# The Northern Boquerón Bay- Punta Montalva Fault Zone; a through going active fault system in southwestern Puerto Rico

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## Abstract

We propose that the North Boquerón Bay-Punta Montalva Fault Zone is an active fault system that cuts across the Lajas Valley in southwestern Puerto Rico. The fault zone has been recognized and mapped based upon detailed analysis of geophysical data, satellite images and field mapping. In this work we demonstrate that the fault zone consists of a series of Cretaceous bedrock faults that reactivated and deformed Miocene limestone and Quaternary alluvial fan sediments. The fault zone is seismically active (ML < 5.0) with numerous earthquakes, locally. Focal mechanism solutions suggest strain partitioning with predominantly east-west left-lateral displacements with small normal faults oriented mostly toward the northeast. Evidence for recent displacement can be found in intermittent streams that cut through the Quaternary alluvial fan deposits along the southern margin of the Lajas Valley, an E-W trending 30-km long fault-controlled depression. This evidence consists of fractures and small normal faults oriented mostly northeast. Areas of preferred erosion, within the alluvial fan, trend toward the west-northwest parallel to the on-land projection of the North Boquerón Bay Fault. Beyond the faulted alluvial fan and southeast of the Lajas Valley the Northern Boquerón Bay Fault aligns with the Punta Montalva Fault. Both faults show strong southward tilting of Miocene strata. On the western end the Northern Boquerón Bay Fault is covered with flat lying Holocene sediments whereas in the southern end the Punta Montalva Fault shows left lateral displacement of stream drainage on the order of a few hundred meters. This suggests that most of the displacement along the North Boquerón Bay Fault Zone and the Punta Montalva fault is older than the Holocene, and that the rate of displacement is low such that the development of fault escarpments all along the fault zone has yet to occur.

## I. Introduction

Puerto Rico is located within the complex boundary zone between the North American Plate and the Caribbean Plate (Figure 1), and has a history of damaging earthquakes (Clinton et al., 2006). The boundary zone is characterized as a transition zone of dominantly subduction to the east along the Lesser Antilles, and a dominantly strike-slip boundary to the west. Major plate-boundary structures are located offshore (Muller et al., 2003) although recent studies (Prentice and Mann, 2005) have documented a secondary onshore fault with Holocene activity.

## II. Area of Study

Southwestern Puerto Rico is characterized by a high concentration of on-land shallow crustal seismicity. The relation between previously mapped faults and the distribution of the seismic events in the area however has proven difficult to establish. The tectonic geomorphology of southwestern Puerto Rico is dominated by the Lajas Valley, an E-W trending, 30 km long, 1.5-9.0 km wide, flat, low, linear depression. The valley resembles a half graben, bound by abrupt mountain fronts with steeper slopes on the south side and more gentle slopes on the north. It is characterized by closed drainage depressions of the former Laguna Cartagena, Laguna de Guánica, and Ciénaga El Anegado (Cameron, 2004; Prentice and Mann, 2005). Geologically, the the Lajas Valley is underlain and surrounded by the Jurassic to Early Cretaceous Bermeja Complex; a Late Cretaceous suite of volcanic, volcaniclastic, plutonic, and sedimentary rocks; Late Cretaceous and Tertiary limestone formations; and Quaternary alluvium deposits of age. The Bermeja Complex encompasses the oldest rocks found in Puerto Rico (Schellekens,1998).

A previously unmapped fault has recently been recognized along the southern margin of the Lajas Valley. The South Lajas Valley Fault (SLVF) was discovered using detailed analysis of geophysical data and aerial photographs (Prentice, 2000; Meltzer and Almy, 2000). Holocene displacement has only been documented along a small fault segment south of the main fault (Prentice and Mann, 2005). Although recognized at depth in seismic reflection profile, the main SLVF exhibits no obvious surface expression or pattern of seismicity. No recent or Neogene deformation was recognized in seismic profiles across the off-shore continuation of the main fault (Grindly et al., 2005). The SLVF is, however, considered as a possible seismogenic source in the most recent seismic hazard map of the U.S. Geological Survey (Muller et al., 2003). The SLVF is shown to extend west to east from the southwestern edge of the Lajas Valley along the entire length of the valley (~30km) and the northern flank of Sierra Bermeja.

Ocasio (2004) proposed the existence of the WNW-ESE trending North Boquerón Bay Fault (NBBF) based on total magnetic-intensity data and the offshore seismic profiles of Grindly et al (2005). It was suggested that the NBBF extended from the north side of Boquerón Bay inland across the Lajas Valley. Several geophysical investigations (Roig, 2004; Martinez, 2005; Martinez, 2006; and Rivera, 2006) were concentrated along the western end of the valley and delineated the on-land extension of the NBBF (Roig and Asencio, 2007).

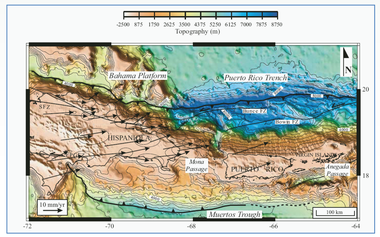


**Figure 1.** Bathymetric and raised relief map of the Hispaniola, Puerto Rico and Virgin Islands showing main active faults and GPS-derived velocities with respect to the North American Plate (From Mann, 2005).

## III. Aerial Photos and Remote Sensing data

Observation and analysis of aerial photographs, Landsat TM, and RADARSAT-1 images lead to the identification and delineation of lineaments along southwestern Puerto Rico (Figure 2). Lineations were mapped and the mean linear orientation was computed. Result from these calculations yield a NE preferred orientation.

## IV. Outcrop data

A series of recent sediment and bedrock outcrops that align along the trend of the NBBF and the PMF were examined and their deformational structures analyzed. Site DD1 is located along the banks of an intermittent stream in the alluvial fan on the north flank of the Sierra Bermeja. Steep NE trending normal faults and fractures cut the Quaternary fanglomerates (Figure 3). Orientation of the faults and fractures indicates NW-SE extension (Figure 4). Two additional streams in the alluvial fans west of the previous site were investigated. Bedrock outcrops at the top of the alluvial fans were marked by WNW trending shear zones characterized by left-lateral-reverse faulting and pervasive shear foliations. The bedrock shear zones are aligned WNW with the DD1 faulted fanglomerate site and parallel to the projected trend of the NBBF. The WNW alignment of the faulted outcrops in the alluvial fan suggests that the fault zone cuts the bedrock hills at the eastern end of the Sierra Bermeja. A small bedrock hill composed of highly deformed sedimentary layers of Cretaceous Parguera Formation lies along this same trend in the valley just southeast of the Sierra Bermeja. An outcrop on the west side is cut by large WNW trending vertical faults (Figure 5). Stratigraphic relations across the faults suggest left-lateral displacement. Other structures at the site are consistent with NE-SW directed shortening and NW-SE extension (Figure 4). Miocene limestone exposed on Punta Montalva strike WNW and are steeply inclined to the south. Within only a few tens of meters south of the point these same layers are subhorizontal. These steeply inclined layers define the PMF and were also encountered at the western end of the fault. Similar southward tilting of Neogene strata along the NBB was observed in the offshore seismic profiles (Grindly et al 2005).

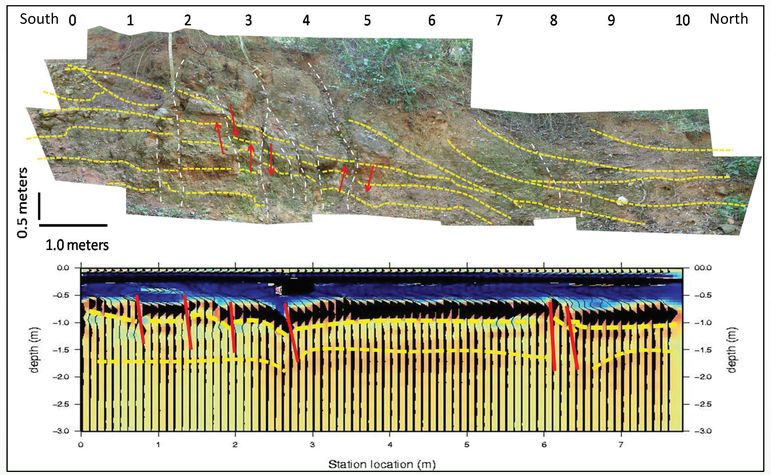


**Figure 3.** Outcrop of alluvial fan deposits on the channel banks of an intermittent stream on the north flank of the Sierra Bermeja at site DD1. Outcrop wall displays a series of fractures and normal faults oriented to the NE. A Ground Penetrating Radar (GPR) survey line was conducted along the stream bed adjacent and parallel to the outcrop. The reflectors (shown in yellow) show normal displacement.

**Table 1.** List of felt events along the NBBF- PMF trend.

| EVENT | DIP | STRIKE | RAKE (SLIP) | FAULT TYPE -BASED ON THE RAKE OF SLIP (CRONIN, 2004) | FOC. MECH. |
|---|---|---|---|---|---|
| 07 1991 -12 -26 | 5.0 | 40.0 | 90.0 | Pure dip -slip reverse | |
| 26 1999 -11 -13 | 35.53 | 329.28 | 30.64 | Reverse left -lateral oblique | |
| 30 2000 -08 -19 | 35.53 | 268.88 | -53.95 | Normal left -lateral oblique | |
| 37 2003 -03 -22 | 54.37 | 41.40 | 58.87 | Reverse left -lateral oblique | |
| 39 2003 -03 -22 | 46.03 | 17.58 | 54.04 | Reverse left -lateral oblique | |
| 42 2003 -03 -23 | 51.62 | 358.03 | 70.72 | Reverse | |
| 47 2007 -03 -15 | 82.36 | 91.72 | -49.57 | Reverse left -lateral oblique | |
| 49 2004 -11 -04 | 74.81 | 271.71 | 48.24 | Normal left -lateral oblique | |
| 52 2006 -03 -08 | 54.07 | 309.46 | 37.45 | Reverse left -lateral oblique | |
| 53 2006 -04 -18 | 81.82 | 110.16 | 54.59 | Reverse left -lateral oblique | |
| 60 2007 -05 -01 | 20.0 | 195.88 | 0.0 | Pure Strike-Slip | |
| 70 2008 -03 -28 | 61.98 | 41.77 | 67.20 | Reverse left -lateral oblique | |

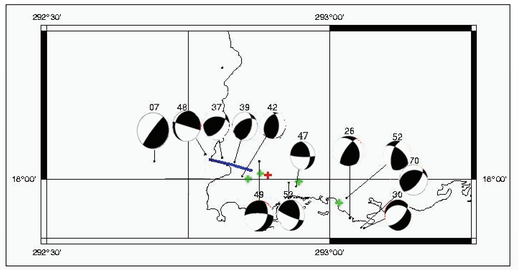


**Figure 6.** Focal Mechanisms results for felt earthquakes located parallel the NBBF and PMF trends. Focal mechanism solutions suggest strain partitioning with predominantly east-west left-lateral displacements with small normal faults oriented mostly toward the northeast and some reverse faulting oriented to the northwest.

## V. Seismicity

A pattern of seismic activity clearly follows the combined trend of the NBBF and PMF and includes at least 12 felt earthquakes, including the 3.5 magnitude event of March 15th, 2007, for which focal mechanisms calculation is consistent with left-lateral faulting and transtension (Figure 6). A few events in the alignment suggest a component of NW shortening which is not consistent with transpression but is consistent with differential motion between southwest and northwest Puerto Rico as suggested by Jansma and Mattioli (2005) in their interpretation of local GPS data.

## VI. Conclusions

Based on previous studies and data collected in this investigation the NBBF and PMF are interpreted to form a major through going left-lateral strike slip fault zone that cuts across the southwest corner of Puerto Rico. The NE trending active segment of the SLVF may be related to transtension along the NBB-PMFZ. The fact that the NBB-PM Fault Zone cuts across the geomorphic grain of the area and follows bedrock faults suggests the fault is a young incipient system that has developed by reactivation of older extinct faults. This is supported by the lack of geomorphic expression and limited deformation of Quaternary sediments. Left lateral displacement of stream drainage along the Punta Montalva Fault is on the order of a few hundred meters whereas the western offshore end of the Northern Boquerón Bay Fault is covered with flat lying Holocene sediments. This suggests that most of the displacement along the NBB-PM Fault Zone was pre-Holocene and that the rate of displacement is low such that the development of fault escarpments all along the fault zone has yet to occur. The orientation and displacement of the faults and associated structures are consistent with a small amount of strain partitioning within the plate boundary between the Caribbean and North America Plates and differential movement between fault block within Puerto Rico.

## VI. Acknowledgements

Funding for the acquisition of the RADARSAT-1 image of south western Puerto Rico was provided by the Puerto Rico Seismic Network.

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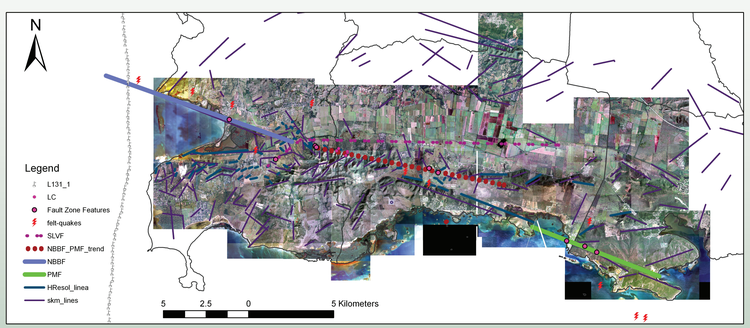


**Figure 2.** Southwestern Puerto Rico, and location of the Lajas Valley. Image generated using ArcGIS with high resolution Orthoimages. Hresol lines and skm lines corresponds to lineaments identified on the high resolution Orthoimagery and the Lansat TM respectively; NBBF shows the proposed location of the North Boquerón Bay Fault; PMF shows the location of the Punta Montalva Fault (Addarich Martinez, 2008); SLVF shows the location of the South Lajas Valley Fault as projected by Muller et al. (2003); NBBF_PMF_trend shows the parallel trend of both North Boquerón Bay Fault –Punta Montalva Fault where deformation is documented (pink dots); L131_1 shows the location of the seismic reflection line conducted by Western Geophysical in the 1970's; and red thunder rays shows the location of felt earthquakes along the trend of the NBBF and PMF.

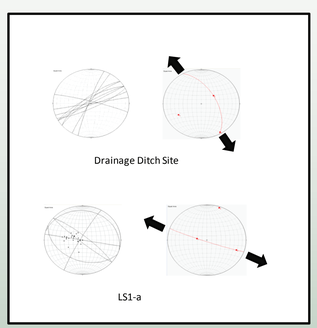


**Figure 4.** Summary results for structural data collected along the DD1 site and the LS1-a (Parguera Limestone) site. Both sites record extension oriented NW-SE.

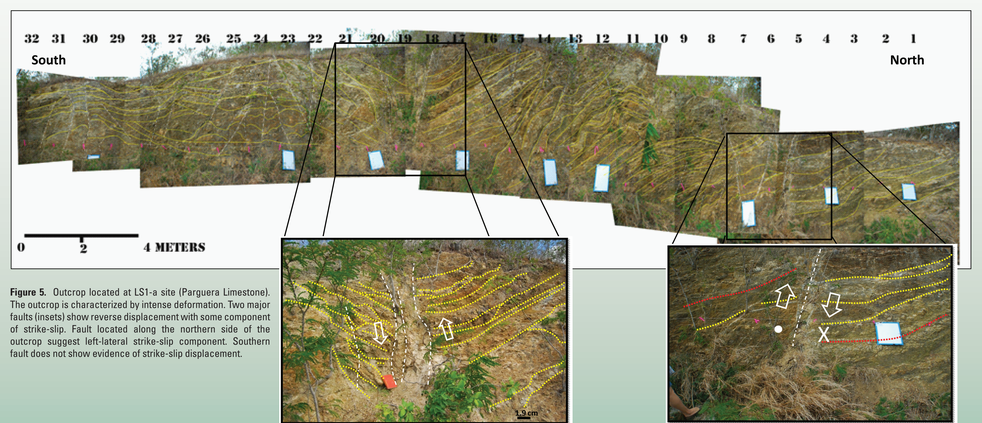


**Figure 5.** Outcrop located at LS1-a site (Parguera Limestone). The outcrop is characterized by intense deformation. Two major faults (insets) show reverse displacement with some component of strike-slip. Fault located along the northern side of the outcrop suggest left-lateral strike-slip component. Southern fault does not show evidence of strike-slip displacement.

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