Evidence for late Quaternary faulting of the south-central coastal plain of Puerto Rico

Joanna Redwine, Sarah A. Derouin, Lucille A. Piety, Ralph E. Klinger

Bureau of Reclamation, Seismotectonics and Geophysics Group, P.O. Box 25007, 86-68330, Denver, CO 80225, jredwine@usbr.gov

ABSTRACT

As a result of a seismic hazard assessment for the Puerto Rico Electric Power Authority, a number of west- and northwest-trending lineaments on the south-central coastal plain of Puerto Rico have been identified as late Quaternary active faults. LiDAR imagery was collected along an 11-km-wide and 60-km-long strip from just east of Punta Arenas continuing west past Juana Diaz. The imagery shows two zones of lineaments that cut across topography and are coincident with topographic scarps on Quaternary deposits. To the north, the relatively straight, more northwest-trending lineaments are coincident with large bends in streams suggestive of right-lateral strike-slip offset. Where these lineaments cross generally southward flowing streams there are dramatic changes in the channel geometry (width and slope), the depth of channel incision, thickness of channel alluvium, the preservation of stream terraces, and the evolution of some drainages against the regional slope. This zone of lineaments coincides closely with the mapped trace of the Great Southern Puerto Rico Fault Zone (GSPRFZ).

To the south, the more westerly-trending lineaments form a sinuous ~0.5-km-wide zone composed of two or more sub-parallel lineaments. This zone is coincident with the Salinas fault zone (SFZ) and continues to the east and appears to merge with the mapped trace of the GSPRFZ. The northernmost lineament is a nearly continuous and consistently south-facing topographic scarp. The southernmost lineaments are discontinuous, with both north- and south-facing scarps. Topographic profiles constructed across the zone consistently display up to 2 to 3 m of displacement. Excavations across the scarps expose displace late Quaternary deposits. Evidence points to at least two late Quaternary surface rupturing events with both vertical and lateral motion.

METHODOLOGY

Our investigative approach included:

1. Review of literature, mapping and prior studies in Puerto Rico
2. Collect LiDAR data
3. Create geomorphic map on LiDAR identifying Quaternary deposits/ landforms, scarps, and any tectonically-produced landforms or signatures (e.g.- offset drainages, shutter ridges)
4. Field reconnaissance (March 2012) to check locations of mapped scarps, areas of interest, identify potential trench locations
5. Trenching investigation on scarps located on Quaternary deposits

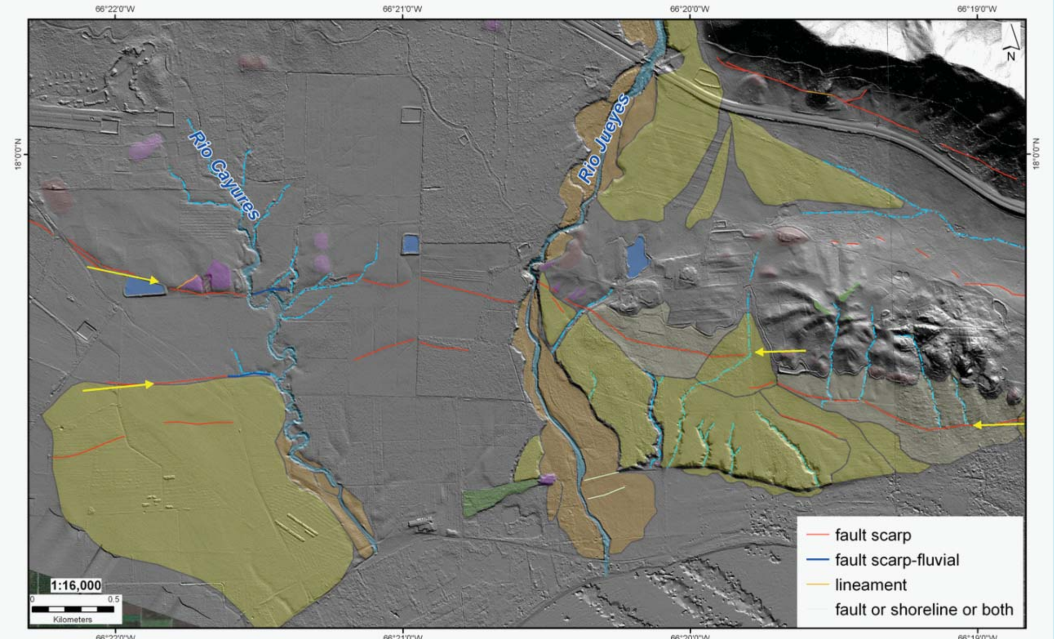


Figure 1: (Step 3 in methodology)- Part of a geomorphic map used to identify tectonic features and locations for further, detailed study. In this figure there is a broad alluvial plain (partially outlined in yellow) that is composed of coalescing alluvial fans. This alluvial plain is cut by a shoreline (dated from shells as being a minimum of ~3,000 yrs before present (Prentice and others, 2004). Inset alluvial fans and fluvial deposits (mapped in tan) are inset into the older alluvium and are not faulted.

PRIOR WORK ON THE SALINAS FAULT AND THE GREAT SOUTHERN PUERTO RICO FAULT ZONE (GSPRFZ)

We are not the first to work in this area. Geomatrix (1988) concluded any fault displacements on the Salinas fault are older than Holocene (~10,000 years ago), but that displacements younger than about 35,000 years ago could not be precluded. Wong and others (2004) also concluded that any displacements on the Salinas fault are older than Holocene based on their examination of aerial photographs. Based on displaced bedrock along a nearby fault system, Geomatrix (1988) and Wong and others (2004) inferred about 35 m of post-Oligocene vertical displacement and used this vertical bedrock displacement and rock age to estimate a low long-term vertical slip rate for the Salinas fault.

The GSPRFZ is shown by Glover (1971) as a zone of generally northwest-striking faults through bedrock composed of the Esmeralda fault and the Cañas Abajo fault (Glover, 1971). Glover (1971) interpreted these faults as normal faults, although he noted that, overall, displacement on the GSPRFS has been both vertical and left lateral, with a total of about 10 km of left-lateral strike slip. Evidence for Quaternary displacement on the GSPRFZ is primarily from observations on the shallowly submerged shelf off the south coast of Puerto Rico, the Muertos insular shelf of Garrison (1969). Glover (1971) noted lineaments from bathymetric data correlate with discontinuities in total magnetic intensities identified by Geddes and Dennis (1964) and Griscom and Geddes (1966). Also, Garrison (1969) measured seismic profiles near Bahia de Jobos and interpreted a N65°W-striking fault with a 15-meter-high, down-to-the-southwest scarp and interpreted this as most likely an active fault. Lineaments were also reported by Grindley and others (2000) and McCann (2002) used inferred sea level changes to estimate a maximum vertical slip rate of 0.14 mm/yr or 0.19 mm/yr for that 15-m-high scarp. Mann and others (2005) reported deformation of recent (Holocene) sediments immediately offshore along the trend of the southeast GSPRFZ.

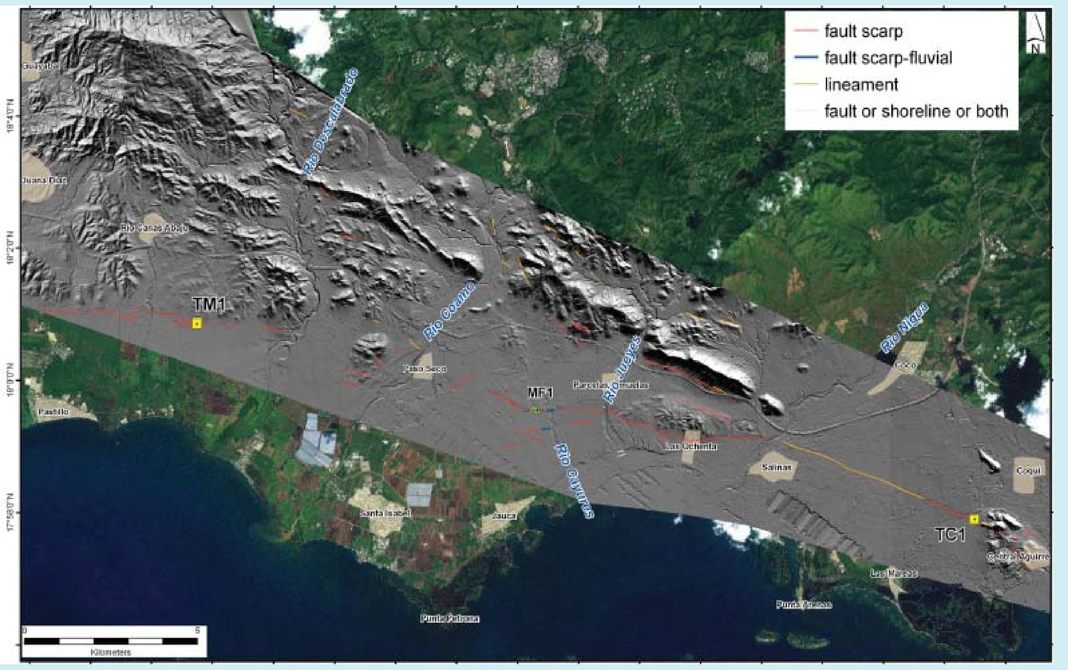


Figure 2: Step 3,4,5 in methodology. LiDAR imagery with mapped scarps and lineaments (Step 3). MF1 was the preliminary trench excavated during Step 4. TM1 and TC1 were the two trenches excavated and presented here (Step 5). TM1 was located on the Salinas fault and TC1 was located on the intersection of the Salinas and GSPRFZ.

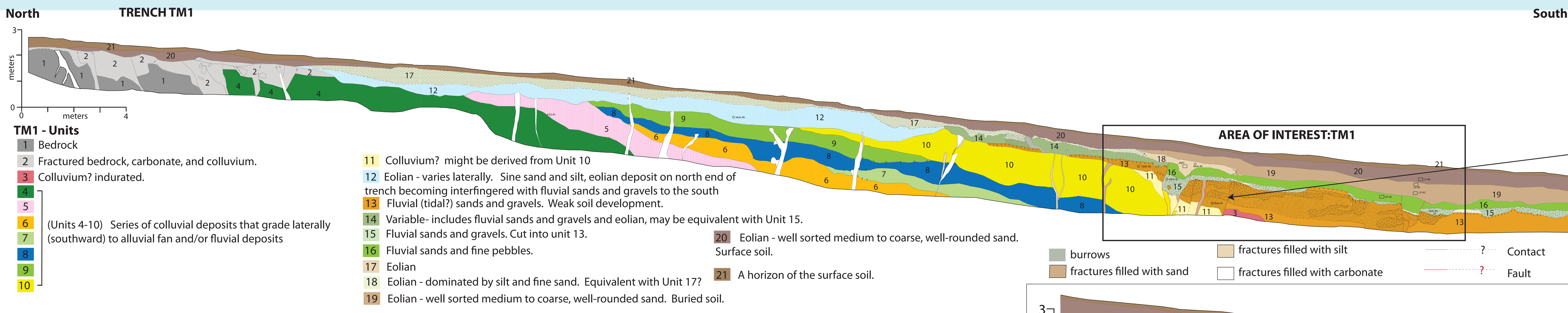


Figure 3: Trench TM1. This ~55-m-long trench across the fault exposed a fairly long and complex middle-to-late(?) Pleistocene and Holocene depositional and faulting history. A brief and over-simplified summary follows. The lower Units (4-10) are interpreted as a nested sequence of interfingered colluvial and alluvial deposits. These units all have a carbonate fabric, most likely of pedogenic origin, and some have carbonate shears (without offset). These deposits are deformed; the basal contacts of these units become progressively steeper with time (older units have steepest contacts) and the carbonate shears and pedogenic features appear to rotate from south-dipping on the north side of the trench, to vertical, and then north-dipping near the shear zone. We interpret this package of sediments has been faulted and possibly folded. We do not know how many events may be represented with this deformation.

A younger group of deposits have been displaced by the two most recent faulting events. Units 13-16 are interpreted as fluvial deposits based on sorting and rounding. An alternative interpretation is that some of these deposits (Unit 13) may be inter-tidal. Three or four generations of eolian deposits overlie the fluvial deposits (Units 17 -20) and were deposited against the fault scarp, therefore post-date the MRE.

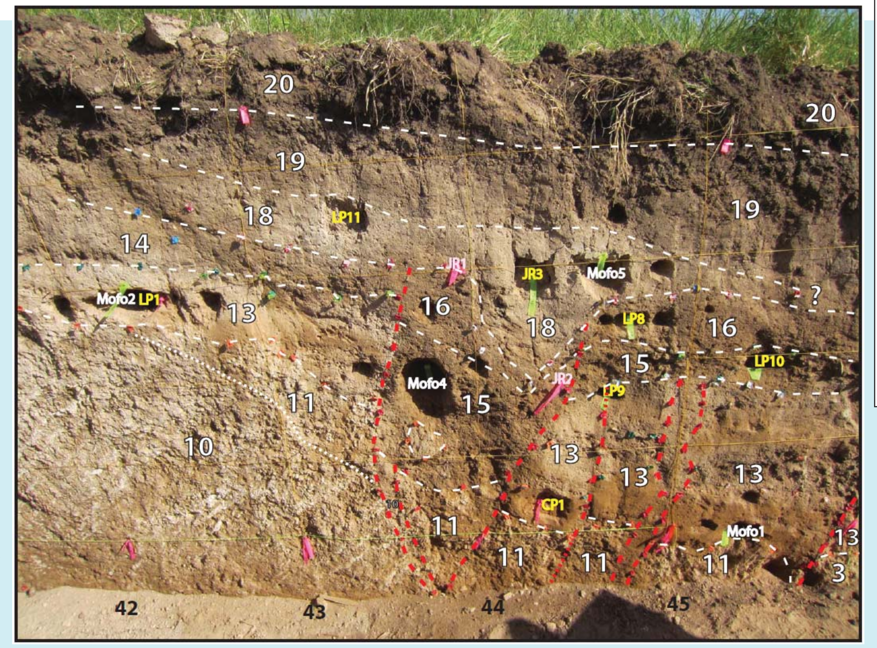


Figure 4: Photo of main fault zone in TM1. 14C dates are in yellow, OSL dates in white, and shell samples in pink.

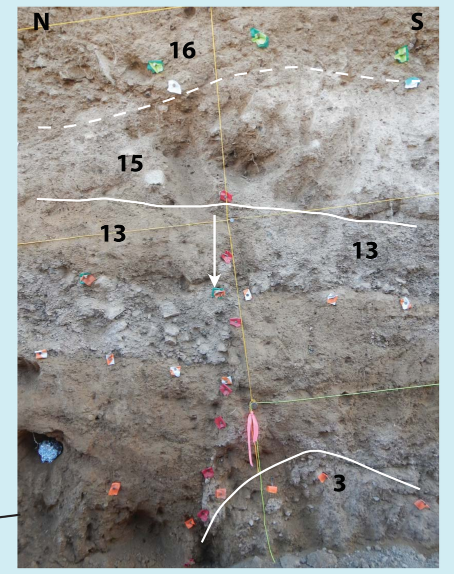
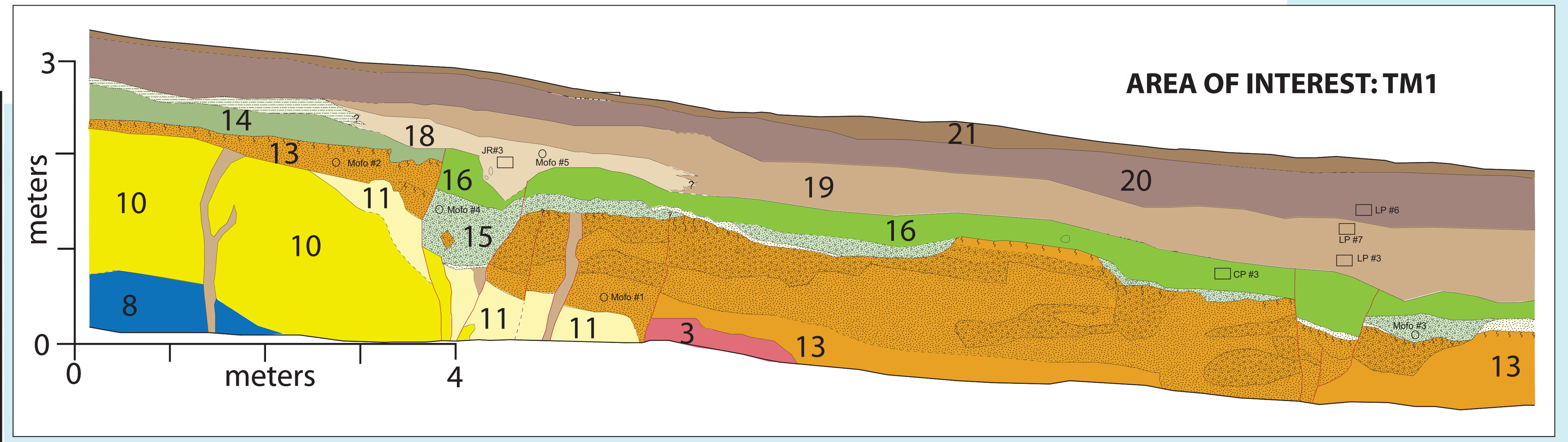


Figure 5: Photo of fault zone in TM1. White arrow shows relative displacement of stratigraphic units.



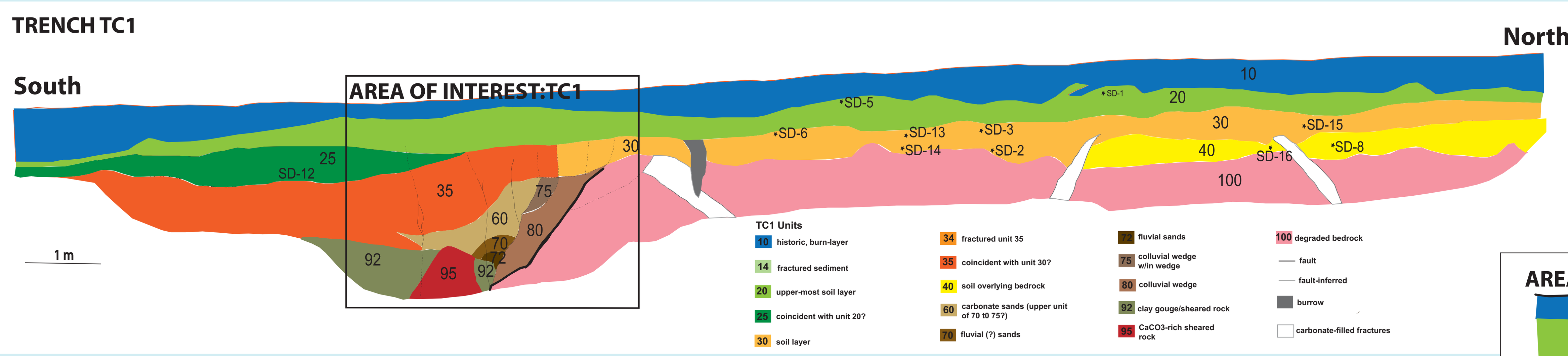


Figure 6: Trench TC1. This ~20-m-long trench is across a fault trace that could be the GSPRFZ, the Salinas fault or a combination of the two. This trench exposes middle to late(?) Pleistocene to Holocene soils overlying weathered bedrock. A brief summary follows. The basal unit of the trench is weathered bedrock, likely volcaniclastic, with many carbonate-filled fractures. Two soils were developed into the bedrock (Unit 40 and 30). This soil is also in part eolian, demonstrated by a large amount of shells and fine-grained material incorporated into the units. There are many carbonate shears within the trench, one of which displaces Unit 40 (a sandy soil horizon). Unit 30, the middle soil, extends across the trench (we tentatively correlate Unit 35 with Unit 30). Shells within these upper soil horizons have not been analyzed at this time.

The main fault zone juxtaposes sheared bedrock against sedimentary deposits. At least two carbonate-rich colluvial wedges were deposited against the shear zone. Units 92 and 95 are clay-rich with zones of concentrated calcium carbonate that we have interpreted as sheared bedrock. Overlying is a package of sandy deposits interpreted aas fluvial based on the presence of sand lenses (Unit 35). Unit 30 also has some few sand lenses and is not displaced by the fault in TC1; however, fractures aligned along the fault plane do extend upward through unit 30 and 20. We have interpreted this as evidence of a second earthquake. Multiple colluvial wedges and different amounts of displacement o f Unit 40 relative to Unit 30 indicate multiple events. We have interpreted this fault as mostly or all strike-slip based on the laterally discontinuous stratigraphy, alternating direction of the scarp along the length of the fault, the low-relief of the multiple-event-fault-scarp, and the wide shear zone.

SUMMARY OF EARTHQUAKE HISTORY

TM1

Penultimate Event :

Unit 13 and underlying units are displaced across the fault zone. Some faults terminate upward at the top of this unit. Preliminary 14C and Optically Stimulated Luminescence (OSL) dates suggest Unit 13 may be 16 to 9 ka.

Most Recent Event:

Overlying Units 15 and 16 are also displaced across the fault zone. Upward terminations of some faults end at the top of unit 16. We interpret this as the most recent event. Units 18-20 have been interpreted as unfaulted windblown deposits against the fault scarp.

TC1

Penultimate Event:

Unit 100 has been faulted (zoned rupture) within the trench, including a smaller truncation of Unit 40 on the north end of the trench, and main fault zone in a ~5-m-wide zone in the deepest part of the trench. The main fault zone created at least two colluvial wedge deposits (Units 60 through 80), including fluvial sand deposits (Units 60, 70, and 72) that suggest flowing water at the base of the fault scarp.

Most Recent Event:

Deposits overlying the faulted bedrock and colluvial wedges have soils forming into them and have been faulted sometime after the penultimate veent. Fractures from the younger event terminate upward into Unit 20. We are still waiting for ages of Unit 30, which will provide a bracketing age for the latest rupture (post deposition of Unit 30).

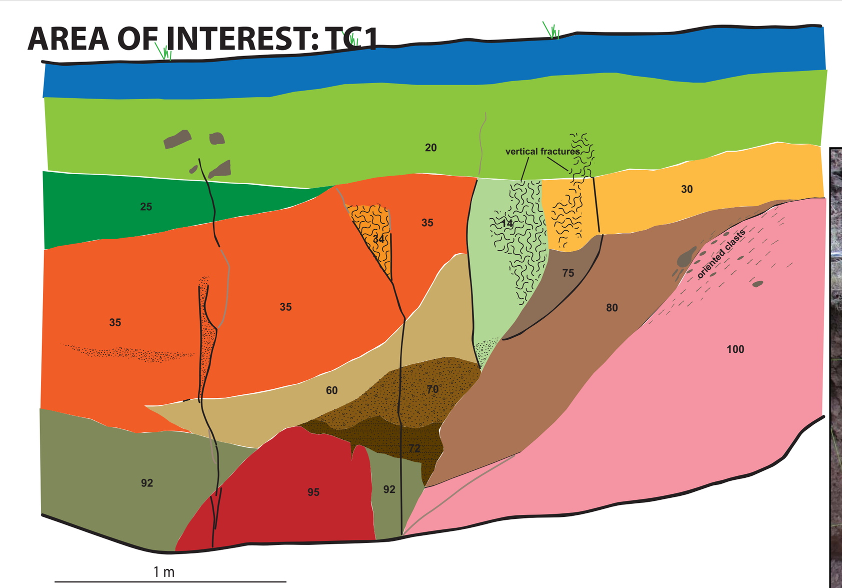


Figure 7: Photo of TC1 with flagging. Note truncated bedrock unit (Unit100) and sedimentary colluvial package to the south (left) of the fault.

WHAT TYPE OF FAULT IS THIS?

We interpret the Salinas and GSPRFZ to likely be strike-slip with a possible component of compression.

The lateral interpretation is based on the following observations:

- There are changes in unit thickness across the fault zone
- The units on either side of the fault do not match
- The faults are near vertical
- The shear zone is wide
- There are both north- and south-facing scarps along the same fault strand

The component of compression is based on the following observations:

- The meandering map pattern of this fault system, suggests a shallow-dipping-fault
- The rotation of the carbonate shears and pedogenic features in TM1, show apparent folding
- Progressive tilting may be shown by an increase in steepness of the basal contact in progressively older alluvial units
- Any compression may be localized along a primarily strike-slip system

However, we do not have clear evidence for the type of motion in terms of piercing points or matching correlative stratigraphy on either side of the fault. More work is needed to document and understand the sense of motion of these faults.

CONCLUSIONS

1. There are active, latest Pleistocene to Holocene onshore Quaternary faults in Puerto Rico

2. There is evidence for ≥ 2 events in each trench

3. Timing of events appears to be latest Pleistocene to Holocene. Preliminary dates say 2 earthquakes since 16-9 ka

4. Fault type is unclear, although currently interprested as most likely a strike slip fault with a component of compression

ACKNOWLEDGEMENTS

We would like to thank the following people for their exceptional assistance during our investigation:

From PREPA:
- Rubén Estremera, Principal Engineer Supervisor
- Jorge Cintrón, Irrigation Supervisor
- Carlos Ayala, Principal Clerk Irrigation Services
- Efraín Rodriguez, Irrigation System Maintenance Worker (excavator operator)
- Alvin Aponte, Operator Services Irrigation Channels

- Carol Prentice, USGS
- Keith Kelson, URS
- Shannon Mahan, USGS
- PaleoResearch

REFERENCES

Geomatrix Consultants, 1988, Geological-seismological evaluation to assess potential earthquake ground motions for the Portugues Dam, Puerto Rico [DRAFT REPORT], Geomatrix Consultants, Report completed under Contract No. DAWC17-88-C-0003, submitted to Department of the Army, Jacksonville District, Corps of Engineers, Jacksonville, Florida, Project1311A, variously paged.

Glover, L., 1971, Geology of the Coamo area, Puerto Rico, and its relation to the volcanic arc-trench association, U.S. Geological Survey Professional Paper 636, 4 pls., 102 p.

Garrison, L.E., 1969, Structural geology of the Muertos insular shelf, Puerto Rico, U.S. Geological Survey Open-File Report 69-103.

Geddes, W.H., and Dennis, L.S., 1964, Preliminary report on a special aeromagnetic survey of the Puerto Rico trench, A study of serpentintite: National Academy of Science, National Research Council Publication 1188, p. 25-29.

Grindley, N.R., Abrams, L.J., Mann, P., and Del Greco, L., 2000, A high-resolution sidescan and seismic survey reveals evidence of late Holocene fault activity offshore western and southern Puerto Rico [abs.]: EOS Trans. AGU, Fall Meeting Supplement, v. 81, no. 48.

Griscom, A., and Geddes, W.H., 1966, Island-arc structure interpreted from aeromagnetic data near Puerto Rico and the Virgin Islands: Geological Society of American Bulletin, v. 77, p. 153-162.

Mann, P., Prentice, C.S., Hippolyte, J.-C., Grindlay, N.R., Abrams, L.J., and Laó-Dávila, D., 2005, Reconnaissance study of late Quaternary faulting along Cerro Goden fault zone, western Puerto Rico: Geological Society of America Special Paper 385, p. 115-137.

Mann, P., Hippolyte, J.-C., Grindlay, N.R., and Abrams, L.J., 2005, Neotectonics of southern Puerto Rico and its offshore margin: Geological Society of America Special Paper 385, p. 173-214.

McCann, W.R., 2002, Earthquake submarine geology and estimates of fault slip rates in Puerto Rico and the U.S. Virgin Islands [abs.]: Geological Society of America Abstracts with Programs, v. 34, p. 6.

Prentice, C.S., and Mann, P., 2005, Paleoseismic study of the South Lajas fault: First documentation of an onshore Holocene fault in Puerto Rico: Geological Society of America Special Paper 385, p. 215-222.

Prentice, C.S., McGeehin, J.P., Simmons, K.R., Muhs, D.R., Roig, C., Joyce, J., and Taggart, B.E., 2004, Holocene marine terraces in Puerto Rico--Evidence for tectonic uplift? [abs.]: Geological Society of America Abstracts with Programs, v. 36, no. 5, p. 288.

Wong, I., Fenton, C., Dober, M., Nemser, E., Thomas, P., and Terra, F., 2004, Deterministic and probabilistic seismic hazard analyses, Portugues Dam, Puerto Rico: Oakland, California, URS Corporation, Report prepared for U.S. Army Corps of Engineering, Jacksonville District, Jacksonville, Florida, variously paged.