Field Trip: Recent Tectonics and Paleoseismology in Western Puerto Rico
May 3-4, 2003
Seismological Society of America

Leaders: Carol Prentice, Hernan Santos, Paul Mann, Martitia Tuttle, Eugenio Asencio, Nancy Grindlay, and James Joyce

ITINERARY

Saturday, May 3:

7:30 leave San Juan

9:00 arrive Salinas site- Introduction to trip leaders; Introduction to Puerto Rico geology; Introduction to Puerto Rico seismology; young stranded shoreline STOP LEADERS: CAROL (introduction to trip); HERNAN and JIM (introduction PR geology); EUGENIO (introduction to PR seismicity); CAROL (young shoreline).
10:00 depart Salinas site

10:45 arrive Holiday Inn overlook STOP LEADERS: PAUL, NANCY . (Note: this is a bathroom break).
11:15 depart Holiday Inn

11:25 arrive landfill STOP LEADER: PAUL
11:55 depart landfill

12:30 arrive lunch stop (bathrooms available)
1:15 depart lunch stop

2:00 arrive Lajas overlook STOP LEADERS: CAROL (geomorphology of Valle de Lajas); HERNAN (geology of southwestern Puerto Rico); EUGENIO (seismicity of southweswern Puerto Rico)
2:30 depart Lajas overlook

2:40 arrive trench site STOP LEADER: CAROL (Holocene fault exposed in trenches)
3:40 depart trench site

4:10 arrive Cabo Rojo STOP LEADERS: PAUL, NANCY
4:45 – 5:30 swim
5:30 depart Cabo Rojo

6:30 arrive Mayaguez Resort and Casino

Sunday, May 4:

8:30 leave Mayagüez; break into two groups - Group 1 goes to Rio Culebrinas liquefaction sites (STOP LEADER: TISH)

Arrive put-in 9:00, return at 11:30.

Group 2 goes to Rincón

8:30 leave Mayagüez

8:45 arrive overlook platform off highway 115 STOP LEADERS: PAUL, NANCY. EUGENIO
9:30 depart overlook

9:45 arrive lighthouse STOP LEADERS: CAROL, JIM
10:15 depart

10:25 arrive Pool's beach STOP LEADERS: JIM , CAROL
11:00 depart

11:30 arrive Rio Culebrinas. Reconvene the two groups for lunch (Rio Culebrinas) (bathrooms available)

12:30: Group 2 to Rio Culebrinas liquefaction
put in 12:30, return 3:00

Group 1 to Rincón in three vans:

12:30 depart Rio Culebrinas

1:00 arrive overlook platform off highway 115 STOP LEADERS: PAUL, NANCY
1:40 depart overlook

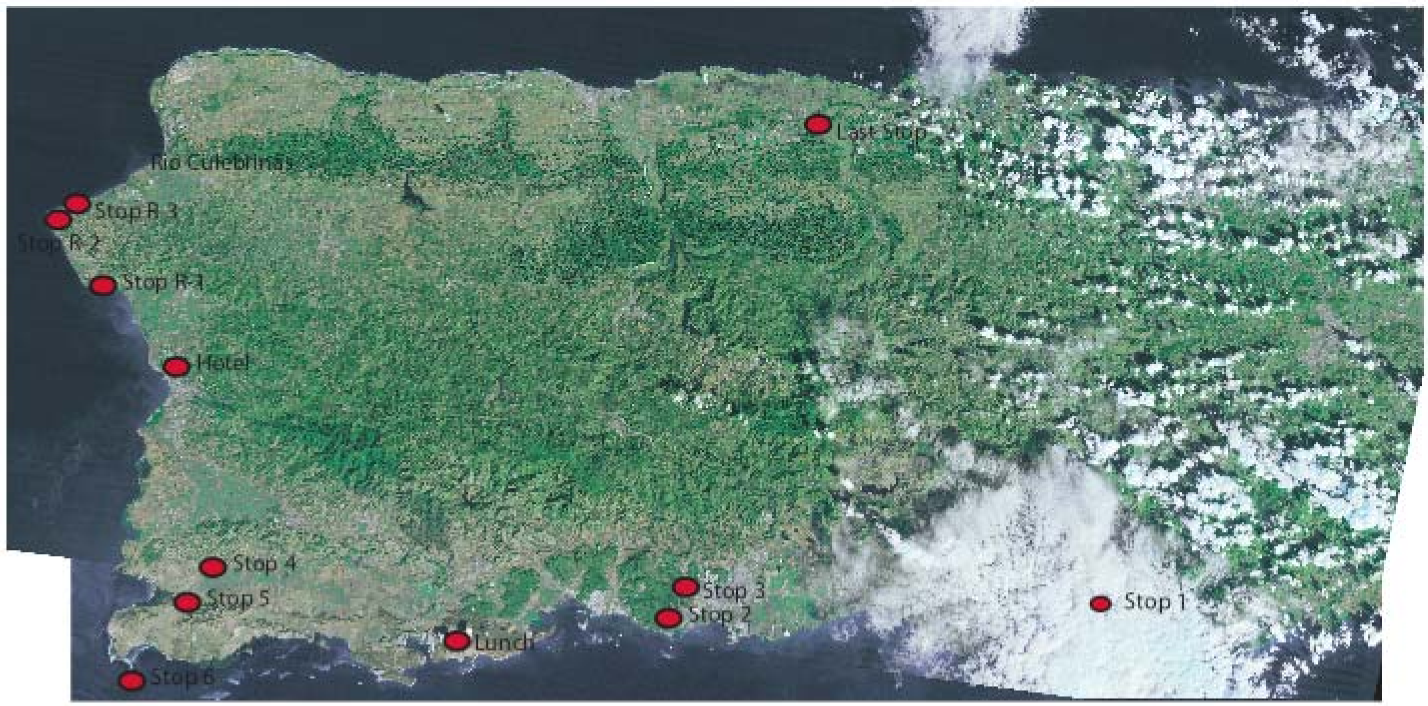
1:55 arrive lighthouse STOP LEADERS: CAROL, JIM
2:20 depart

2:30 arrive Pool's beach STOP LEADERS: CAROL, JIM
3:00 depart

3:30 Reconvene at Rio Culebrinas and depart (after short bathroom break)

Arrive Manatí site 4:30
Depart 5:30

Arrive San Juan 6:30



Landsat image showing locations of field trip stops (image processed by Michael Rymer, USGS).

Day 1, Saturday, May 3

Stop 1: Introduction to the geology of Puerto Rico (Jim Joyce and Hernan Santos); Introduction to Puerto Rico seismology (Eugenio Asencio)

Young shoreline near Salinas (Carol Prentice)

One of the primary themes of this field trip is that the Quaternary of Puerto Rico is poorly known. Without a better understanding of the basic Quaternary geology of the island it is not possible to adequately assess seismic hazard.

This stop is intended to highlight how little known the Quaternary of the island is. Here is a prominent and obvious stranded shoreline (figure 1-1). The geologic map of this area (Glover, 1961) shows Quaternary beach deposits below this feature, but the author makes no comment on this feature. An unpublished report by Geomatrix Consultants (1988) notes the presence of this shoreline and suggests a late Holocene age. I have found no other studies of this feature.

The morphology of the shoreline suggests that it is very young: it is very steep and uneroded, and a number of well-preserved beach ridges are present shoreward of this feature. In the plowed fields below the shoreline are sands and gravels deposited by nearshore processes, as well as abundant shells and corals.

The last time global sea level was higher than it is today was approximately 120,000 years ago, during oxygen isotope stage 5e. Sea level at that time is known to have been approximately 6 meters above today's sea level. The elevation at the base of the shoreline here is about 3 meters above sea level, so this is unlikely to represent the stage 5e sea-level high-stand. More likely, given its fresh appearance, associated well-preserved beach ridges and low elevation, this is a Holocene shoreline.

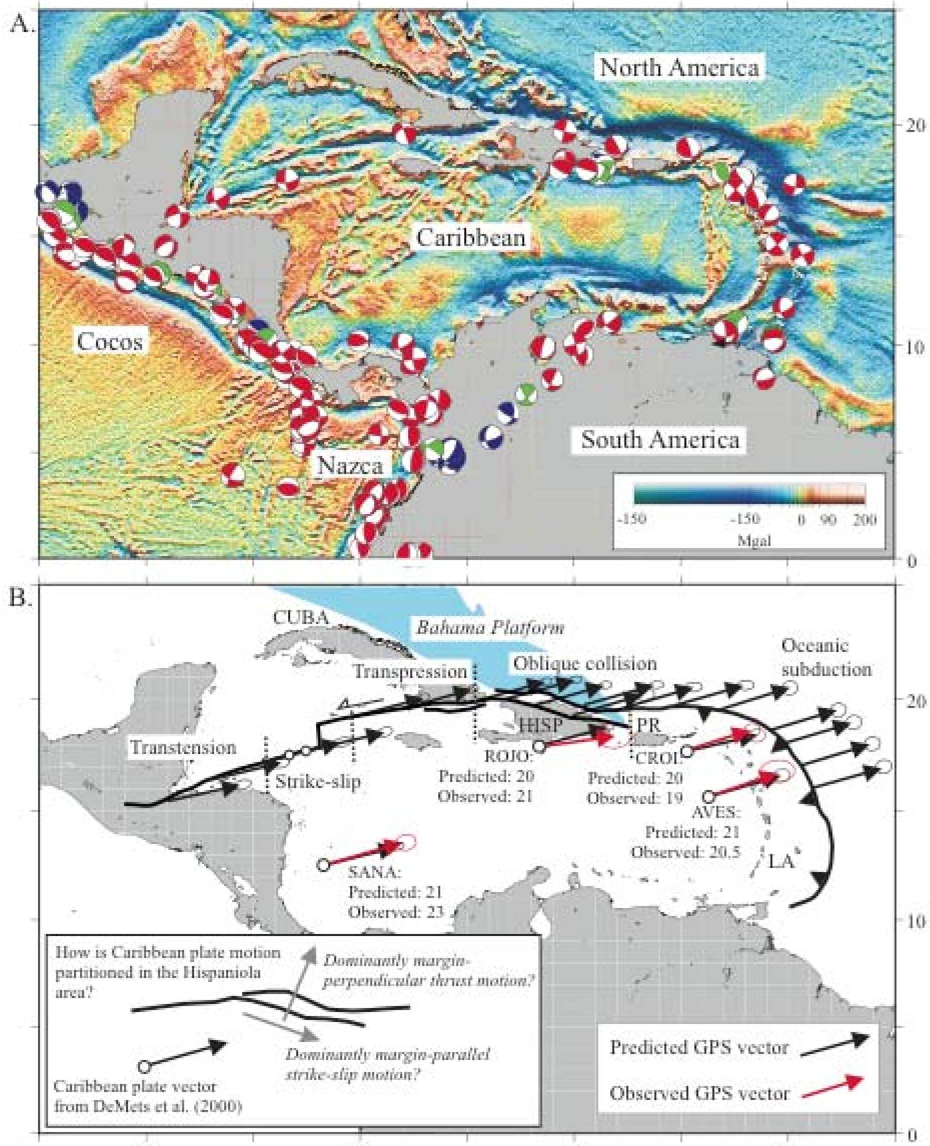
The presence of a Holocene shoreline implies one of two possible scenarios: either rapid tectonic uplift (possibly coseismic), or glacio-hydro-isostatic uplift, a mechanism that has been suggested for similar features in the Pacific ocean basin, but that has not been reported for the Caribbean. In either case, detailed study of this feature has the potential to increase the understanding of Quaternary deformation. Whether its uplift is due to tectonic or non-tectonic processes, dating it and mapping it carefully to see whether or not it is deformed will be a key to begin to understand the Quaternary deformation of the island. Initial mapping suggests that this shoreline may have been affected by the Great Southern Fault. Marine terraces provide important datums for measurement of Quaternary deformation, and mapping and dating this and other marine terraces on the island will provide a crucial first step toward a better understanding of seismic hazard.

Figure 1-1: 1937 aerial photograph showing young, stranded shoreline near Salinas. (Width of photograph shows about 4.5 km

Stop 2: Ponce Holiday Inn overlook (Paul Mann and Nancy Grindlay)

Holiday Inn overlook near Ponce, Figure A. Major plates of the Caribbean region and compilation of earthquake focal mechanisms showing present-day plate kinematics and plate-scale setting of Puerto Rico. Focal mechanisms shown in red are from earthquakes from 0 to 75 km in depth; blue mechanisms are from earthquakes 75 to 150 km in depth; and green mechanisms are > 150 km in depth. **B.** Caribbean-North America velocity predictions of DeMets et al. (2000) based on GPS velocities at four sites in the stable interior of the plate (gray vectors) and two fault strike measurements in the strike-slip segment of the North America-Caribbean boundary (open circles). The predicted velocities are consistent with the along-strike transition in structural styles from transtension in the northwestern corner of the plate to oblique collision between the Caribbean plate and the Bahama platform in the northeastern corner of the plate. Puerto Rico is situated at the eastern edge of the ongoing oblique collision between the southeastern extension of the Bahamas carbonate platform on the North America plate and the Caribbean plate in the island of Hispaniola.

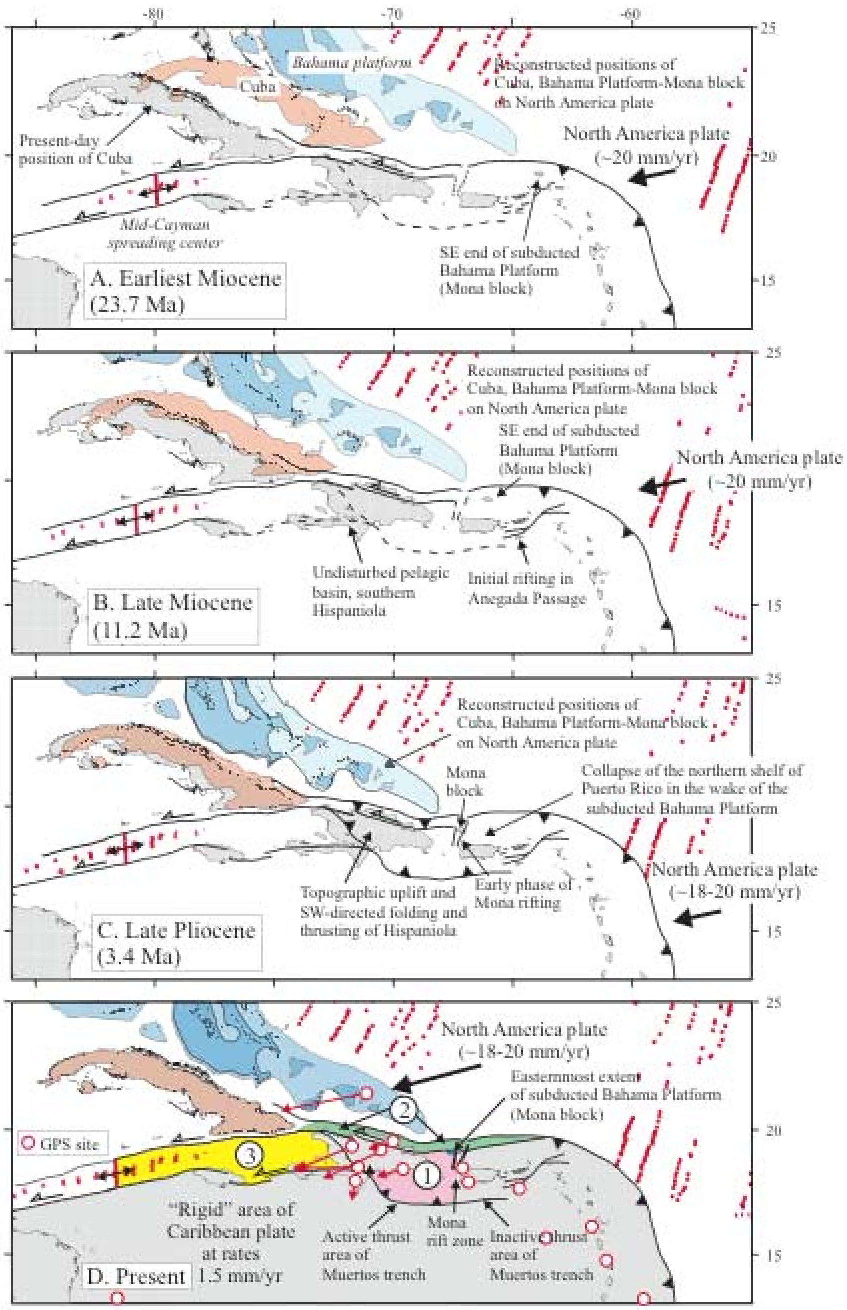
Holiday Inn overlook, Figure A



From Mann et al., 2002

Holiday Inn overlook near Ponce, Figure B. Plate reconstructions of the Hispaniola-Bahamas collision zone for four intervals done using the UTIG PLATES software program: **A**: Earliest Miocene (23.7 Ma); **B**. Late Miocene (11.2 Ma); **C**. Late Pliocene (3.4 Ma); and **D**. Present (GPS vectors from Mann et al., 2002). Numbers correspond to proposed terranes: **1** = Septentrional microplate; **2** = Hispaniola microplate; **3** = Gonave microplate. In our interpretation, the Mona block represents the southeasternmost extension of the Bahamas platform and is tracked on successive reconstructions. Note that the Mona block and its thickened Bahamian crust "misses" colliding with Puerto Rico. Areas of thick Bahamian crust west of the Mona block are actively colliding with the island of Hispaniola where elevations reach over 3 km, great thrust-type earthquakes have occurred in historical times, and folding and thrusting of late Neogene sedimentary rocks are widespread. Collision began in late Miocene time and continues to the present. We infer that the Muertos trench south of eastern Hispaniola is a "backthrust" response of the Bahamas collision as it pushes Hispaniola to the S and SW over the Caribbean plate (cf. GPS vectors plotted in a Caribbean framework). Because Puerto Rico was largely "missed" in a collision by the Bahamas platform, its Neogene rock record is deformed mainly by normal faults related to regional extension and CCW rotation.

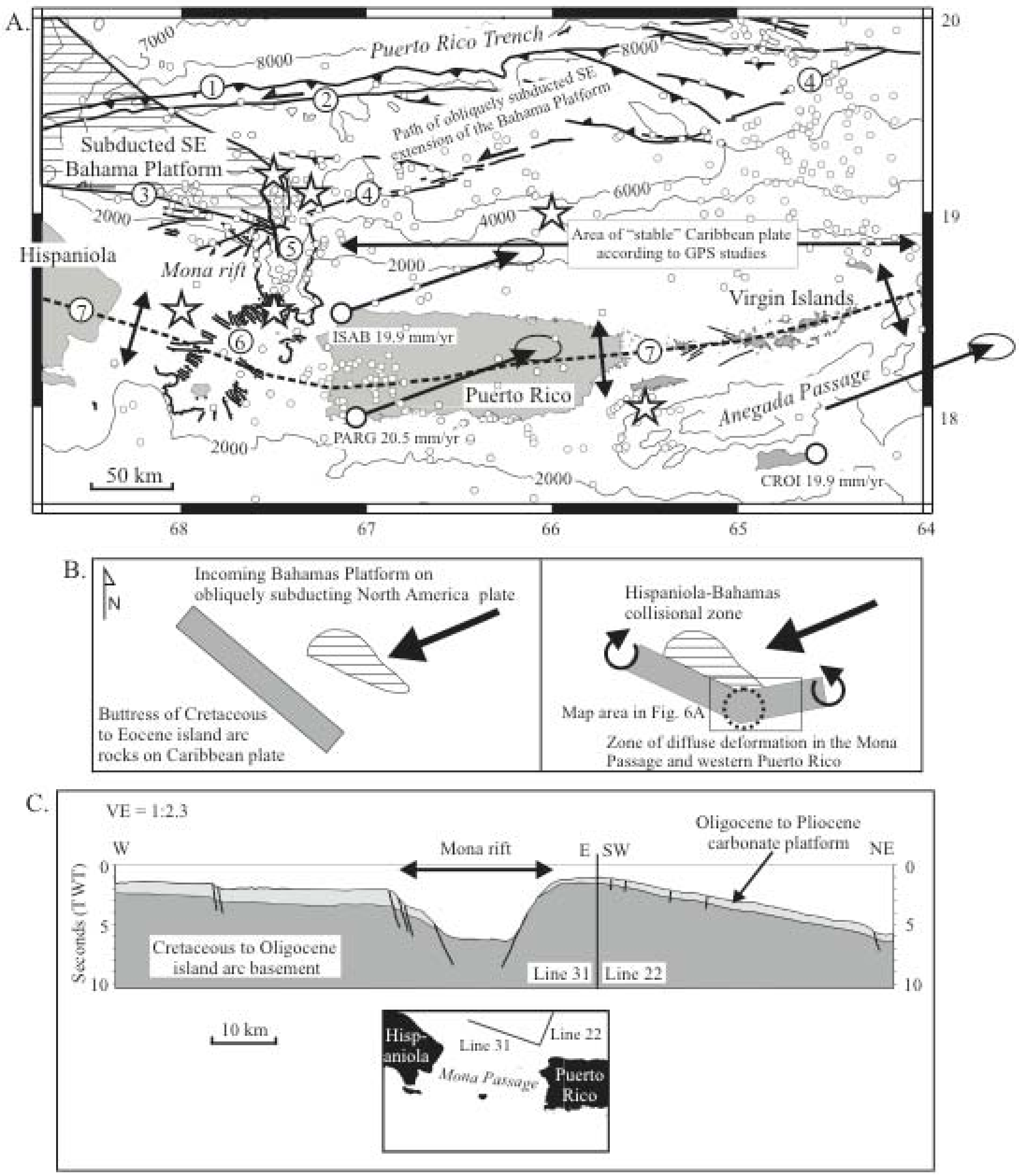
Holiday Inn overlook, Figure B



From Mann et al. (2002)

Holiday Inn overlook near Ponce, Figure C. A. Bathymetric and tectonic map of the Puerto Rico-Virgin Islands area showing faults in the Mona Passage separating the islands of Puerto Rico and Hispaniola from Grindlay et al. (1997, 2003) and van Gestel et al. (1998). Motions of GPS sites at St. Croix (CROI), Parguera (PARG) and Isabella (ISAB) are indistinguishable from the larger Caribbean plate (Jansma et al., 2000; 2003). **B.** Approximately east-west seismic line across the Mona rift showing its localized disruption of an otherwise undeformed Oligocene-Pliocene carbonate cap. The Mona rift is the boundary between colliding areas of the Bahama Platform to the west (Mona block, Silver Bank, Mouchoir Bank, etc.) and areas of subduction of Atlantic oceanic crust to the east. GPS vectors from Jansma et al. (2000), Calais et al. (2001), and Mann et al. (2002) show that Puerto Rico and the Virgin Islands moves in an ENE direction at a faster rate that than the collided or "pinned" area of Hispaniola to the west. The relative difference in rates between the collided and uncollided rates is manifested by diffuse early Pliocene-recent normal faulting in the Mona Passage, Mona rift, and its onland extension in NW Puerto Rico (Hippolyte et al., 2003).

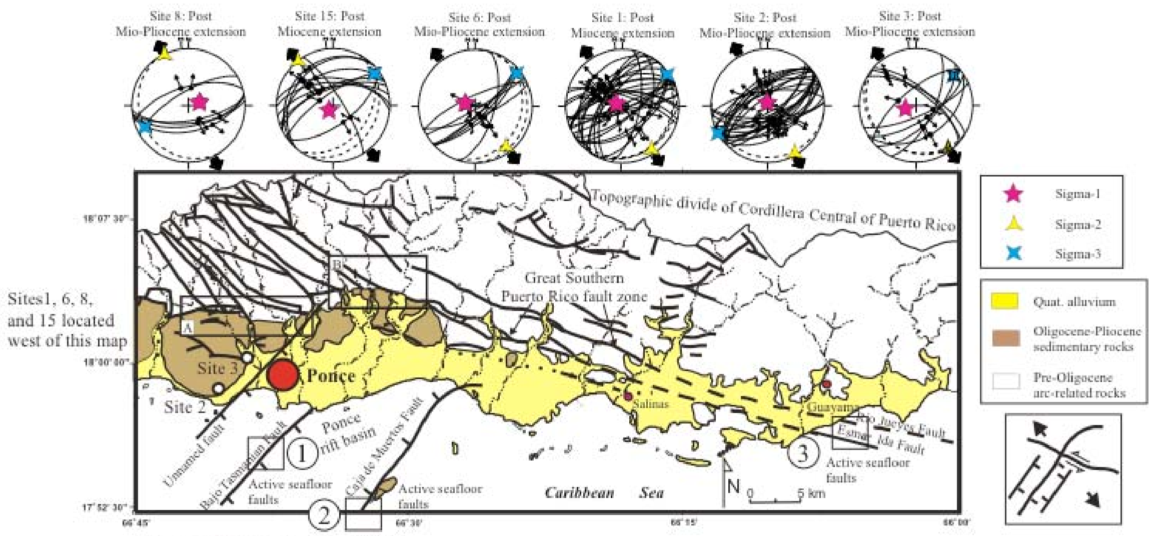
Holiday Inn Overlook Figure C



From Mann et al. (2002)

Holiday Inn overlook near Ponce, Figure D. Tectonic map of southern Puerto Rico and its offshore shelf. Onland faults in older, arc-related rocks and in younger Oligocene-Pliocene marine sedimentary rocks have been compiled from USGS quad maps. In a reconnaissance offshore survey, we identified zones of active, seafloor faulting in the boxed areas. Onland fault striation measurements in the youngest stratigraphic unit of Mio-Pliocene age in southern Puerto Rico (Ponce Formation) indicate southeastward extension probably related to the formation of the Anegada rift, a post-Oligocene, deep-water strait separating Puerto Rico and St. Croix (US Virgin Islands). Extensional effects are also expressed in the scalloped southern coastline, the presence of the Bajo Tasmanian and Caja de Muertos late Quaternary faults, and the thick sedimentary fill of the Ponce basin between these two faults. Based on these observations, we propose a late Quaternary fault pattern schematically shown in the inset diagram. Note reactivation of the older, WNW arc-related trends by SE extension.

Holiday Inn Overlook, Figure D



From Mann et al., 2003

Stop 3: Ponce Landfill (Paul Mann)

LUNCH – Guánica Dry Forest

Stop 4: Lajas Valley overlook (Carol Prentice, Hernan Santos, and Eugenio Asencio)

The Lajas Valley is a prominent topographic feature in southwestern Puerto Rico. It is a linear valley bounded by the Sierra Bermeja on the south and the San German range on the north (figure 4-1). The valley is about 29 km long and 1.5-9 km wide. The maximum elevation of the valley floor is less than 15 meters above sea level. The Lajas valley features several closed depressions including the former Laguna de Guánica, the former Cienega El Anegado, and Laguna Cartagena. The linear nature of the valley combined with internal drainage implies that the valley is fault controlled, making it a target of investigation for our Quaternary fault studies.

Our studies of 1936 aerial photography revealed a scarp traversing an alluvial fan in the southwest part of the valley (Prentice et al., 2000) (figure 4-2; figure 4-3). A test trench cut across this scarp showed it to be associated with a fault that breaks Holocene alluvium, radiocarbon dated at about 5000 ybp . Although this fault is accommodating only a very small fraction of the plate-boundary motion, it is significant because it is the first documented Holocene fault on the island.

Lajas Valley has been intensely impacted by a long history of agricultural activities. In the early part of the 20th century, groundwater from shallow wells was used to irrigate sugar cane. This produced two significant problems: because the groundwater is slightly saline, salt build-up began to damage the soil and decrease productivity. In addition, the irrigation produced artesian conditions in the eastern part of the valley, forcing saline groundwater to the surface which caused waterlogging of the soils in addition to problems with high salinity (Anderson, 1977).

In the 1950's, an ambitious project of irrigation and drainage was undertaken to increase agricultural productivity in the valley. Fresh water was brought in from a reservoir on the Rio Loco, and a major drainage canal that drained Laguna de Guánica and Cienaga El Anegado was constructed (figure 4-4). The influx of fresh water relieved the problems of salt build-up in the soils, but exacerbated the problems of waterlogging in the eastern part of the valley (Anderson, 1977).

Figure 4-1: Landsat image of SW Puerto Rico showing Lajas Valley. Image produced by Michael Rymer, USGS.

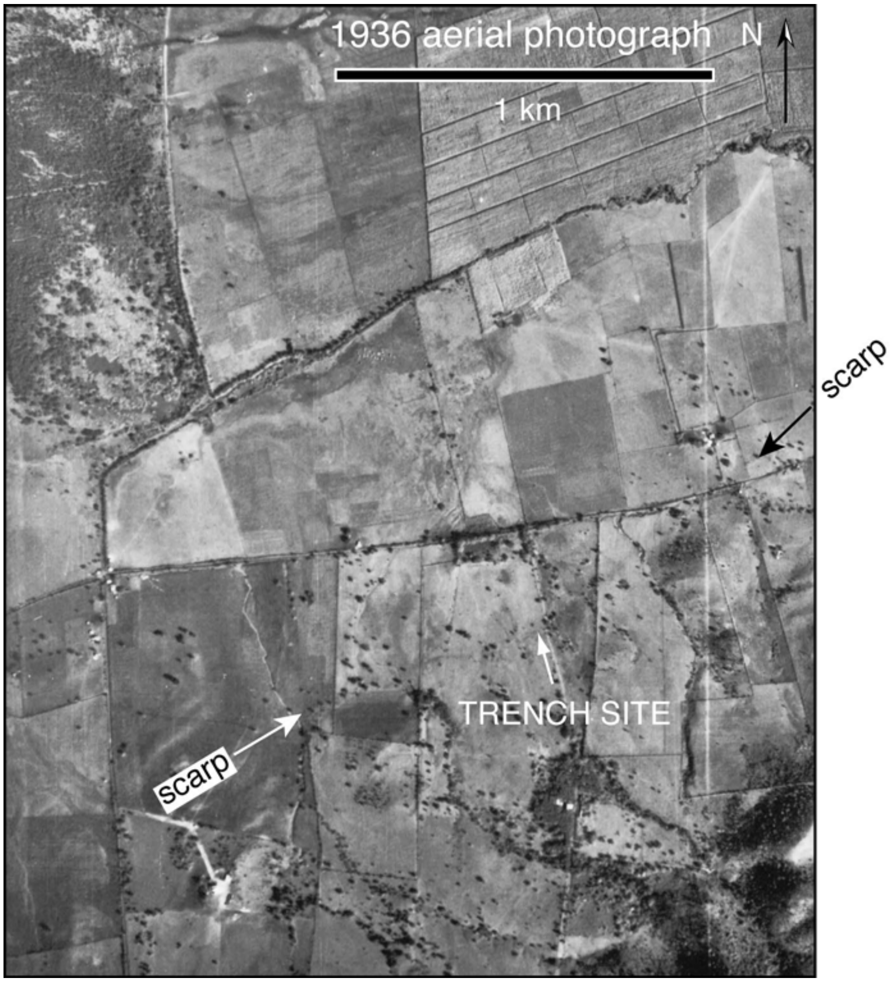


Figure 4-2: 1936 aerial photography of SW Lajas Valley showing scarp across alluvial fan surface.

Figure 4-3: Scarp across alluvial fan in SW Lajas Valley.

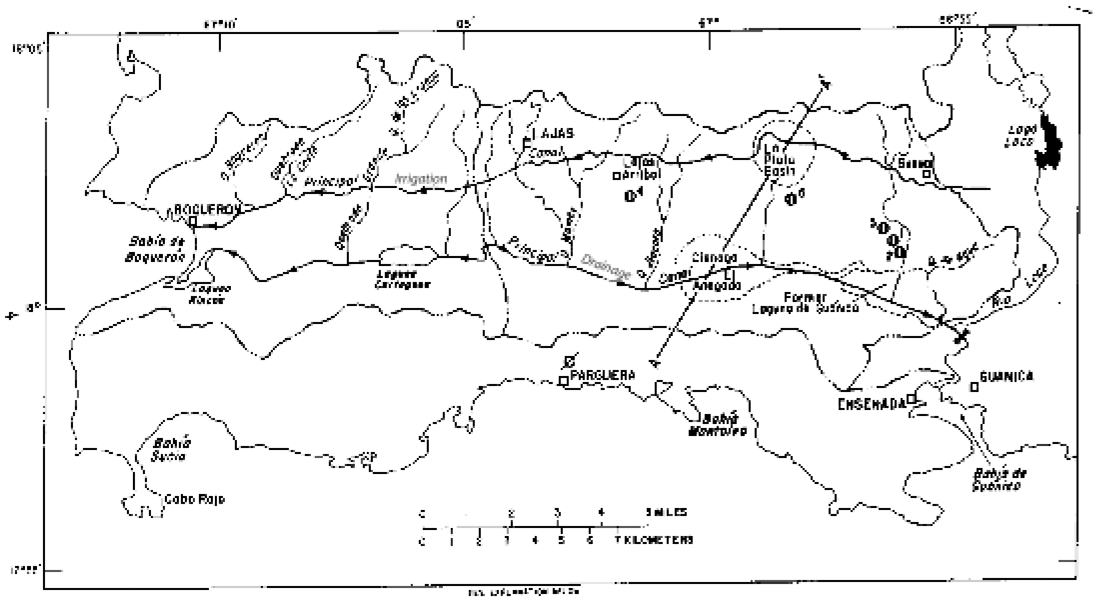


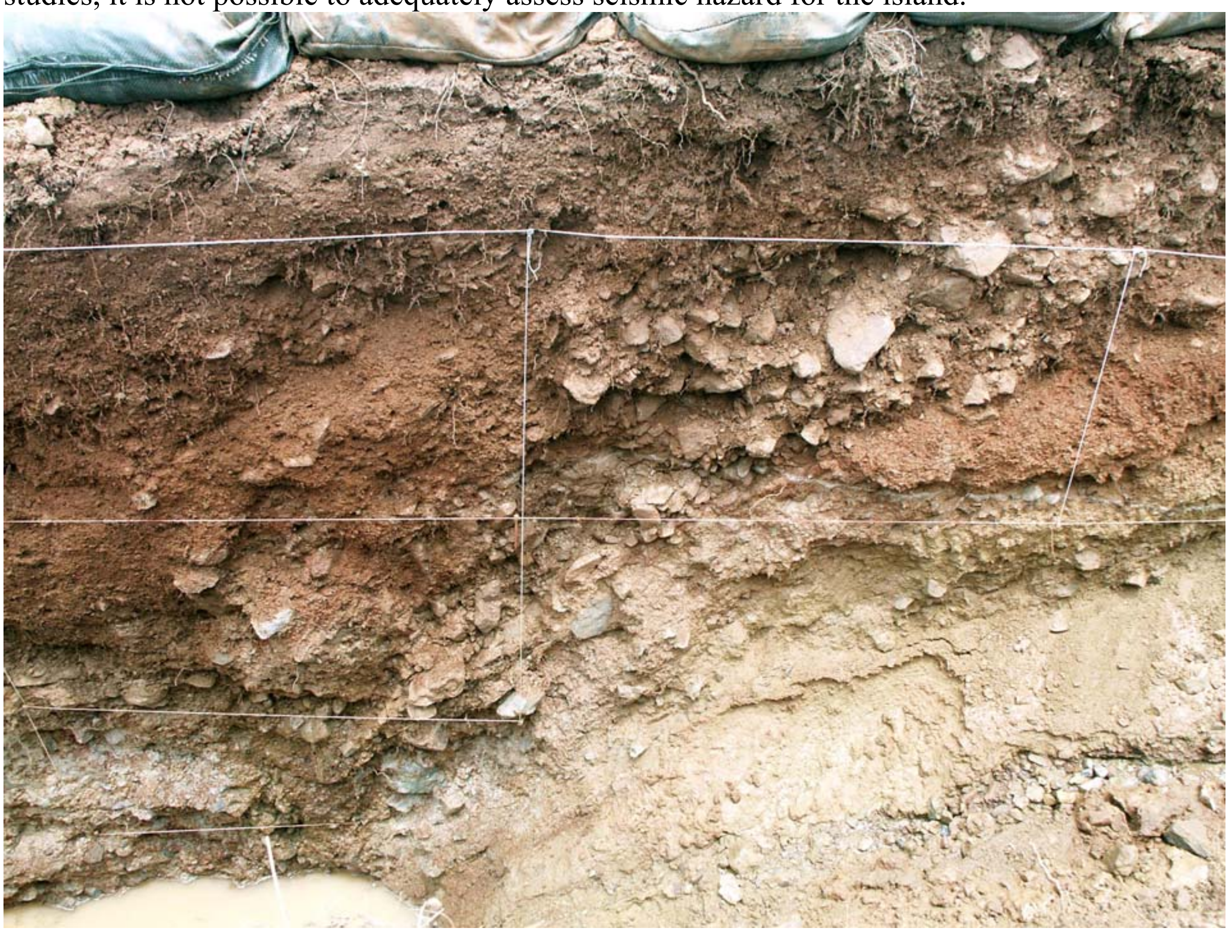
Figure 4-4 map of Lajas Valley showing drainage and irrigation canals (from Anderson, 1977)

Stop 5: South Lajas fault trench site (Carol Prentice)

In 2000, our test trench at this site clearly showed evidence for Holocene fault displacement. However, we were unable to conduct the necessary research to provide more information about this fault. In 2003, we have re-excavated our original trench in addition to excavating several additional trenches.

We have two cross-fault exposures open for the field trip. The best exposure is in Trench 5, which shows that the displacement is normal, north side down. Mismatches of units across the fault strongly suggest a component of strike-slip displacement. The presence of two colluvial wedges suggests at least two earthquakes. Unfortunately, we have found very little material suitable for radiocarbon dating, so will not be able to determine very precise ages for the occurrence of these earthquakes. However, preliminary correlation of with units dated in 2000 indicates that both earthquakes have occurred during the last approximately 7ka.

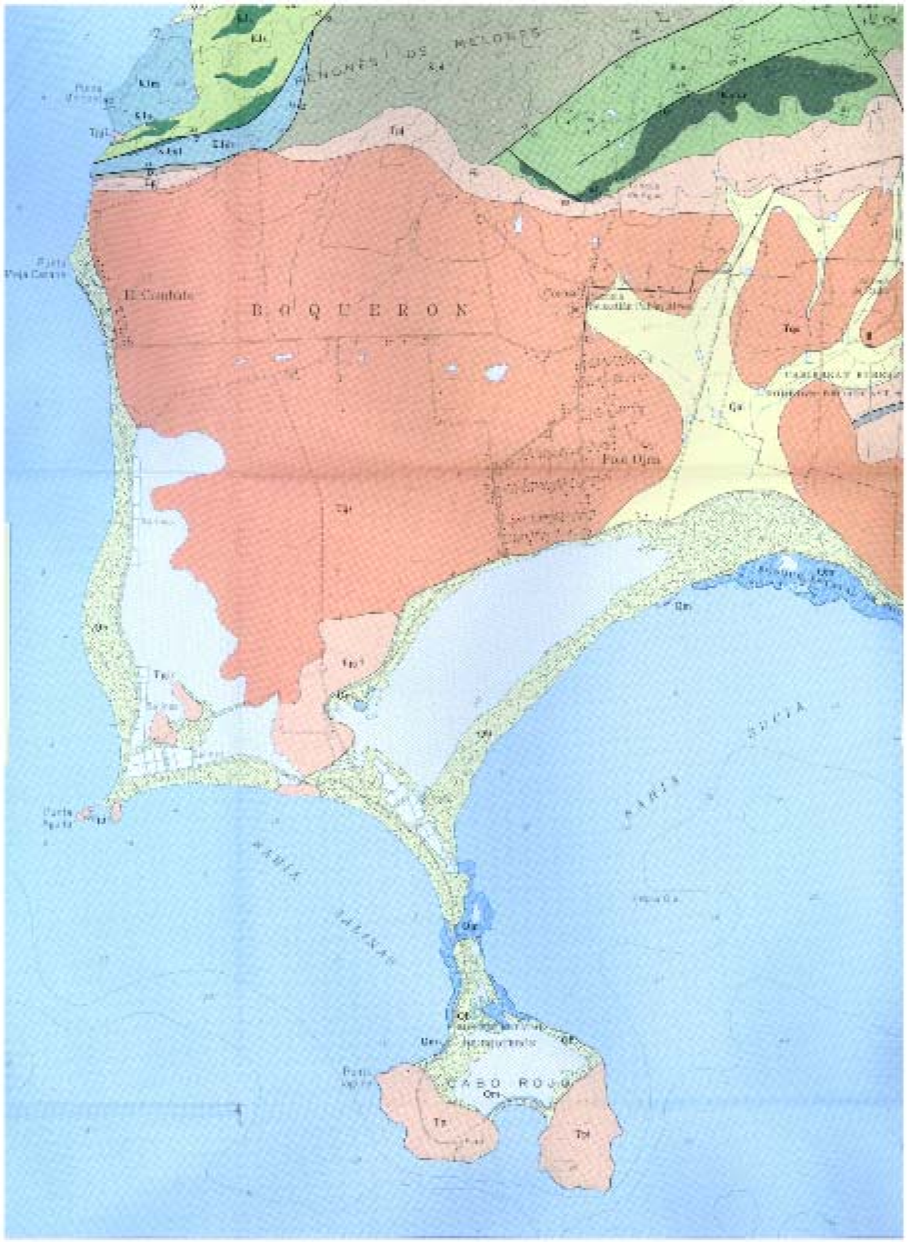
This is the first study to demonstrate Holocene surface rupture of an onshore fault in Puerto Rico. It is unlikely that this is the only onshore Holocene fault, and additional studies are needed to locate and characterize other potential onshore seismic sources. Without such studies, it is not possible to adequately assess seismic hazard for the island.



Stop 6: Cabo Rojo (Paul Mann and Nancy Grindlay)

Cabo Rojo, Figure A. Scan of USGS quad map by Volckmann (1984) including the region of Cabo Rojo (narrow peninsula near bottom of map). Unit Tpj is mapped as "undivided Ponce limestone and Juana Diaz Formation of Miocene and Oligocene age". Qb are beach deposits of Holocene age. Tqs are quartz sand deposits of Tertiary? age. All these younger units unconformably overlie folded and thrusted late Cretaceous to Eocene units. The overall dip of the upper Cenozoic section is about 20 degrees south and reflects broad, late Neogene arching of Puerto Rico. The axis of the regional arch is shown on Figure C of the Holiday Inn overlook. In 2000, we conducted a shallow seismic survey of the waters surrounding Cabo Rojo but recognized no prominent zones of late Quaternary faulting.

Cabo Rojo, Figure A



From Volckmann (1984)

Day 2, Sunday, May 4

Note: The field trip will split into two groups. Group 1 will visit the Rio Culebrinas stops in the morning and the Rincón stops in the afternoon. Group 2 will visit the Rincón stops in the morning and the Rio Culebrinas stops in the afternoon.

Rincón Stops (Eugenio Asencio, Paul Mann, Nancy Grindlay,)

Stop R-1: Overlook platform on Highway 115

1918 earthquake (Eugenio Asencio)

The most recent large earthquake in Puerto Rico's historical record occurred on October 11, 1918 offshore in the Mona Rift (see figure 1 for Rio Culebrinas stop). This earthquake caused a tsunami which impacted the west coast of the island. The largest runups were north of this location, between Punta Higuero and Punta Agujereada (figure R-1-1) and reached values of up to approximately 6 meters. 114 deaths were attributed to the tsunami. A repeat of this event today would cause much more damage and many more casualties due to the large amount of coastal development that has occurred since 1918.

The following descriptions are from Reid and Taber, 1919:

"The earthquake began suddenly without warning. No shocks had been felt in this part of the island for seven or eight months. At almost 10:15 am on October 11 there were two severe shocks separated by an interval of two to three minutes. The first shock was the most severe and is described as having a strong vertical movement; it was followed by horizontal oscillations, which caused most of the damage. Shocks of less intensity were felt at frequent intervals thereafter for several weeks, and in the beginning the ground appeared to tremble without cessation for considerable periods. The strong aftershocks on October 24 and November 12 differed from the first disturbance in that they seemed to consist chiefly of horizontal oscillations.

..........the majority of observers report that the principal horizontal vibrations were east and west, and this is supported by much confirmatory evidence. Many facts indicate that in the extreme west and southwestern part of the island the principal horizontal component was in a northwest-southeast direction and, perhaps, in some places nearly north and south. As evidence of vertical motion the following facts are cited.....At **Rincon** the bars of doors were raised permitting doors to open. At a house near **Mayagüez** wooden columns supporting a porch roof jumped up and down, and after the earthquake a shoe was found between the base of one column and the floor of the porch. .... the dominant horizontal motion appears to have been in an east-west direction.... At **Aguadilla** the front and west wall of the church was cracked horizontally at the height of the side walls and the upper portion nearly toppled over. The side walls were not affected. A large building facing east on the plaza has a flat brick roof which showed large cracks running parallel and close to the east and the west parapet walls. These walls were badly cracked above the roof line, and one was tilted towards the west while similar walls running east and west remained in tact. Another nearby building had north-south cracks near the walls but no east-west cracks.

At **Punta Jiguero**, on the other hand, the evidence is indicative of a dominant north and south movement. the lighthouse tower was badly cracked horizontally and the north side was offset toward the south abut 15mm; the parapet walls enclosing the roof were damaged by cracking and scaling on the north and south sides, while the east and west walls were uninjured. Interior walls one brick thick, running north and south, showed well developed diagonal shearing cracks intersecting at angles of 90°.

At **Central Corsica**, 4 kilometers south of Rincon, observers report visible undulations in the surface soil moving in a southeasterly direction, and the upper third of a brick smoke stack, 38 meters high fell in a direction N30°W. At **Central Eugenia** between Rincon and Añasco, numerous cracks running about northeast and southwest were formed through out the cane fields, which are in soft alluvial ground.

Mayaguez

Mayaguez, the largest town in the western part of the island, having a population of about 17,000 is between isoseismals VIII and IX. The intensity of the shock as measured by its effect on buildings, was nearly as great as at Aguadilla, although Mayagüez is further from the seat of the disturbance. the relatively high intensity at Mayagüez is due to the fact to the fact that much of the town is built on alluvial ground which is in places saturated by water. The theater is on about 5 meters above sea level and here the water stands within a meter of the surface, at times coming up through the floor of the basement......

The collapse of “La Habanera,” a large two story cigar factory in the lower part of the city resulted in the loss of several lives. The walls of this building were of concrete, 6 inches thick, with half-inch rods placed about 1 foot apart. The concrete was deficient in cement and composed of poor materials, so that it could be easily picked to pieces.

In Mayagüez brick and mamposteria buildings were more or less badly cracked, but comparatively few walls were overturned, although many heavy masonry cornices came down. A few concrete buildings of very poor material were seriously damaged, but most concrete and reinforced concrete buildings were uninjured, except where the plaster on thin divisional walls was cracked or thrown down, as in the Science Building at the School of Agriculture and in the parish house of the Redemptorist Fathers. Many of the telephone and electric light poles in Mayagüez are of reinforced concrete and some of them were destroyed by the earthquake.

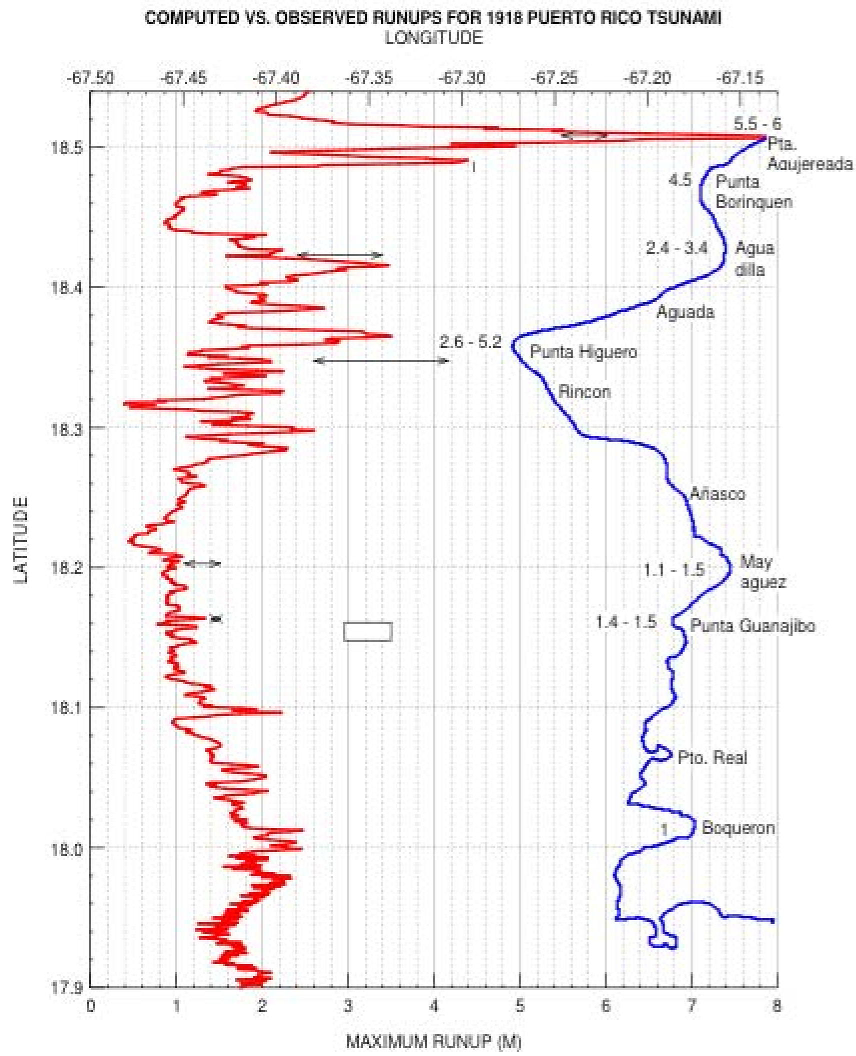
Añasco is built on flat alluvial land about 7 meters above sea level, the water level is close the surface, as water stands in wells at depths of from 1 to 3 meters. Here, the first shock, starting with a vertical vibration, is said to have been most severe. People report having seen undulations of the surface, and cracks were formed in the alluvial ground. All brick buildings were destroyed or so badly injured as to make it necessary to pull them down. The municipal building which was built in 1880 of brick with very poor mortar, was almost completely thrown down, while the walls that remained standing were badly cracked. .....Other buildings, one and two stories in height, built of good concrete and well reinforced with steel rods, were uninjured except for a few cracks of little importance. Wood frame buildings were not damaged except in a few instances where the timbers had rotted.

At Añasco the people observed undulations of the surface in the plaza and elsewhere, especially near the coast . Cracks were formed in the ground , and water come up through them, bringing black sand which was deposited on the surface . The water table is here very close to the surface.......

One effect of the squeezing of water from interstitial spaces in saturated alluvium, and perhaps from fractures in rocks was to increase the flow of water in streams and ditches. In cane fields at Central Eugenia many small cracks running about northeast and southwest, were formed and immediately after the earthquake the fields were covered by an outflow of water although the ditches crossing these fields were dry before the disturbance. The water continued to flow in these ditches for several weeks.

At Central **Corsica**, 4 kilometers southeast of Rincon, Mr. Jaime Sifre, the general manager, while standing on the office steps looking in a southwesterly direction, noticed waves moving across the surface to the southeast. He states that the waves moved faster than a railroad train, and estimates the wave lengths at about 1 meter and the amplitude at about 15 centimeters. The high brick chimney of the central was seen to fall during the passage of he sea waves. The local manager, Mr. Antonio Fraticelli states that he saw similar waves at the time of the earthquake on November 12. Cracks were formed in the lowlands in this vicinity and from them water issued bringing up sand.

Rincon is several kilometers nearer the origin of the disturbance than Añasco; yet no walls were thrown down, and the injury to masonry was so much less that it caused general comment. The relative immunity of Rincon is to be explained partly by its foundations in rock and thin residual soil and partly by the character of the buildings, most of which are of concrete or of wood and are only one story in height."



Reference: Numerical simulation of the 1918 Puerto Rico tsunami. A. Mercado and W. McCann, 1998. Journal of Natural Hazards, Vol. 18, 57-76.

Figure R-1-1: Figure showing 1918 tsunami runups along the west coast of Puerto Rico (blue is coastline) as reported in Reid and Taber (1919). Red indicates numerical simulation of tsunami runup. From Mercado and McCann, 1998.

Hwy 115 Overlook, Figure A. Shaded relief map of western Puerto Rico and offshore region. Ship tracks for May 2000 marine geophysical survey shown in thin solid lines. Location of the Cerro Goden fault zone determine from McIntyre (1971) and Mann et al, (2003) and location of South Lajas fault from Glover, (1970), Meltzer et al., (1998; 2000), and Prentice et al., (2000, 2003). Dashed line with question makes is the hypothesized eastward extension of the Cordillera fault. Serpentinite bodies mapped onland are shown as areas with striped fill pattern. Inferred axis of E-W trending arch formed during Late Miocene -early Pliocene is shown as dashed thick black line.

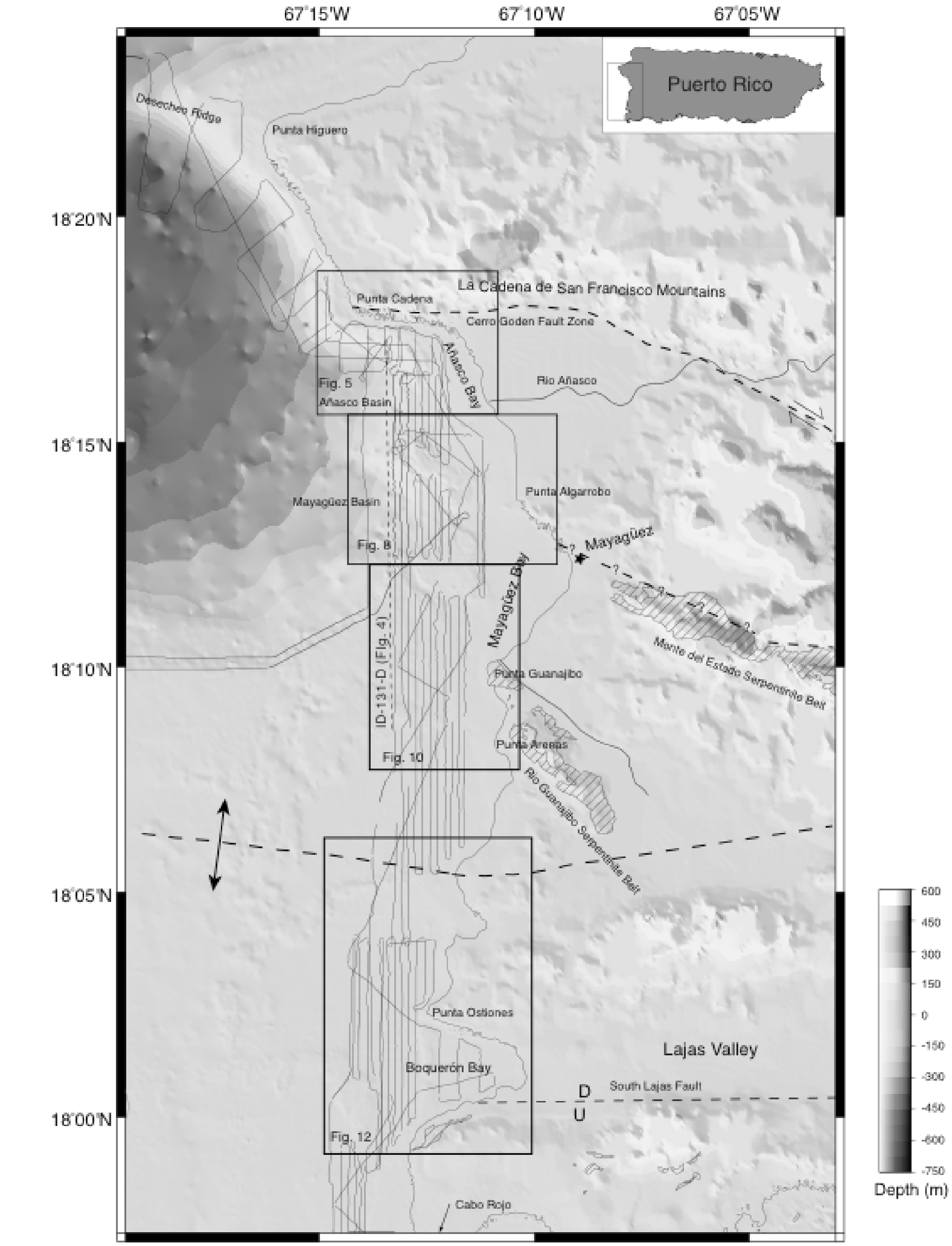
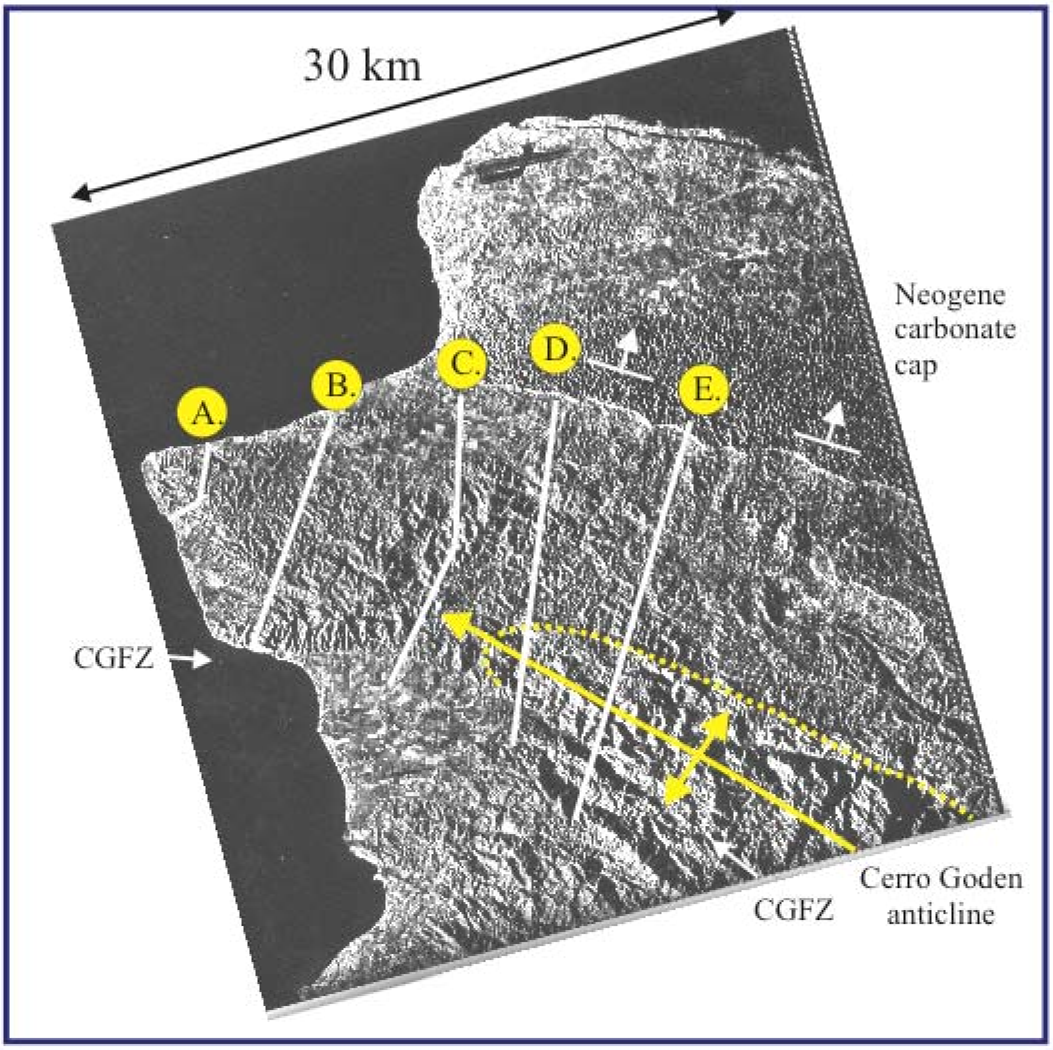


Fig. 3, Grindlay et al., 2003

Hwy 115 Overlook, Figure B. Radar image showing linear and continuous trace of the Cerro Goden fault zone (CGFZ). In the Anasco Valley marine profiling and field studies suggests that the late Quaternary CGFZ is situated about 1 km south of the prominent mountain front lineament formed in older bedrock. The Anasco valley lineament south of the mountain front projects to the mapped bedrock trace of the Cerro Goden fault in the elevated area to the southeast of the Anasco Valley. The Cerro Goden fault and thrust structures seen on sections A-E formed during an Eocene orogeny. The north dip of the Neogene carbonate cap is related to the major late Neogene arching event affecting Puerto Rico. Carbonate rocks in the cap are largely devoid of convergent structures or striated faults and instead reflect a history of either EW extension (in NW Puerto Rico) or SE extension (in southern Puerto Rico).

Highway 115, Figure B



From Mann et al. (2003)

Hwy 115 Overlook, Figure C. a and b) Single-channel seismic (SCS) profiles across the Cerro Goden fault zone (depth scale assumes V=1500 m/s). Approximately 20-25 m of sediment fills depressions between exposed reef heads. Acoustic basement in these profiles is interpreted as the boundary between alluvium (Holocene?) and well indurated sediments and sedimentary rock. Offsets (dashed lines) of seafloor, and offsets and tilting of sediment indicates recent fault displacement. c) Multi-channel seismic (MCS) line XI-108D shows offset (dashed line) of the Oligocene-Pliocene carbonate platform and overlying section which is assumed to be Pliocene and younger in age. d) Map view showing MCS and SCS tracklines (solid lines) and the fault segments within the Cerro Goden fault zone (CGFZ).

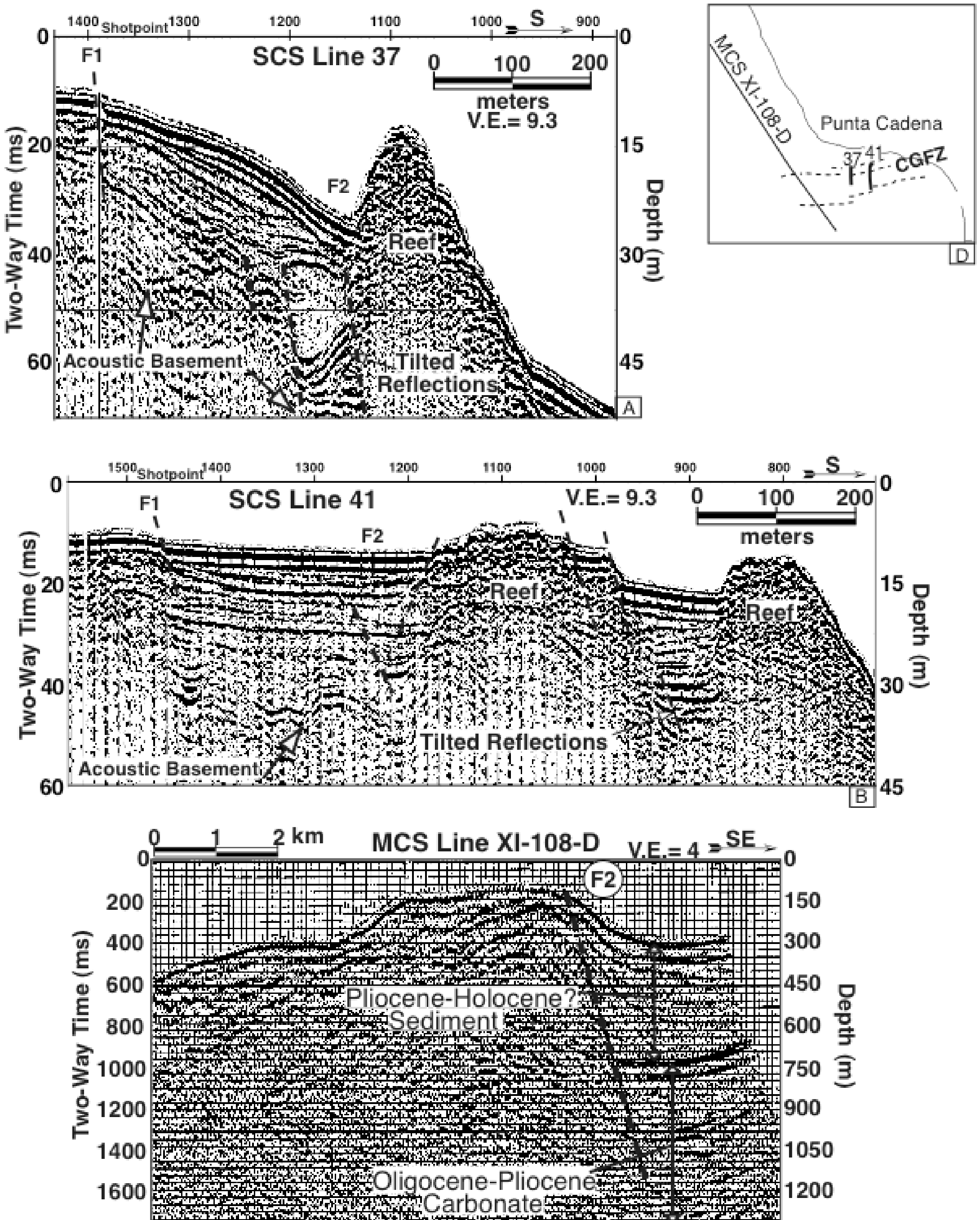


Fig. 7, Grindlay et al., 2003

Hwy 115 Overlook, Figure D. Residual magnetic intensity map for western Puerto Rico (after Bracey, 1968). Contour interval = 50 gammas. Filled pattern locates serpentinite and offshore faults identified by Grindlay et al. high-resolution marine geophysical study (2003) and faults with proposed Quaternary activity onland shown by dashed lines. Dashed line with question marks locates the projection of the Cordillera fault along the serpentinite belt to the western coast. Note the close correspondence of the Punta Algarrobo/Mayaguez fault zone (PA/MFZ), the Monte del Estado peridotite/serpentinite belt onland and shaded zone of low magnetic intensity. The Punta Guanajibo/Punta Arenas fault zone (PG/PAFZ) mapped offshore project to the Rio Guanajibo Serpentinite Belt mapped onland. CSA = Cordillera de Sabana Alta.

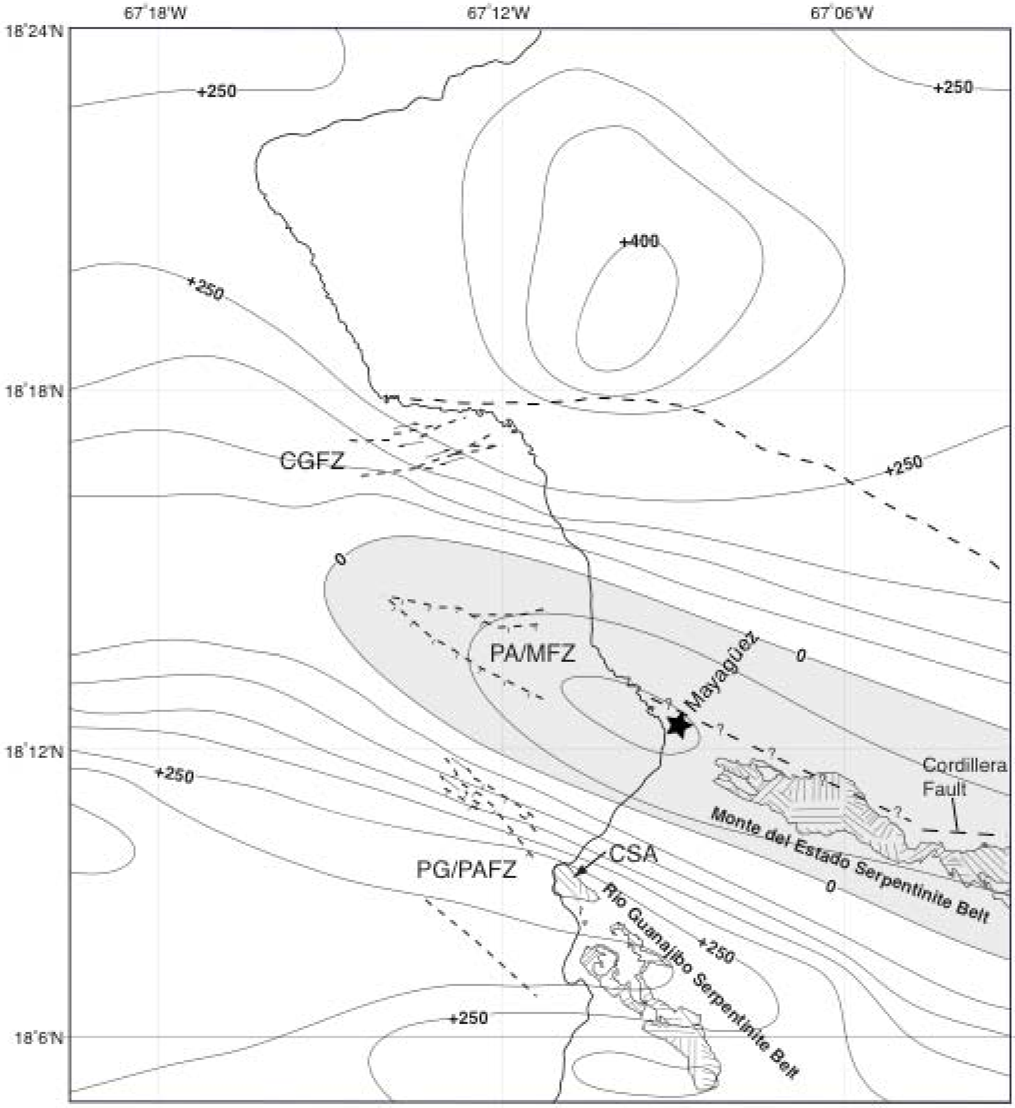
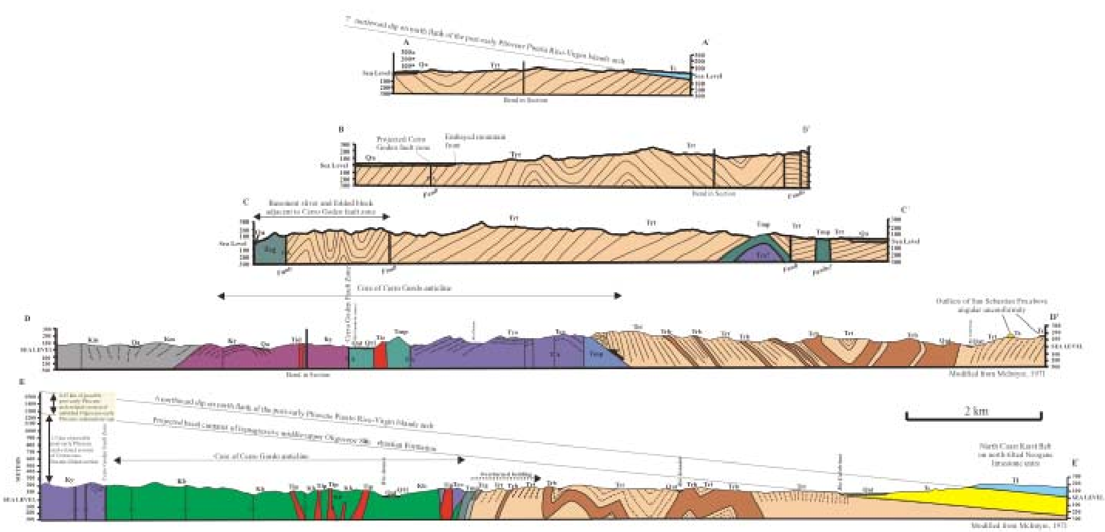


Fig. 14, Grindlay et al., 2003

Hwy 115 Overlook, Figure F. Serial cross sections drawn across the Cerro Goden fault zone. Sections A-C are from Mann et al. (2003) and sections D-E are from the USGS quad map by McIntyre (1971). Shortening is related to a major Eocene folding event with northward fold vergence. Note the major unconformity overlain by north-dipping rocks of the Oligocene-Miocene carbonate cap. The late Neogene Cerro Goden fault overprints this older Eocene deformation event. We infer that the Cerro Goden fault is behaving as a right-lateral strike-slip fault in late Neogene time.

Hwy. 115 Overlook, Figure F



Stop R-2: Rincón lighthouse (Carol Prentice and James Joyce)

At this location corals are exposed on a terrace surface. These corals were dated by Bruce Taggart and reported in an unpublished Ph.D. dissertation in 1993. The dates indicate that this terrace represents the 5e sea-level high stand. Dan Muhs (USGS) and Carol Prentice, in collaboration with Bruce Taggart and Jim Joyce, have recollected at several of Taggart's sites in order to more precisely date this surface using modern mass spectrometry. This terrace is at a height of about 12 meters. The 5e highstand was about 6 meters above modern sea level, and this implies a very low uplift rate at this location. At other locations around the island, a terrace at about 6m is probably the same terrace. This difference in elevation suggests Quaternary fault displacement.

At this location the 1918 tsunami runup was greater than 5.2m. Below is the description from Reid and Taber:

1918 "The Point Jiguero Lighthouse is also close to the seat of the disturbance. The building is of limestone trimmed in brick, the foundation resting on solid rock. In general plan it is similar lighthouse at Punta Borinquen but the mortar seems to be of better quality, the main walls showed a few cracks, mostly in the mortar, but in places breaking directly across the bricks; the thin divisional walls suffered more damage than the main walls. The tower was cracked horizontally and so was a small chimney; the parapet surrounding the roof was slightly injured on the north and south sides.

At the Point Jiguero lighthouse the keeper, shortly after the earthquake, saw the ocean retire from the shore; and, up on returning almost 2 minutes later, it uprooted coconut palms a short distance north of the lighthouse and crossed the railroad track, leaving fish between the rails, Which are here 5.2 meters above sea level. At the time of our visit the vegetation by the track still showed marks of the rush of the water. For a short distance the coast to the southeast was somewhat protected by the point and the wave was much smaller. About a kilometer from the lighthouse it was 2.7 meters high, and a kilometer further it was only 2.6 meters in height."

Stop R-3: Pool's Beach (James Joyce, Carol Prentice and Paul Mann)

The view from the beach looks out to the Mona Canyon (epicenter of the 1918 earthquake) (see figure A below) and to Aguadilla (devastated by this earthquake). The rock outcrop at the end of the beach is composed of approximately 120,000 year old lithic calcarenites overlying fine grained foraminiferal packstones of Miocene age. Between the east and west ends of the outcrop we can see a younger terrace deposit composed of large blocks and pieces of the older deposit. The top of this deposit is marked by wave cut notch at about 3 meters above sea level and along the older Miocene-Quaternary unconformity. Bruce Taggart (PhD study at UPRM, 1993) recovered corals from this deposit that were dated as about 125 thousand years old (like Punta Higüero) and 1,500 to 2,000 years old. Taggart interpreted the older coral to be reworked fossils from the higher deposits. The younger corals indicate the deposit is much younger and that relative sea level was some 3 meters higher than present. Taggart found and dated similar deposits at Punta Borinquen north of Aguadilla. The significance of this deposit is major but the problem remains unresolved. Most Caribbean sea level workers believe regional sea level has not been higher than present for the past 10 ,000 years. If this is true, then some 3 meters of uplift in this area must have occurred over the last 1,500 years at a rate of about 1 meter per 500 years. This is 40 times faster than the uplift of 5 meters per 100,000 years suggested by the elevation of the 125,00 year old deposit. Was there a late Holocene eustatic sea level high stand, or could this be a local (Rincon-Aguadilla-Desecho Island) co-seismic event caused by a great earthquake in the past?

Dan Muhs (USGS) and Carol Prentice resampled the corals here for U-Th dating using mass spectrometry. The new techniques will give better precision ages and will largely eliminate problems of contamination by recrystallization. This is another example of a Quaternary feature in Puerto Rico that is poorly understood. Understanding the genesis and age of this young terrace is essential to providing a better understanding of seismic hazard.

From this beach, we look out to Aguadilla and Punta Borinquen, sites that were impacted by high tsunami runups in 1918. From Reid and Taber (1919):

"Aguadilla, with a population of over 6,000, is the largest town lying within the isoseismal IX. The majority of the buildings destroyed or badly damaged by the earthquake were built on the flat land in the western part of the city bordering the water front; buildings east of the plaza are mostly of wood and their foundations rest on rock or residual soil. Brick and mamposteria buildings were as a rule, badly cracked, and some walls were partly thrown down. .... The concrete and especially steel reinforced-concrete buildings in Aguadilla were practically uninjured, although in a few instances small cracks such as those due to settling, were formed.

At Aguadilla the height of the wave seems to have varied somewhat in different parts of the city but at no place were the measurements less than 2.4 meters above sea level and near the head of the bay the crest of the wave must have been at least 3.4 meters in height. In this town, 32 people are said to have been drowned and about 300 little huts, built along the beach were destroyed. Estimates of the time interval between the earthquake shock and the arrival of the sea wave, made by different observers, range from 4 to 7 minutes.

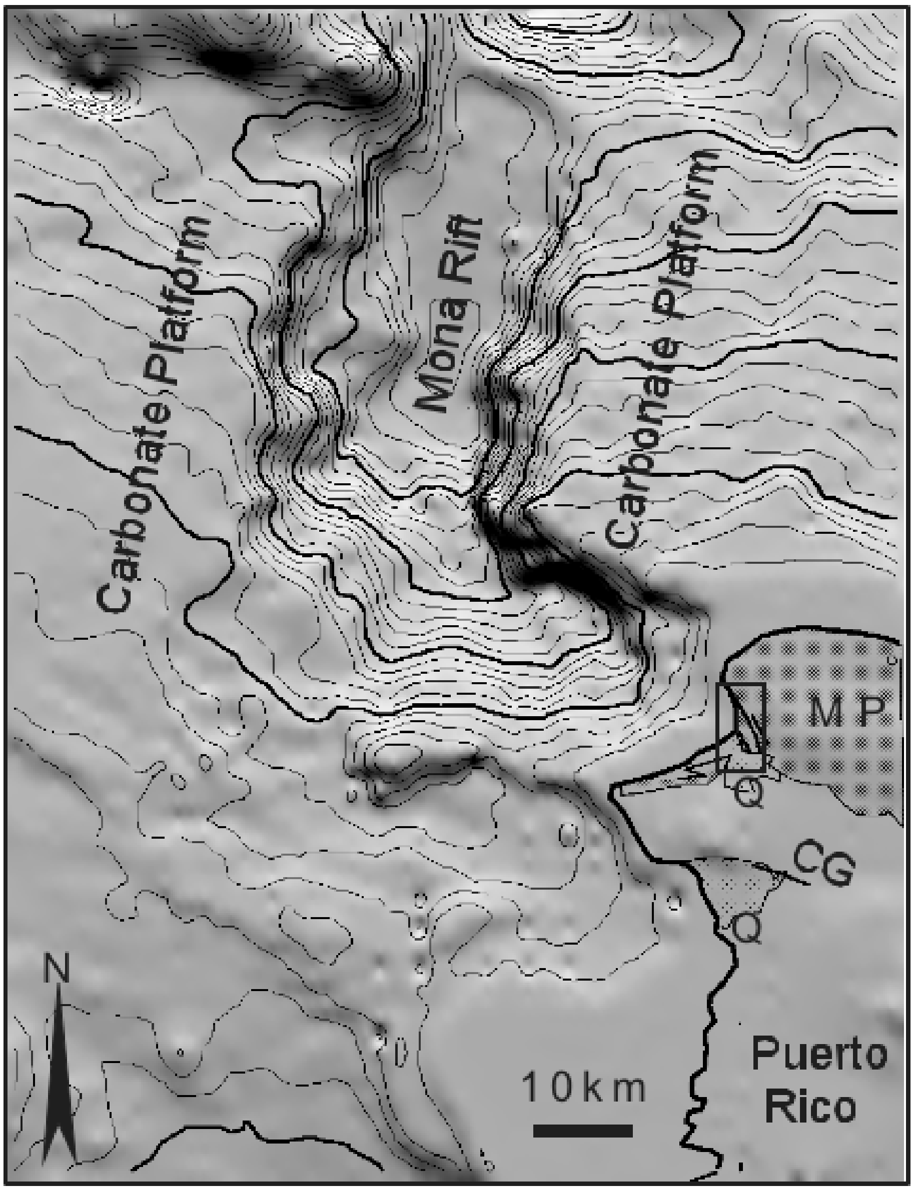
At Point Borinquen Lighthouse the keeper, who was up in the tower when the earthquake began, immediately started down the stairs and when he went down he noticed that the water along the shore had already begun to recede. It returned quickly and the measurements to points indicated by him shows that the height reached by the water, not counting the wash of the wave, was about 4.5 meters. Just southwest of the lighthouse, where the land is lower the water was reported to have washed 100 meters inland into a grove of coconut palms. The lighthouse keeper had the impression that the wave came form the northwest.

At Point Agujereada the limestone cliffs are 100 to 120 meters in height, and at their base there is a narrow strip of beach which in wider places was planted with coconut palms and used for pasturage. Several hundred palms were uprooted by the wave and the beach was turned into a sandy waste. In this vicinity a few small houses were destroyed and eight people are reported to have drowned. Several people visiting the district soon after the occurrence estimate height of the wave as 5.5 to 6 meters, and the evidence remaining at the time of our visit supported these estimates"

Paul Mann:

Pool's Beach, Figure A. Bathymetry of the L-shaped Mona rift off the northwestern corner of Puerto Rico from Hippolyte et al. (2003) using bathymetric data from Grindlay et al. (2003). The boxed areas represent an area of onland, post-Miocene faults whose striations reflect EW extension consistent with opening of the Mona rift. These faults and the Cerro Goden fault to the south appear to act as the southern terminus of the Mona rift and transfer that component of North America-Caribbean plate boundary motion across the land area of Puerto Rico. Right-lateral motion along the Cerro Goden fault is consistent with continued opening of the Mona rift as known from GPS studies (Jansma et al., 2000; 2003).

Pool's Beach, Figure A



Hippolyte et al, revised

Rio Culebrinas (Martitia Tuttle)

BOAT TRIP ALONG RIO CULEBRINAS TO VIEW EARTHQUAKE-INDUCED LIQUEFACTION FEATURES

LOCATION

This trip was originally planned for the Río Grande de Añasco, where there are many good examples of sand dikes and sand blow. But due to especially low river levels this spring, the trip has been moved to the more navigable lower 4 km of Río Culebrinas (see Figures 1, 2, 3, and 4). The Río Culebrinas drains northwestern Puerto Rico near the towns of Aquadilla and Aguada. To date, no Holocene faults have been recognized in the Río Culebrinas Valley. During this trip along the lovely Culebrinas, we will visit two liquefaction sites where you will have the opportunity to disembark and examine the features, if you so desire. In addition, we will see other liquefaction features exposed in the river cutbanks.

WORDS OF CAUTION! If you are inclined to get out of the boat to examine the liquefaction features, please be warned that river cutbanks can be unstable. It would be best not to load up the banks with more than a few people at a time. If you have gotten your hands dirty or wet at the outcrops, we strongly suggest that you cleanse your hands at the end of the trip.

SIGNIFICANCE

By the time of this field tip, you will be well aware that several large to very large earthquakes have struck Puerto Rico over the past 400 years. These include a moment magnitude, **M** ~7.5 event in 1943 located northwest of Puerto Rico, a **M** ~7.3 event in 1918 centered in the Mona Passage, a **M** ~7.3 event in 1867 in the Anegada Passage, a **M** ~7.3 event in 1787 possibly related to the Puerto Rico Trench, and a **M** ~6 event in 1670 in western Puerto Rico (Figure 1). The 1918 earthquake reportedly induced liquefaction in the Añasco River Valley and generated a tsunami that struck the western coast of the island, killing at least 114 persons and causing $4 million in damage (Reid and Taber, 1919). In fact, the tsunami impacted the villages of Aguada, Aguadilla and Espinar near the mouth of Río Culebrinas. Moya and McCann (1991) suggested that the 1918 earthquake may also induced liquefaction near Aguadilla. Because the western coast is much more heavily populated now (486,800 in the Mayagüez-Aquadilla area) than it was earlier in the century, a repeat of a 1918-type event could cause considerably more deaths and damage.

The liquefaction features that you will see along Río Culebrinas were found during a paleoliquefaction study currently underway in coastal areas of Puerto Rico. The study is sponsored by the U.S. Geological Survey's Earthquake Hazard Reduction Program. Participants in the study include Kathleen Dyer-Williams, Juan Carlos Moya, Carol Prentice, Holly Schroeder, Buddy Schweig, Dorian Belan, and Tish Tuttle. The objectives of the study are to help constrain the locations and magnitudes of historic earthquakes and to estimate the timing, source areas, and magnitudes of prehistoric earthquakes that may have struck the island during the Holocene. Towards this end, we are conducting (1) river reconnaissance for, and study of, liquefaction features along the western, northern, and eastern coasts of Puerto Rico, (2) radiocarbon dating of organic samples found in association with liquefaction features, and (3) liquefaction potential analysis of fluvial deposits.

RESULTS OF PALEOLIQUEFACTION STUDY

During reconnaissance along the western coast of Puerto Rico, we found twenty-seven liquefaction features at ten sites along Río Culebrinas, thirty features at eighteen sites along Río Grande de Añasco, and two features at two sites along Río Guanajibo (Figures 2, 3, and 4). The liquefaction features include small sand blows and small to moderate-sized sand dikes. On the basis of radiocarbon dating, many of the liquefaction features probably formed during the 1943, 1918, or 1670 earthquakes (Table 1). Those liquefaction features for which we have a maximum age constraint of A.D. 1640 could have formed during either of the 1670, 1918, or 1943 events. Those features with maximum age constraint of 1670 or later probably formed during the 1918 or 1943 earthquakes. At least one liquefaction feature on the Río Culebrinas appears to have formed between A.D. 1300 and 1508. Although additional earthquakes cannot be ruled out, other liquefaction features documented along the three rivers probably formed during one of these four earthquakes. Along the northern coast of the island, we found liquefaction features at two sites along Río Grande de Manati about 50 km west of San Juan (Figure 2). Weathering characteristics indicate that a sand dike at one of the sites is probably historic in age, whereas a sand blow and related dike at the other site are probably prehistoric in age. The latter liquefaction features appear to be older than any of the features found on the west coast. If we can gain permission from the property owner and if time allows, we will visit this site of prehistoric liquefaction on the way back to San Juan Sunday afternoon.

We evaluated several scenario earthquakes using liquefaction potential analysis of sandy sediments along the four rivers searched. For the analysis, we compiled borehole data, including blow counts, previously collected by the Puerto Rico Department of Transportation and Public Works at bridge crossings of the rivers and applied the revised simplified procedure, also referred to as the stress method, of Seed and Idriss (1982) and Youd and Idriss (1997). For each borehole site, we determined whether or not representative sandy layers below the water table would be likely to liquefy during the scenario earthquakes. Estimates of peak ground acceleration for the scenario earthquakes are based on ground-motion relations developed for California (Boore et al., 1997). Results appear to be consistent with the observation that the 1918 earthquake induced liquefaction in the Añasco River Valley and gives us confidence that application of the revised simplified procedure is appropriate in this setting (Table 2). The analysis also suggests that the 1670 earthquake, which appears to have produced liquefaction features along both Río Grande de Añasco and Río Culebrinas, may have been of **M** ~7 and located in or near the Añasco River Valley. The source and magnitude of the A.D. 1300-1508 event is unknown, but the analysis indicates that it was probably of **M** $\geq$ 6.5 to induce liquefaction along Río Culebrinas. According to the analysis, fluvial sediments along Río Manati could liquefy during an earthquake similar to the **M** ~7.5 1943 earthquake located near the Southern Puerto Rico Slope fault zone.

On the basis of these early results from river reconnaissance and liquefaction potential analysis, preliminary liquefaction fields for historic and prehistoric earthquakes can be delineated as shown in Figure 5. Although other interpretations are possible, this model seems the most plausible given the current data. As additional reconnaissance is performed, a more complete picture of age and size distribution of liquefaction features will emerge. This information combined with further evaluation of scenario earthquakes will lead to a revised and better constrained model of earthquakes that caused strong ground shaking in Puerto Rico during the Holocene. For those who want to learn more about this study, we refer you our paper to be published in the Geological Society of America Special Paper entitled, " Active tectonics and seismic hazards of Puerto Rico, the Virgin Islands, and offshore areas."

LIQUEFACTION FEATURES ALONG THE LOWER RIO CULEBRINAS

We will first visit site RC1, where we discovered a buried sand blow and related feeder dike during river reconnaissance several years ago (Figure 3). At that time, several dikes could be seen extending into the base of a paleosol characterized by soil structure and organic accumulation. The largest dike, up to 23 cm wide, could be traced through the paleosol and broadened upward as a vent structure into the base of an overlying sand lens (Fig. 6). The sand lens was up to 20 cm thick and of limited lateral extent, pinching out away from the sand dike. The sand lens is interpreted as a sand blow that was deposited on the paleosol that was at the ground surface at the time of the earthquake. Radiocarbon dating of charcoal located 10 cm below the base of the sand blow and within the paleosol yielded a calibrated date of A.D. 1300-1370, 1380-1430. Given that it was collected from the paleosol below the sand blow, the charcoal sample is thought to be of local origin and to provide a close maximum age for the liquefaction features. If so, the features formed after A.D. 1300, and possibly after A.D. 1430. Since there is no large earthquake recorded by the Spanish following colonization in A.D. 1508 and prior to the earthquake in A.D. 1670, the event that induced liquefaction at this site is estimated to have occurred between A.D. 1300 and A.D. 1508.

Site RC1 occurs along an actively eroding bend in the river, and as a consequence, the liquefaction features have also been eroded since first discovered. Today, we can still see the feeder dike and part of the sand blow but the upper part of the sand dike connecting the two is gone. Liquefaction features that we will see down river from RC1 were found last month during preparation for this field trip and were not exposed several years ago. Changes in exposure along Río Culebrinas illustrate that different parts of the earthquake record are visible at different times and that the record is being washed down the river.

Down river from and within 300 m of RC1, we will see at least seven sand dikes. They range in width from 2.5 to 6 cm in width and pinch out more than 2 m below the present surface. In the currently exposed section, none of the dikes appears to have extended to the ground surface at the time of formation. Dating of these features would provide only maximum age constraint; whereas dating of the paleosol on which the sand vented at RC1 provides a close maximum age estimate.

We will also stop at site RC13, about 1 km downstream from RC1, where we recently found rather obscure liquefaction features. Here, an 8-cm-wide sand dike widens upward and into a

12-cm-thick sand lens occurring within a paleosol. The sand lens is interpreted as a sand blow. The sand dike becomes quite narrow downward and then connects with a sandy layer near the base of the cutbank. This sandy layer may be the source bed of the sand dike. Radiocarbon dating of charcoal samples collected last month above and below the sand blow should help to estimate its age. Another sand lens occurs higher in the section, above the sand dike and related sand blow. Given its similarity to the sand blow and its position above the sand dike, this sand lens may be another sand blow. This interpretation remains equivocal, however, since there is no apparent connection of the sand lens to a feeder dike.

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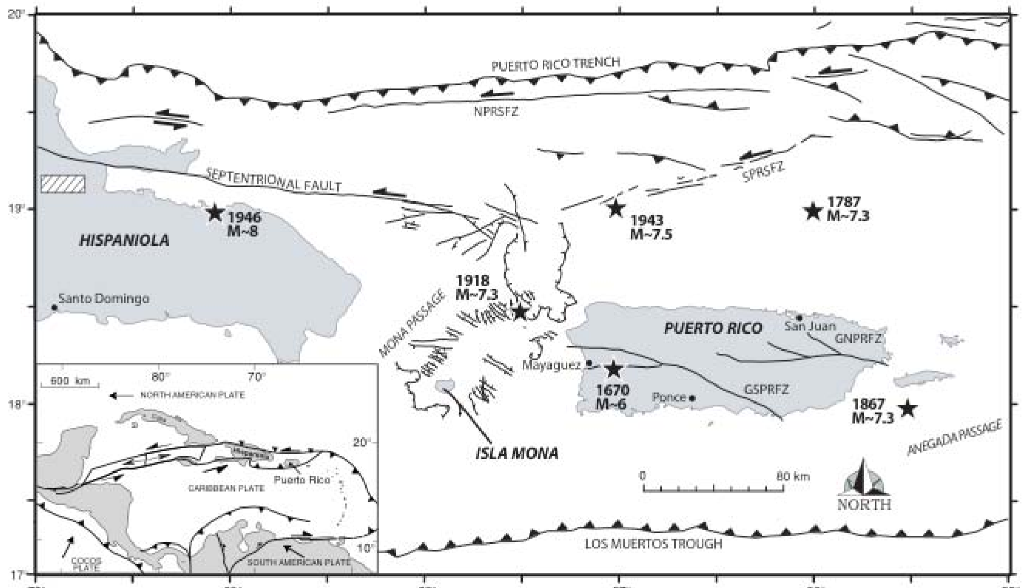

Figure 1. Location map of northeastern Caribbean in vicinity of Puerto Rico showing major onshore and offshore faults (Grindlay et al., 1997; Dolan et al., 1998) and locations of large historical earthquakes (1986 MIDAS catalogue; Dolan et al., 1998). GSPRFZ = Great Southern Puerto Rico fault zone; GNPRFZ = Great Northern Puerto Rico fault zone; NPRSFZ = Northern Puerto Rico Slope fault zone; SPRSFZ = Southern Puerto Rico Slope fault zone. Hispaniola study area, where liquefaction features may be related to 1946 M ~8 event and to 2-4 closely timed M 7-8 earthquakes circa A.D. 1200, indicated by rectangle (Tuttle et al., 2003). Inset map shows plate-tectonic setting of greater Caribbean region.

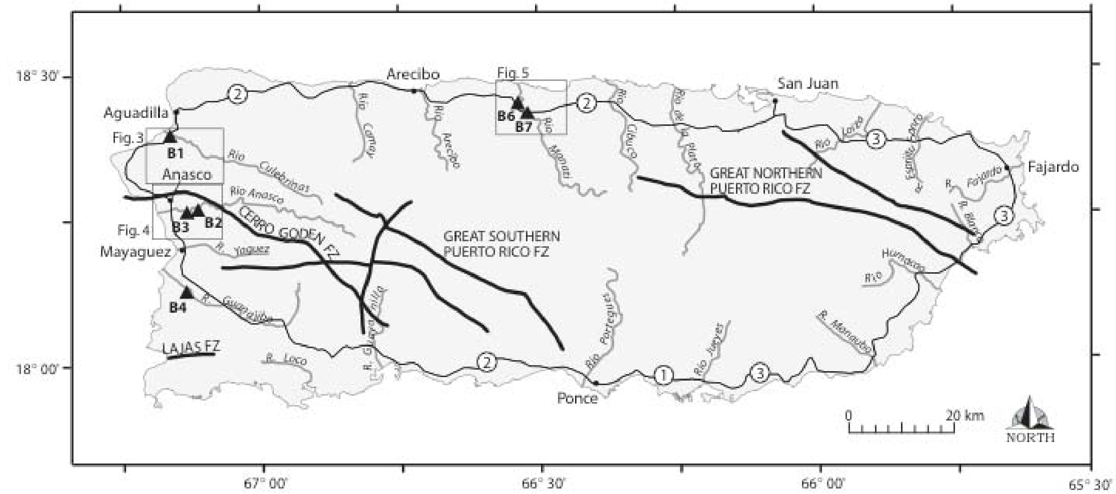

Figure 2. Map of Puerto Rico showing principle faults (Larue and Ryan, 1998; Jolly et al., 1998; Lao-Davila et al., 2000; Meltzer and Almy, 2000; Prentice et al., 2000), major rivers, areas of Figures 3 and 4, labeled F3 and F4, and borehole sites, labeled B1-B6.

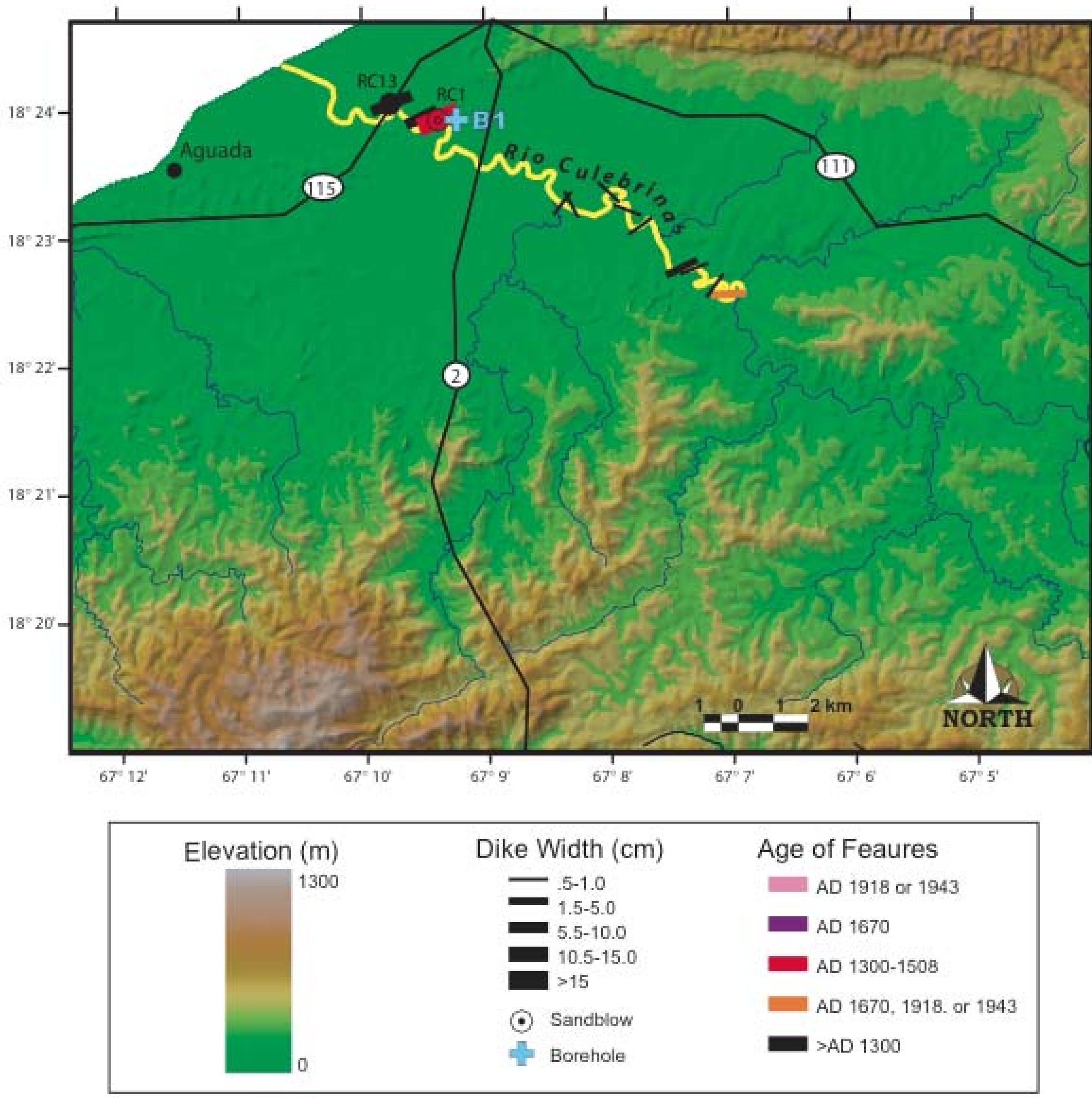

Figure 3. Digital elevation model of the Culebrinas River Valley showing locations, sizes, and estimated ages of earthquake-induced liquefaction features. Portion of river searched shown with yellow line and borehole location indicated by blue cross. See Figure 2 for location of area shown.

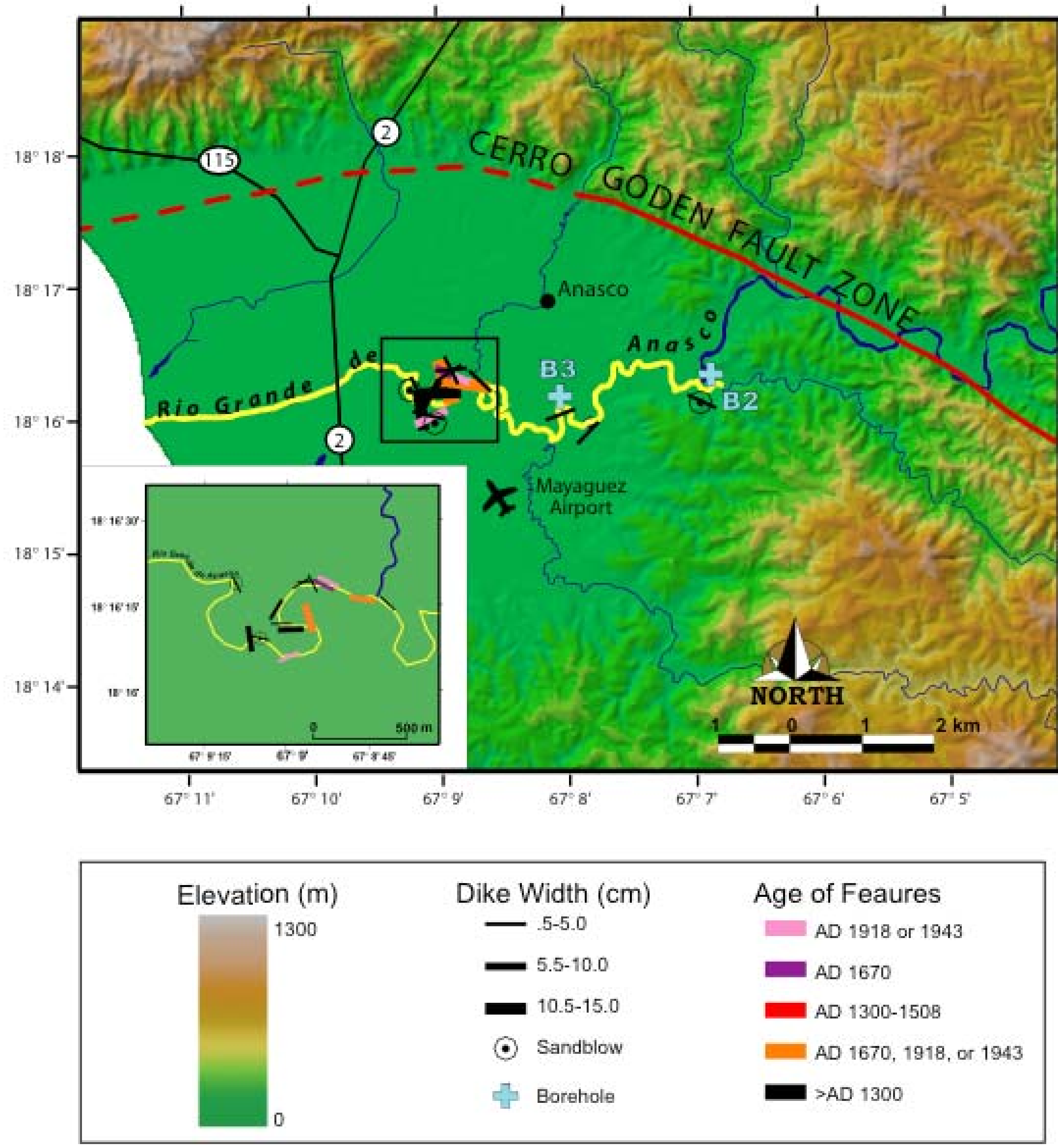

Figure 4. Digital elevation model of the Añasco River Valley showing locations, sizes, and estimated ages of earthquake-induced liquefaction features. Portion of river searched shown with yellow line and borehole locations indicated by blue crosses. Inset is enlargement of area with numerous liquefaction features. See Figure 2 for location of area shown.

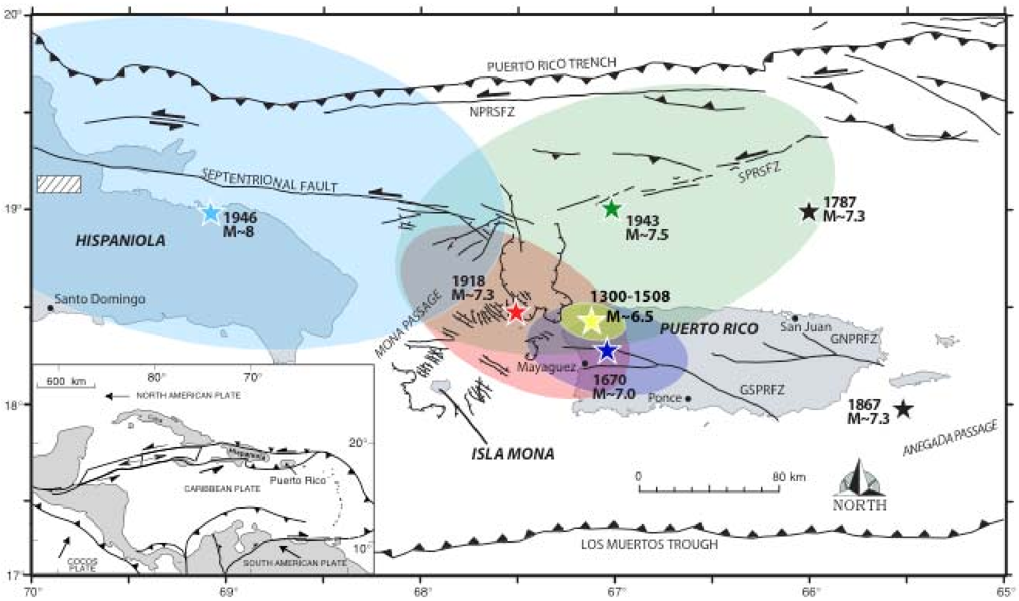

Figure 5. Map of northeastern Caribbean showing preliminary liquefaction fields for various earthquakes constrained by field observations and liquefaction potential analysis.

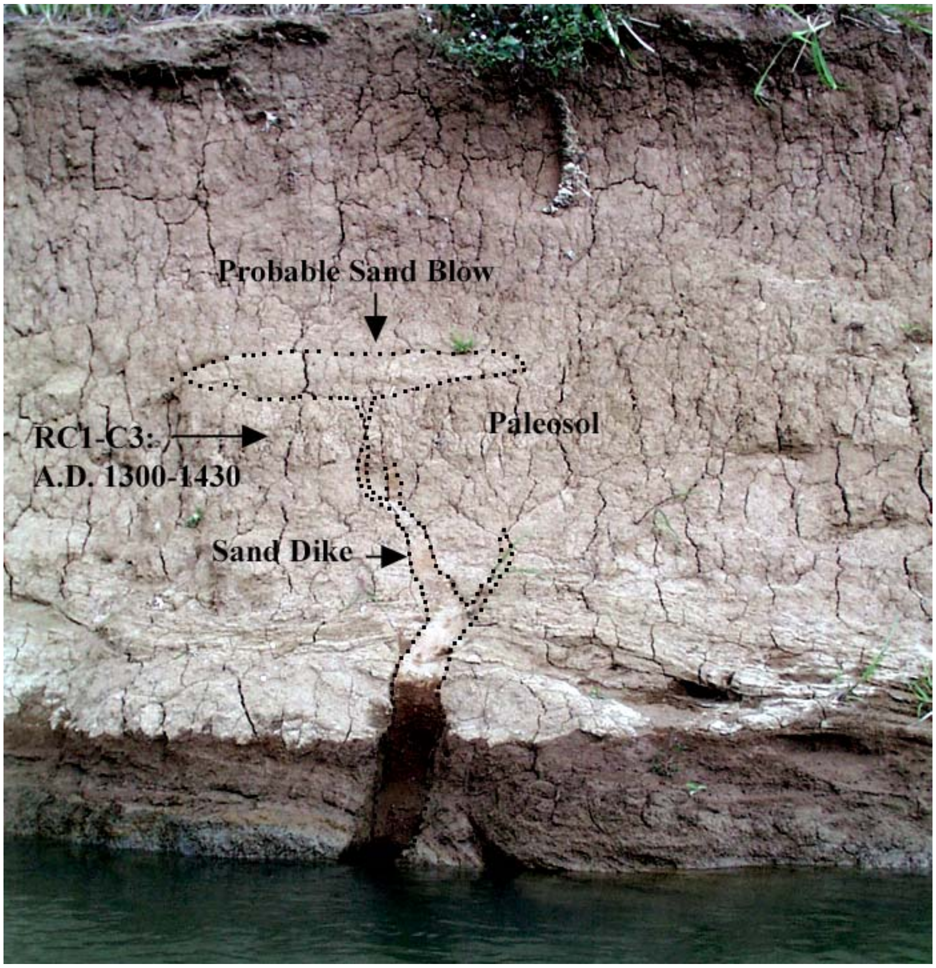

Figure 6. Photograph of sand dike and related sand blow at site RC1 taken several years ago. Charcoal from a paleosol crosscut by sand dike and overlain by sand blow provides close maximum age of A.D. 1300-1430. Exposure of liquefaction features is different today due to erosion of cutbank.

Table 1. Results of reconnaissance and radiocarbon dating of liquefaction features.

Site Name	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Thickness of Sand Blows (cm)	Width of Sand Dikes (cm)	Strike and Dip of Largest Sand Dikes	Preliminary Age Estimate (A.D.) of Features
Río Grande de Manati						
1	18.442060	66.529410	22	20	N54°E, 81°NW	Holocene
2	18.440040	66.531760		1	N35°W, 84°NE	Historic
Río Culebrinas						
1	18.401183	67.158133	20	23, 10, 7, 3, 3, 2	N68°E, 80°NW N38°E, 78°NW N83°E, 75°NW	1300-1508
2	18.377583	67.117267	possible	6, 2	N88°E, vertical	1670, 1918, or 1943
3	18.378450	67.119000		4, 1.5	N38°E, vertical	>1300
4	18.380700	67.121883		4.5	N68°E, 78°NW	>1300
5	18.381117	67.123750		8	N64°E, vertical	>1300
6	18.386333	67.129100		3, 2, 1.5, 1.5, 1.5	N53°E, 81°NW	>1300
7	18.388417	67.130917		3	N68°W, vertical	>1300
8	18.390667	67.133450		5	N47°W, 87°NE	>1300
9	18.389150	67.138500		1.5	N27°W, vertical	>1300
10	18.389333	67.139833		3, 2, 1, 0.5, 0.5	N38°E, vertical	>1300
Río Grande de Añasco						
1	18.271940	67.153040	possible, 8	3.5	N27°W, vertical	>1300
2	18.269710	67.152690		13, 1	N7°W, vertical	>1300
3	18.268790	67.151670	possible, 0.5	3, 2.5	N77°W, vertical	>1300
4	18.268650	67.151420		8, 4.5	N66°E, 86°SE N23°E, vertical	1918 or 1943
5	18.271600	67.115200				>1300
6	18.270300	67.115800	3.5	5	N67°W, 80°SW	>1300
7	18.266333	67.130733		3, 1, 1	N43°E, 82°SE	>1300
8	18.268700	67.134333		3	N71°E, 80°NW	>1300

9	18.272983	67.144783		3	N45°W, vertical	>1300
10	18.272950	67.146450		13, 4, 1	N82°W, vertical N27°W, 88°SW	1670, 1918, or 1943
11	18.274050	67.148350	12	9, 6	N68°W, 70°NE N57°W, 81°NE	1670 and 1918 or 1943
12	18.274333	67.148600		4	N27°W, vertical	>1300
13	18.274467	67.148667		2, 1	N83°E, 72°NW	>1300
14	18.274000	67.148983		4	N57°E, vertical	>1300
15	18.271433	67.151567		6	N33°E, vertical	>1300
16	18.271567	67.149800	possible, 6	1	N89°E, vertical	>1300
17	18.271783	67.150117		15	N87°W, vertical	>1300
18	18.273150	67.149233		16	N14°W, vertical	1670, 1918, or 1943
Río Guanajibo						
1	18.138833	67.141083		3	N48°E, 80°SE	>1300
2	18.156933	67.165833		0.5	N87°W, vertical	>1300

Table 2. Summary of interpretations of field observations, radiocarbon dating, and liquefaction potential analysis.

River Names	SPRSFZ M ~7.5 1943	Mona Passage M ~7.3 1918	Cerro Godin FZ M ~7.0 1670	NW Puerto Rico M $\geq$ 6.5 1300-1508
Río Grande de Manati	Liquefaction	NA	NA	NA
Río Culebrinas	No Liquefaction	No Liquefaction	Liquefaction	Liquefaction
Río Grande de Añasco	Liquefaction	Liquefaction	Liquefaction	No Liquefaction
Río Guanajibo	NA	← Liquefaction for at least one of these events →		

NA - not available because analysis has not yet been performed for this location.

Last Stop: Rio Manatí (Tish Tuttle)

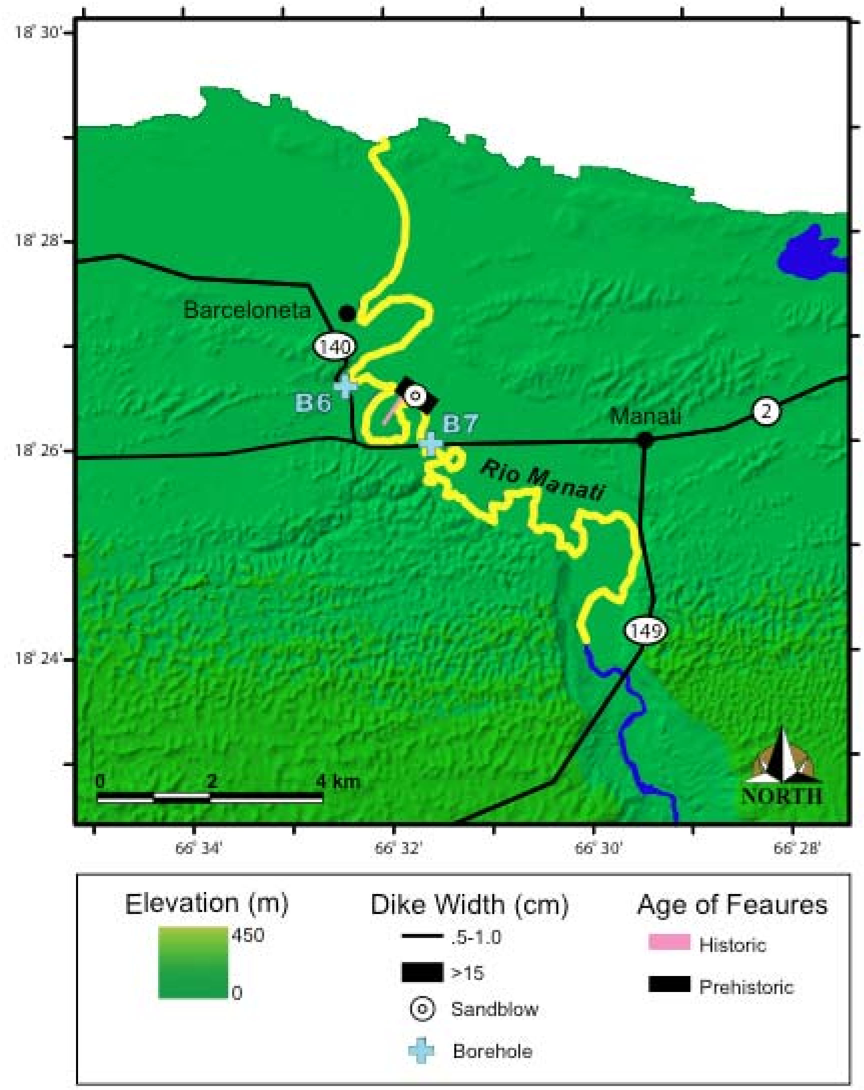

Figure 7. Digital elevation model of Manati River Valley showing locations, sizes, and estimated ages of earthquake-induced liquefaction features. Portion of river searched shown with yellow line and borehole locations indicated by blue crosses. See Figure 2 for location of area shown.