish brown (5YR 5/4) granule sand fines up to silty to coarse sand with some sorting in the coarse fraction (weak interbeds), upper sand is massive to very weakly bedded, very hard and brittle, common granules, matrix of the basal coarser fraction is as above. <overbank deposit>.

Unit 60 Weakly bedded reddish brown (5YR 4/4) silt and coarse sand, common granules, hard, brittle; similar to units above. <overbank deposit>.

Unit 70 Fining up light reddish brown (5YR 6/4) mottled with yellowish red (5YR 5/6) granule sand and very fine sandy silt, hard, silt is cohesive <alluvium/overbank deposit>.

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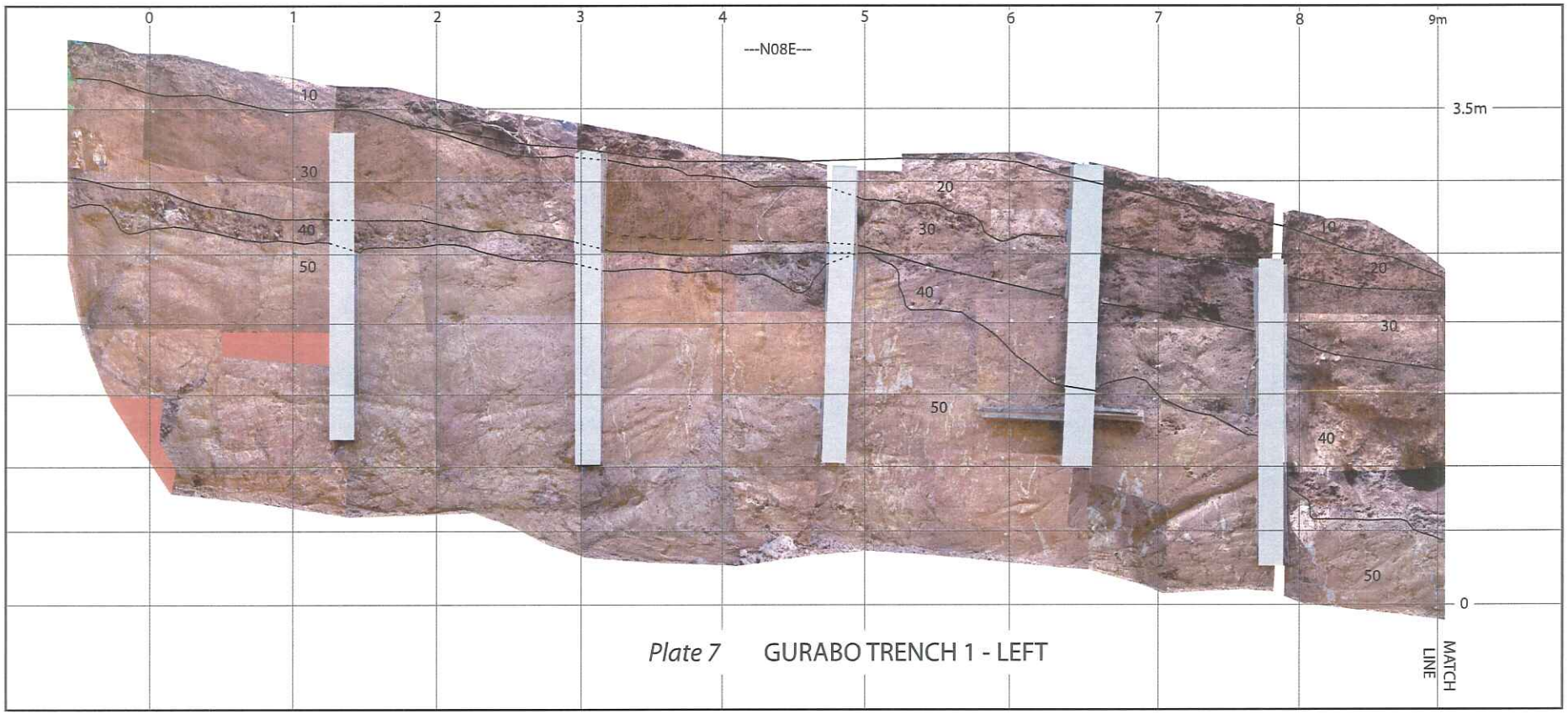

Plate 7 GURABO TRENCH 1 - LEFT

Unit 10 Upper portion is massive, mixed gray-brown (5YR 4/3) silty-granule sand, very loose and soft <slope deposit/colluvium>.
lower portion is massive dark reddish brown (5YR 3/4) clay to sandy silt, firm, pilly texture, weak to no clay coatings, fine sandy silt <soil developed on u20>.

Unit 15 Massive red (2.5YR 4/8)silt/clay, saturated color is very distinctive, soft <volcanic-derived slope debris>.

Unit 20 Massive to very weakly bedded yellowish red (5YR 4/6) clay to sandy silt with common pebbles (up to 2cm), silty plastic, firm to hard <colluvium>.

Unit 30 Similar to unit 20, slightly better sorting, hard, clay very fine sandy silt, locally fills boulder topography of unit below. yellowish red (5YR 4/6) to strong yellowish brown (7.5YR 5/7) with many black manganese stains <colluvium or overbank deposit>.

Unit 40 Massive to weakly bedded unit with 2 components, basal cobble boulder debris with matrix similar to the unit above (unit 30). Body of unit is hard, reddish yellow (5YR 6/6 to 7.5YR 6/6) mottled with black; boulders extremely hard and competent; color of boulder clasts white to pink with black coatings and black fillings in fractures (appears to be vein filling: Quartz) Boulder clasts are angular, a few clast subangular to subrounded, probably from surface weathering on slope above <slope debris>.

Unit 45 Very weathered bedrock body is equivalent to unit 50, dark reddish brown (5YR 3/4) common manganese stained zones; body is locally is mixed with boulder debris <mobile clay sapprolite>.
body contains vertical fabric; 20-30% comprises light gray "veins" 1-10cm wide 20-50 cm long (subvertical) where exposed, the veins contain pebbles, probably infiltrating pebbles from above. <root casts>.

Unit 50 Massive yellowish red (5YR 5/6) silty clay, locally soft (moist) generally firm <bedrock sapprolite>.
Many small scale veins mostly vertical, contain light brown silt and sand grains veins are 20-30% of the unit <root cast>.
Larger scale veins up to 20 cm are filled with hard very weathered vein material <hydrothermal veins>.

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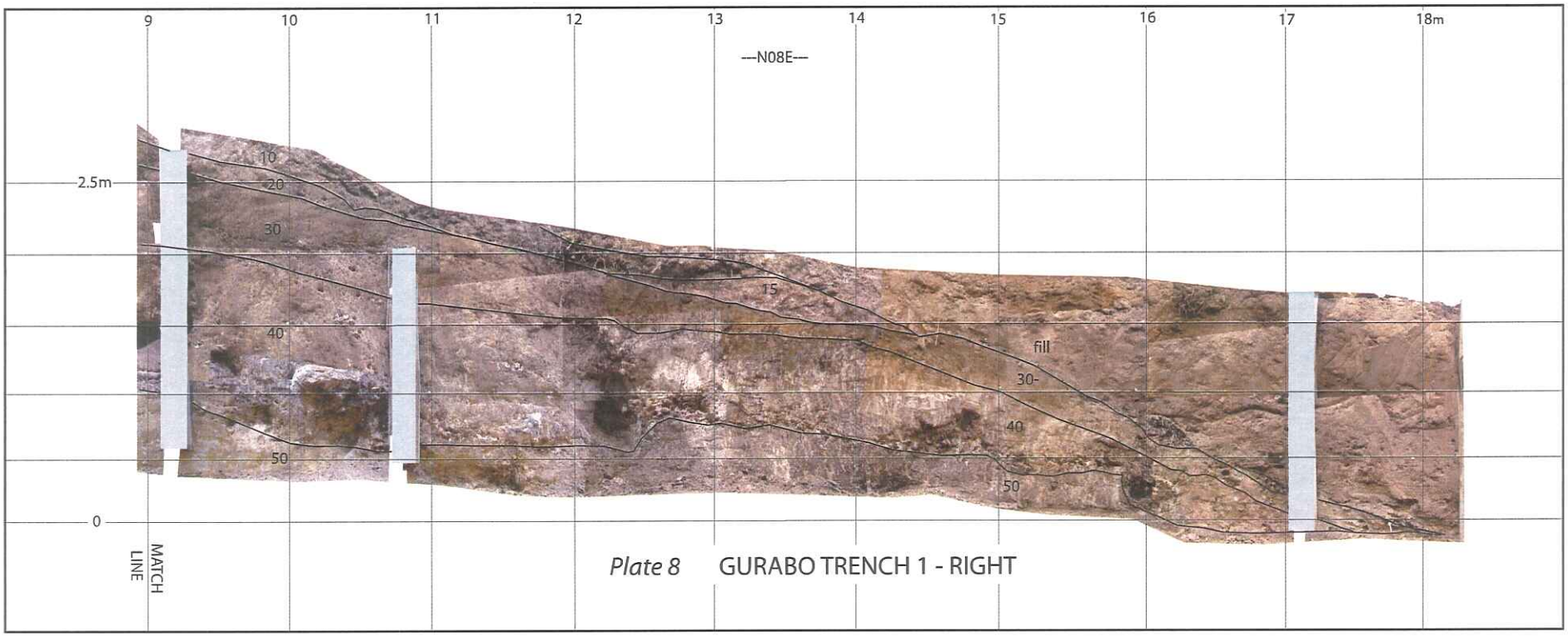

Plate 8 GURABO TRENCH 1 - RIGHT

Unit 10 Upper portion is massive, mixed gray-brown (5YR 4/3) silty-granule sand, very loose and soft <slope deposit/colluvium>.
lower portion is massive dark reddish brown (5YR 3/4) clay to sandy silt, firm, pilly texture, weak to no clay coatings, fine sandy silt <soil developed on u20>.

Unit 15 Massive red (2.5YR 4/8)silt/clay, saturated color is very distinctive, soft <volcanic-derived slope debris>.

Unit 20 Massive to very weakly bedded yellowish red (5YR 4/6) clay to sandy silt with common pebbles (up to 2cm), silty plastic, firm to hard <colluvium>.

Unit 30 Similar to unit 20, slightly better sorting, hard, clay very fine sandy silt, locally fills boulder topography of unit below. yellowish red (5YR 4/6) to strong yellowish brown (7.5YR 5/7) with many black manganese stains <colluvium or overbank deposit>.

Unit 40 Massive to weakly bedded unit with 2 components, basal cobble boulder debris with matrix similar to the unit above (unit 30). Body of unit is hard, reddish yellow (5YR 6/6 to 7.5YR 6/6) mottled with black; boulders extremely hard and competent; color of boulder clasts white to pink with black coatings and black fillings in fractures (appears to be vein filling: Quartz) Boulder clasts are angular, a few clast subangular to subrounded, probably from surface weathering on slope above <slope debris>.

Unit 45 Very weathered bedrock body is equivalent to unit 50, dark reddish brown (5YR 3/4) common manganese stained zones; body is locally is mixed with boulder debris <mobile clay sapprolite>.
body contains vertical fabric; 20-30% comprises light gray "veins" 1-10cm wide 20-50 cm long (subvertical) where exposed, the veins contain pebbles, probably infiltrating pebbles from above. <root casts>.

Unit 50 Massive yellowish red (5YR 5/6) silty clay, locally soft (moist) generally firm <bedrock sapprolite>.
Many small scale veins mostly vertical, contain light brown silt and sand grains veins are 20-30% of the unit <root cast>.
Larger scale veins up to 20 cm are filled with hard very weathered vein material <hydrothermal veins>.

APPENDIX 1 Google Earth summary maps

Figure A1a. Caguas-Gurabo G-Earth planning map. In all Figures north is up. Note Route 52 is at left side of Figure to west and Route 30 is in lower area of Figure. Apparent fault features include north and south-facing slope breaks which are aligned from Rte 52 to east of the Loiza River and several suggestive stream deflections. Features may result from fortuitous alignment of bedrock fault and/or joint patterns and erosion on younger surfaces controlled by bedrock boundaries. The association of several possible active fault features and a bedrock strand of the NPRFZ pose this site for primary investigation in the western Gurabo Valley area..

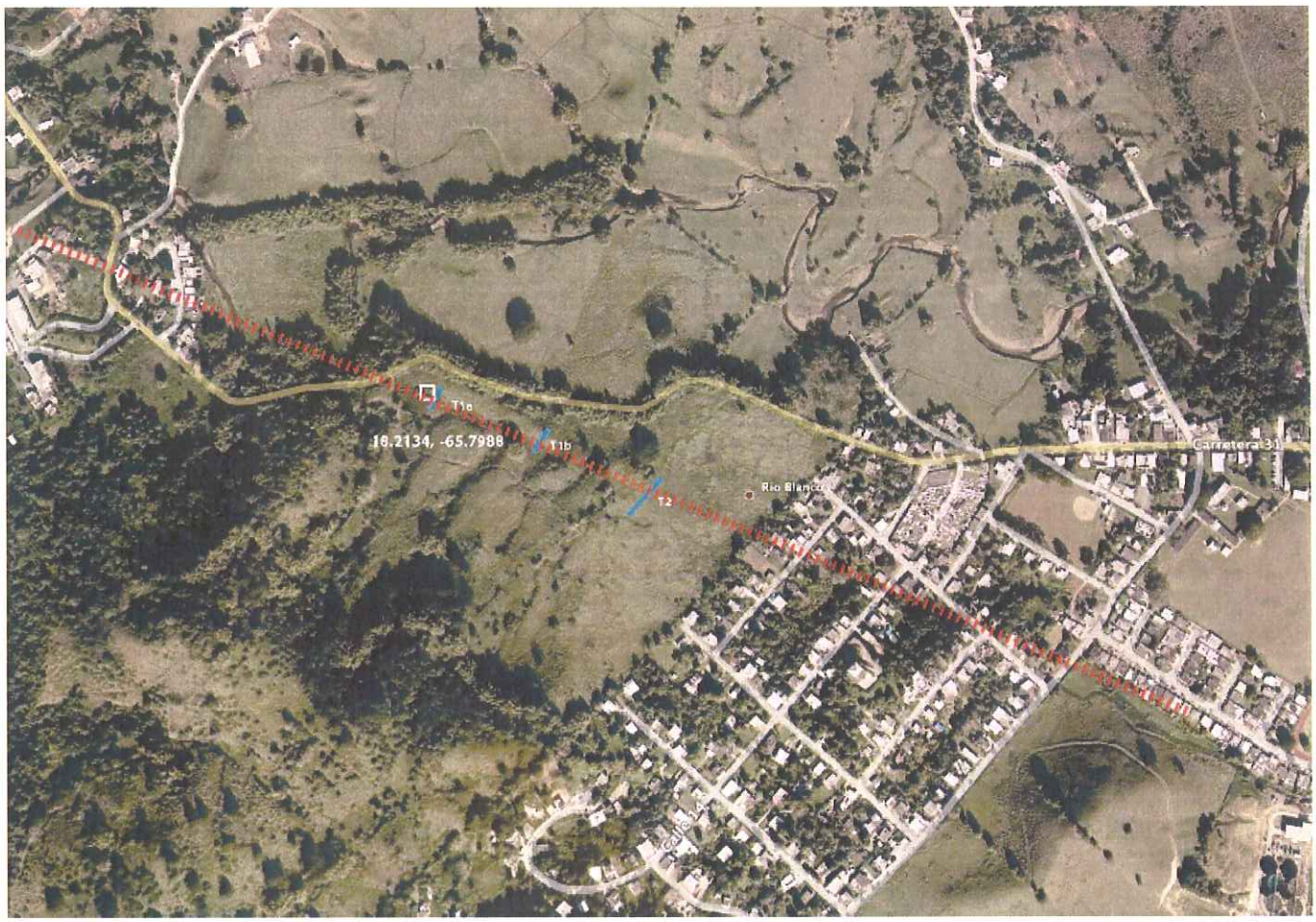

Figure A1b. Rio Blanco G-Earth planning map. Conjunction of possible fault-related stream deflections with location of the Pena Pobre strand of the NPRFZ immediately west of town of Rio Blanco . This association, and presence of late Quaternary and Holocene alluvial deposits in favor this site for primary investigation of potential active faulting in the eastern Gurabo Valley – Rio Blanco Valley area.. Lidar data for this area presented in Figure A3b.

Figure A1c. Humacao River gorge G-Earth planning map. Bedrock mapping of fault in prominent linear valley immediately west of Humacao pose this site for investigation in the easternmost project area. Fault projection passes through broad terrace situated between Route 30-60 intersection and Humacao River. River deposits may record young motion, if present. Lidar data for area of Humacao River gorge sites rms: A3c.