Toward a Deeper Understanding of Northeastern Caribbean Tectonics with Continuously Operated GPS Sites and Ocean Bottom Seismometers

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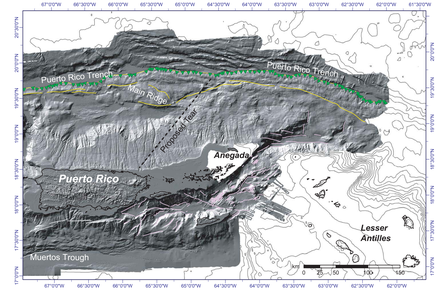
1. Abstract

Figure 1: Instrumentation used to study current tectonics of the NE Caribbean. Top: Ocean Bottom Seismometers. Bottom: Continuous GPS.

Persistent seismic swarms northeast of the Puerto Rico-Virgin Islands (PRVI) tectonic block have been recorded and documented for more than a decade. The heightened seismicity typically lasts for days to weeks and consists primarily of hundreds of Ms < 4 events, but events up to Ms 6 have been recorded. The active region (sometimes called the "Sombrero" region although it is far from Sombrero Island) is located on the forearc of the Puerto Rico trench north of the Virgin Islands. What exactly causes the heightened seismicity in Northeastern PRVI is unclear, however some suggestions seeking to explain its occurrence have included a tear in the subducting North America plate and stress relief associated with subducted ridges, reflecting either asperities in the subduction process or re-activation of faults. Seismic studies of the swarm based on land stations have not succeeded in estimating epicenters accurately because of limitations in the distribution of the network's stations. Deployment of ocean bottom seismometers (OBS) in 2005 and 2007 have been critical to understanding the nature of these events by providing more rigorous constraints on hypocenters and focal mechanisms. Complementing this new data with land stations of the Puerto Rico Seismic Network (PRSN) we seek to answer; 1) Do these seismic swarms represent intraslab processes related to slab tear or re-activation of pre-existing ridge faults? or 2) do they represent episodic tremors and slip events that are associated with forearc relaxation in subduction zones? The island of Anegada, on the northeastern tip of the PRVI block, is an ideal location at which to test the latter question due to its proximity to the Puerto Rico trench, to the north. To test this idea, a continuously operating GPS (CGPS) site was installed in Anegada in March 2007. Here we present results of this data spanning one full year and incorporate them to the seismic data in an effort to provide an improved view of the nature of earthquake swarms in northeastern PRVI.

2. What may be causing the seismic swarms in the Northeastern Caribbean?



Possible suggestions to explain the seismic swarms include:

A) Tear in the subducting NA plate slab: A tear in the subducting slab may occur as a consequence of the subduction of an indentor on an increasing plate boundary curvature (*ten Brink, 2005*). The Puerto Rico-Virgin Islands microblock has rotated ~16° CCW over the last 11 Ma. This has focused and increased the stresses on the NE Caribbean plate boundary and caused the corner to become sharper. In addition, the subduction of the Main Ridge helped focus the tensile stresses and cause a tear (see Figure 3).

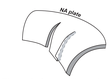


Figure 3: Cartoon illustrating tear in subducting slab to accommodate curvature

B) Subduction of Aseismic ridges: Pre-existing NA plate spreading ridges and/or transform faults being subducted today beneath the CA plate have been suggested to be re-activated (*McCann and Sykes, 1984*). The Main ridge, located north of Puerto Rico and oriented obliquely across the northern slope (see Figure 2), would be such a case. If the subduction of the Main ridge has resulted in its re-activation due to increased stresses, it is possible that it may be directly related to the seismic swarms.

Figure 2: Map of the NE Caribbean with USGS high-resolution shaded relief bathymetry (*ten Brink et. al., 2004*). Black dashed line represents a proposed tear in the NA subducted slab (*ten Brink, 2005*), which may have been initiated due to the subduction of the Main Ridge 3.3 Ma.

C) Episodic tremor and slip events: It has been shown recently for several subduction zones that slow slip events detected on Continuous GPS (CGPS) data correlate with non-volcanic tremors observed on seismometers (Rogers and *Dragert, 2005*). If the seismic swarms are due to forearc relaxation, where energy is released seismically as a result of a aseismic slip loading, then we should see that aseismic slip in the geodetic signal. In March 2007, the USGS installed a CGPS site in the island of Anegada. The island belongs to the British Virgin Islands and is located at the northeastern corner of the PRVI microblock (see Figure 2).

One year of data has been collected and processed in an effort to understand whether seismic swarms are correlated with transient events.

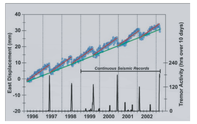
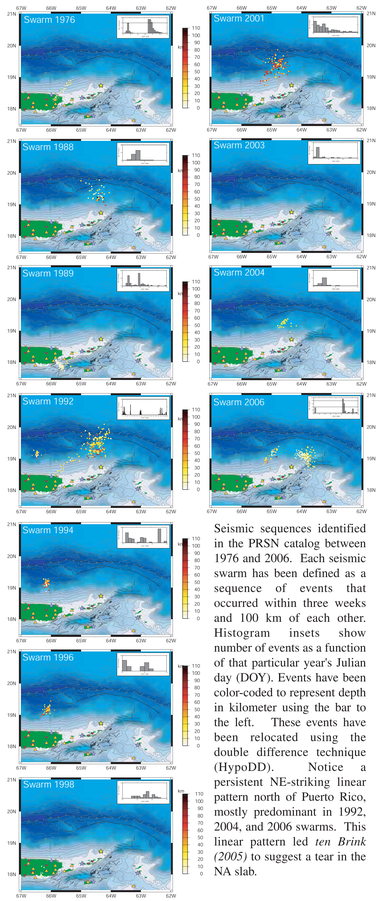


Figure 4: From *Rogers and Dragert (2005)*. Gradual aseismic slip of the the Cascadia forearc loading detected by GPS is matched with faster, seismic relaxation recorded by seismometers

3. Instrumentally recorded Seismic Swarms



Seismic sequences identified in the PRSN catalog between 1976 and 2006. Each seismic swarm has been defined as a sequence of events that occurred within three weeks and 100 km of each other. Histogram insets show number of events as a function of that particular year's Julian day (DOY). Events have been color-coded to represent depth in kilometer using the bar to the left. These events have been relocated using the double difference technique (HypoDD). Notice a persistent NE-striking linear pattern north of Puerto Rico, mostly predominant in 1992, 2004, and 2006 swarms. This linear pattern led *ten Brink (2005)* to suggest a tear in the NA slab.

4. 2005 and 2007 OBS deployments

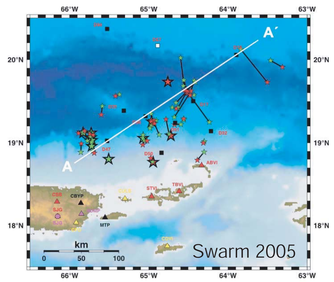


Figure 5: Figure from *Pulliam et. al. (2008)*. Events of the 2005 seismic swarm recorded between August and November. Black squares are short period ocean bottom seismometers (OBS). Large green stars were events not detected by the PRSN stations and recorded only on some of the OBSs. Small green stars are PRSN epicenters, while red stars are relocations incorporating OBS data. Triangles are PRSN stations. Profile A-A' (Figure 6) help visualize hypocenter corrections.

2005:

+ Three months of OBS data merged with ten PRSN land stations.
+ Data analyzed and processed to identify a total of 50 events, of which 15 were only recorded by the OBSs.
+ Upon relocation, the jointly recorded events revealed tighter clustering and clear biases with respect to original PRSN locations.
+ Changes in epicenters were greatest in the NE limit of activity, while there was a consistent progression toward deeper focal depths for events closer to the island of Puerto Rico.
+The average change in focal depth for the cluster of five events closest to Puerto Rico was 35 km.
+Most of the relocated events are consistent with the depth and dip of the subducted NA plate in this region and may therefore be associated with active subduction, rather than the shallow tectonics suggested by original locations.

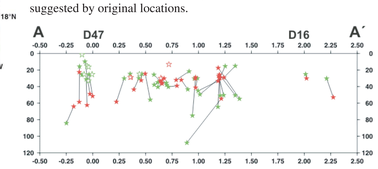


Figure 6: Figure from *Pulliam et. al. (2008)*. PRSN preliminary locations (green) and relocated events (red) projected onto profile A-A'. Focal depths deeper and closer to the island of Puerto Rico may reflect the plate interface. Events near OBS D16 were relocated to be significantly further away from this cross-section.

2007:

+ Five short period OBSs were deployed in March 12-13, 2007 to collect data for six months.
+ A total of 597 events were recorded on the PRSN network for the six month period.
+ Average magnitude of these events is Ms 2.9, with the largest being 4.5.
+ Six month period recorded two swarms.
+ First one consisted of approximately 40 events and peaked between Julian days 106-108 (April 16-18).
+ Second one consisted of approximately 220 events and peaked between days 175-177 (June 24-26). The majority of the events (~183) occurred on day 176.
+ Data analysis close to completion.

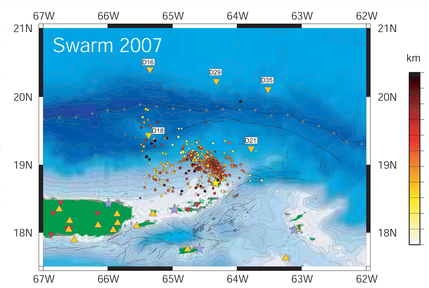


Figure 7: Approximately 600 events were recorded on PRSN land stations (triangles) from March through September 2007. Inverted yellow triangles are the 5 deployed OBSs. Stars are CGPS stations shown in Figure 13. Event color correlates with depth bar to the right. Faults in the Anegada Passage were identified and mapped using recently collected multi-channel seismic profiles.

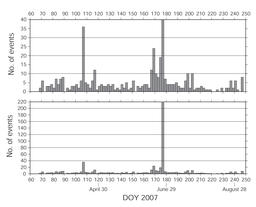


Figure 8: Histogram for the 2007 seismic swarms show number of events as a function of Julian Day (DOY). Bottom panel shows overall coverage, while top panel is an enlarged view to help visualize better the frequency of events for the first smaller swarm (between days 106-108).

5. Preliminary GPS results

+One full year of continous data at the Anegada CGPS (ANEG) site.
+ANEG data shows no discontinuity in the velocity trend for any of the three components for the six month period.
+A lack of correlation between the seismic swarms and the velocities of the three components at ANEG suggests, at least preliminary, that the seismic swarms are not related to forearc relaxation.
+Certainly, a longer time-series, where additional seismic swarms can be recorded, will be able to confirm or reject this theory.

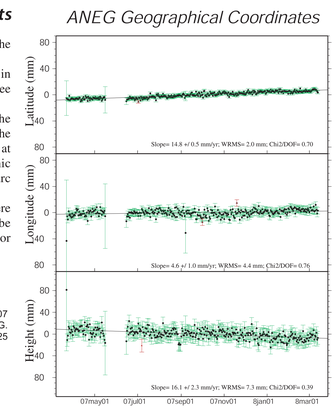


Figure 9: Point-positions from March 2007 through March 2008 for CGPS site ANEG. Data gap corresponds to power loss for 25 days from May 15-June16 (DOY 137-165).

+The following CGPS sites were also processed to assess current NE Caribbean tectonic motions.
+All velocities in IGSb 2000

SITE	Location	Date start	Ve	Vn
ANEG	Anegada, BVI	22-Mar-07	14.8 ±0.5	4.6 ±1.0
CRO1	St. Croix, USVI	28-Oct-03	12.5 ±0.1	11.8 ±0.1
PRMI	Lajas, PR	27-Mar-06	10.0 ±0.1	7.7 ±0.3
PUR5	Isabela, PR	21-Mar-06	10.7 ±0.4	8.4 ±0.9
SMRT	St. Martin, NA	23-May-07	17.4 ±0.5	7.3 ±1.1
VITH	St. Thomas, USVI	18-Aug-06	12.4 ±0.3	11.6 ±0.6
ZSU1	Carolina, PR	28-Oct-03	12.0 ±0.1	11.3 ±0.1

+Used the latest realization of the North America (*Sella, pers. comm.*) and Caribbean (*López et. al., 2006*) Euler poles to place our sites with respect to North America and Caribbean reference frames, respectively.
+Results show that sites in Puerto Rico (PR) and the US Virgin Islands (USVI) have similar velocities to that of the Caribbean plate.
+ANEG and SMRT have more northerly azimuths (similar azimuths to slip vectors shown in Figure 10).
+These results suggest that at least, ANEG and SMRT are being affected by slip partitioning of the forearc due to oblique convergence of the North America plate.

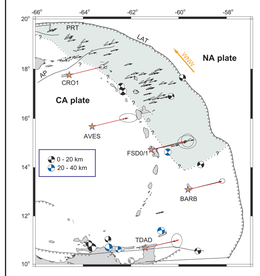


Figure 10: Figure take from *López et al. (2006)*, where they suggest a forearc sliver in the northern half of the arc. The western boundary of such block must be a left-lateral strike-slip fault. Arrows- white: slip vectors; black:predicted.

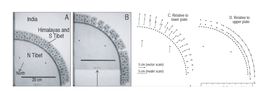


Figure 11: Figure from *McCaffrey and Nabelek (1998)*. Block motions with respect to upper (A) and lower (B) plates. ANEG and SMRT follow strikingly similar behavior.

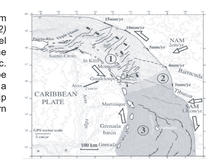


Figure 12: Figure from *Feuillet et al. (2002)* suggesting arc-parallel deformation along the Lesser Antilles forearc. Such motion must be accommodated along a left-lateral strike-slip fault along the western boundary.

+Data supports translation of the forearc.
+Still unclear what features are accommodating such deformation.
+St. Thomas (VITH) closest to ANEG and yet moves with the Caribbean plate.
+This suggests a left-lateral strike-slip fault somewhere between the two islands capable of cross-cutting the Anegada Passage.

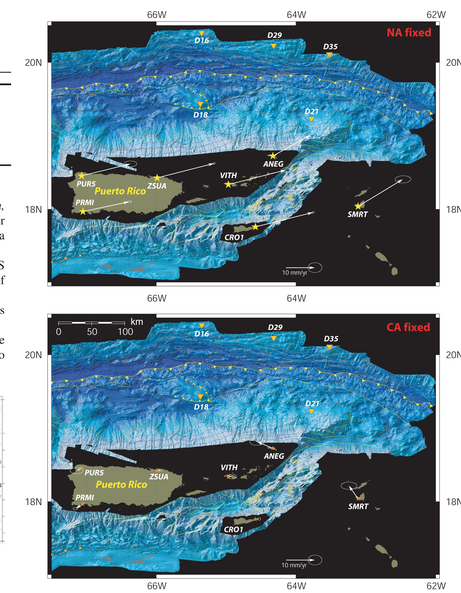


Figure 13: GPS velocities of CGPS sites in the Northeastern Caribbean with respect to North America (top) and Caribbean (bottom) plates. In a North America fixed reference frame (top), CGPS sites in Puerto Rico (PUR5, PRMI, ZSUA), and USVI (VITH, CRO1) possess very similar velocities, whereas SMRT and ANEG are rotated slightly north, an indication of forearc slip partitioning. The discrepancy is more noticeable when all sites are placed on a Caribbean fixed reference frame (bottom). While sites in Puerto Rico and the USVI have minimal velocities (or within their error ellipses), ANEG and SMRT show motions sub-parallel to trench strike.

6. Conclusions

- Seismic swarms in the Northeastern Caribbean might be the results of interactions of the subducted Main Ridge with the upper Caribbean plate.
- Sequence of events from 1976 to 2007 indicate the persistent swarms tend to cluster in distinctive patterns that may be related to a tear in the NA slab.
- Although limited to three months, constraints provided by the 2005 OBS deployment improved both epicentral and focal depth estimates and revealed bias in PRSN locations: North of PR, all focal depths determined by PRSN alone are unreliable and epicenters become increasingly unreliable as a function of distance from PR.
- GPS data from continuous sites in Northeastern Caribbean rejects, at least preliminarily, swarms are related to forearc relaxation, and supports the idea of a forearc sliver moving independently from both North America and Caribbean plates.

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