Mature diffuse tectonic block boundary revealed by the 2020 southwestern Puerto Rico seismic sequence

U.S. ten Brink[1*], L. Vanacore[2], E.J. Fielding[3], J.D. Chaytor[1], A.M. López-Venegas[2], W. Baldwin[1], D. Foster[1], B.D. Andrews[1]

1 – U.S. Geological Survey, Woods Hole Science Center, Woods Hole, MA

2 – Dept. of Geology, U. of Puerto Rico, Mayaguez, PR

3 – Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

* Corresponding author: Uri ten Brink utenbrink@usgs.gov

Key points

-Seismic activity did not follow main shock-aftershock sequence and likely ruptured multiple faults in SWPR

-Geologic indicators suggest long-term diffuse deformation due perhaps to heterogenous arc composition

-This zone may be the southernmost domain of a diffuse deformation boundary between Hispaniola and Puerto Rico

Abstract

Distributed faulting typically tends to coalesce into one or a few faults with repeated deformation. The 2020 seismic sequence in southwestern Puerto Rico (SWPR) was characterized however by rupture of several short intersecting strike-slip and normal faults, although several lines of geological and morphological evidence suggest repeated deformation since post early

Pliocene (~>3 Ma). We mapped these faults by acquiring high-resolution seismic reflection profiles, by modeling shoreline subsidence and displacement from InSAR, and by tracking the progression of clustered medium-sized (≥Mw4.5) earthquakes. The faults underlie the insular shelf and upper slope in the vicinity of Guayanilla submarine canyon. This deformation may represent the southernmost part of a diffuse boundary, the Western Puerto Rico Deformation Boundary, which accommodates differential movement between the Puerto Rico and Hispaniola arc blocks. This differential movement is probably driven by the differential seismic coupling along the Puerto Rico – Hispaniola subduction zone. We propose that the compositional heterogeneity across the island arc retards the process of focusing the deformation into a single fault. Given the evidence present here, we should not expect a single large event in this area but similar diffuse sequences in the future.

1. Introduction

The seismic activity in southwestern Puerto Rico (SWPR) (Fig. 1) consisted of +13,000 earthquakes (M≥2.5) with 43 earthquakes with Mw ≥ 4.5 since its start on December 28, 2019. The largest of these events, an Mw6.4 on Jan. 2020 was located offshore and had a mixed normal and strike-slip motion (Liu et al., 2020, ANSS-ComCat). The earthquake sequence and in particular the Mw6.4 earthquake caused extensive damage in coastal towns (Morales-Velez et al., 2020; Miranda et al., 2020; Von Hillebrandt et al., 2020), co-seismic subsidence around Guayanilla Bay (Allstadt et al., 2020; Fielding et al., 2020; Pérez-Valentín et al., 2021), liquefaction, ground failures, and the collapse of an iconic coastal rock bridge (López-Venegas et al., 2020a, 2020b, Allstad et al., 2020; Pérez-Valentín et al., 2021). The prolonged seismic activity had thus created anxiety among the island's population. The activity was centered around a defunct oil refinery and strategic facilities for the island, such as a liquid natural gas terminal, an electric power station.

The seismic activity as expressed in the earthquakes' b-value is not a typical foreshock, main shock, and aftershock sequence (Dascher-Cousieau et al., 2020). Based on the time series of the b-values, Dascher-Cousieau et al. (2020) interpreted the earthquake activity to indicate that the observed seismic activity to date is part of a foreshock sequence with a larger main shock yet to come. An alternative view which we discuss here is that the seismic activity represents the rupture of small faults, that are part of a diffuse block boundary within the Greater Antilles island arc. A similar diffuse block boundary with associated sequences of seismic activity had been suggested for the 70-100-km-wide Central Costa Rica Deformed Belt across the Costa Rica volcanic arc, which separates the middle America subduction zone from the Panama Block (Marshall et al., 2000).

Deformation due to the seismic activity in SWPR appears to have occurred throughout the Pleistocene (and perhaps part of the Pliocene) and is not a recent phenomenon (e.g., Mann et al., 2005; Prentice, 2005; Piety et al., 2018). The evidence discussed here raises the question of whether there are some tectonic boundaries where deformation remains diffuse over long periods of geologic time and does not coalesce into one or few mature faults and if so, why. This question is important to understanding and predicting seismic hazard.

We address here the following questions: 1. Can we identify the faults responsible for the seismic sequence?.2 Is the activity organized in a predictable way? 3. Is it a recurring activity?

4. What framework tectonics generated this activity?

Most of the seismic activity during this seismic sequence occurred offshore, which complicated the search for the ruptured faults. Mapping faults therefore relied on several lines of evidence: (a) Mapping faults in the shallow sub-seafloor by marine high-resolution seismic reflection survey and evaluating seafloor geomorphology; (b) Matching vertical and horizontal displacement models to observed InSAR coastal deformation around the January 7, 2020 Mw6.4 earthquake and the July 3, 2020 Mw5.3 earthquake; (c) Identifying clusters of medium earthquakes and drawing possible faults based on their focal mechanisms.

2. Background

Puerto Rico and Hispaniola are part of the inactive Mesozoic and early Cenozoic Greater Antilles island arc that accommodated southwestward subduction of the North American plate under the Caribbean plate. Subduction direction changed to WSW starting ~40 Myr ago resulting in a very oblique convergence along the trench north of Puerto Rico (Fig. 1; DeMets et al., 2000). Muertos Trough, a wedge of deformed sediment south of the island accommodates thrusting of the arc over the interior Caribbean plate, likely in a sub-perpendicular orientation (ten Brink et al., 2009).

The 2020 seismic sequence occurred mostly under the insular shelf and slope south of Puerto Rico (Fig. 1). The slope there is dissected by the tributaries of Guayanilla Canyon, which cuts down through unconsolidated Quaternary deposits, the middle Miocene to Early Pliocene shelf carbonates of the Ponce Formation and the deeper Juan Diaz Formation chalks (Trumbull and

Garrison, 1973). The Guayanilla canyon system is the only significant submarine drainage along the south coast of Puerto Rico. The canyon system has eroded into the insular shelf, forming an asymmetric amphitheater (Fig. 1, 2). West and east of this canyon system, the shelf edge is oriented roughly W-E and canyon systems are undeveloped. The shelf width is ≤12 km west and ≤18 km east of the canyon area, respectively, but is as narrow as 1 km in the canyon area, where shallow channels dissect the reef structures.

Very few faults have been mapped on shore in the vicinity of the recent seismic activity. Mid-Holocene faults were trenched in Lajas Valley (Prentice et al. 2005) and near Ponce (Piety et al. 2018). A fault, named San Francisco Fault, which can be extrapolated into Guyanilla Bay was suggested by Grossman (1963) from surface geology. A 33-km-long left-lateral strike-slip fault stretching from Punta Montalva to north Boquerón Bay on the west coast of Puerto Rico was postulated mostly based on morphology by Roig-Silva et al. (2013) (Fig. 3). Garrison (1969) interpreted a several-hundred-milliseconds-deep half graben in Sparker seismic reflection data on the insular shelf south of Ponce. The graben is bounded by the Caja de Muertos Fault on the SE and possibly the Bajo Tasmanian Fault on the NW (Fig. 2). Caja De Muertos Island was proposed to have been uplifted by faulting (Kay, 1957) A narrow elongate bathymetric trough at the upper slope south of the island, named Investigator Fault, was previously considered a left-lateral strike-slip fault, but high-resolution multibeam bathymetry, seismic reflection data (Granja-Bruña et al., 2009; ten Brink et al., 2009) and an ROV dive in 2015 (Kennedy et al., 2015) suggest that this trough is either inactive or that it is formed by a N-S extension. The area of seismic activity is largely devoid of good quality seismic reflection data.

3. Data

We conducted a high-resolution multichannel seismic survey between March 7-13, 2020 aboard the University of Puerto Rico's R/V Sultana based at the Marine Sciences laboratory at Magueyes Island (Fig. 2 and 4) in La Parguera. The seismic sources included a 2.4 kJ Sparker at water depths >500 m, a 1 kJ Sparker at water depths of 100-500 m and a 0.3 kJ mini-sparker on the 8-25 m deep shelf. Acoustic data was received by a 32-channel digital streamer with hydrophone group interval of 1.5625 m. Navigation was enabled differential GPS. A total of 250-line km were collected with common mid-point (CMP) spacing of 0.781 m for lines on the shelf and 3.125 m for lines on the insular slope. The vertical resolution is estimated at a few meters. Data processing included geometry definition, trace edits, static correction, noise reduction (f-k deconvolution, f-k filtering, bandpass filtering (70-1000 Hz), CMP stack, post-stack phase-shift time migration, and spiking deconvolution. Horizon and fault interpretation and visualization were carried out with Kingdom Suite© software. Data penetration was typically ≤ 0.5 s (~500 m) on the slope and ≤0.08 s on the shelf (Fig. 4) Deeper penetration on the shelf was masked by multiples due to the shallow and sometimes hard reef bottom.

Multibeam bathymetry data, collected by the NOAA ships Nancy Foster and Thomas Jefferson prior to 2019 and LIDAR data collected by NOAA on the shelf (seeAppendix A3 for data sources), were gridded at 8 m horizontal resolution. We added these data to an existing compilation of multibeam bathymetry data in the NE Caribbean (Andrews et al., 2014).

We used Synthetic Aperture Radar interferometry (InSAR) measurements of displacements in the radar line-of-sight directions and combined data from different directions to estimate two components of the surface displacement. InSAR measurements from satellites in this region are sensitive to the east and vertical components. The data included C-band (5.6 cm wavelength) SAR from the Copernicus Sentinel-1 satellites, operated by the European Space Agency (ESA), and L-band (24 cm wavelength) SAR from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observation Satellite-2 (ALOS-2) satellite. Two tracks of Sentinel-1 data cover the land area of the seismic activity, and another track covers the area to the east. SAR and InSAR processing were done with the InSAR Scientific Computing Environment (ISCE) v2 (Rosen et al., 2012) starting with the single-look complex images from ESA and JAXA. Stack processing was performed with ISCE on two of the Sentinel-1 tracks descending track D098 and ascending track A135, for all data from July 2019 through early August 2020. Time-series analysis was conducted with MintPy (Yunjun et al., 2019) to reconstruct the line-of-sight displacements for all the dates on each track and to estimate the coseismic step functions at the times of the Mw 6.4 January 7, 2020 earthquake and the events around July 3, 2020 and better separate the earthquake deformation from atmospheric effects (Fielding et al., 2017). We processed wide-swath (ScanSAR) data from ALOS-2 to form a coseismic interferogram on descending path 135 using the ALOS-2 application in ISCE2 (Liang and Fielding, 2017).

We combined line-of-sight (LOS) displacement estimates from the step-function fits to the Copernicus Sentinel-1 time series. The LOS (ground-to-satellite vector) for the Sentinel-1 ascending track A135 is up and slightly north of due west, while the LOS for the descending track D098 is up and slightly north of due east. We used the same reference point at 18.0°N and 67.0°W for both tracks. The displacements are set to zero at the reference point, and all the other displacements are relative to this point. We can combine the two InSAR LOS measurements to estimate two components of the surface displacements that are close to east and vertical but contain a small percentage of any north displacement (Wright et al., 2004). The resulting estimates for the vertical and east components of coseismic displacements were contoured for easier comparison to other data. The estimated vertical component of coseismic displacements due to the Mw6.4 January 7, 2020 (time-series step-function fit at that date) are shown as red contours on Fig. 5. The horizontal component is smaller than the vertical and not shown.

We did a similar step-function fit to the two Sentinel-1 time series for July 3, 2020. As with the January step-function fit, the 12-day intervals between acquisitions on the two Sentinel-1 tracks means that all deformation in the time between acquisitions cannot be separated. For the A135 track, the interval that contains July 3 was 07/02–07/14 and for the D098 track the interval was 06/30–07/12. The conversion to vertical and east components assumes that the surface displacements are the same in the two step-function fits, which should be accurate if nearly all the displacement was between 07/02 and 07/12. This interval includes several earthquakes, the largest were a pair of Mw5.1 and 5.3 on 07/03. The estimated vertical and east components are shown on Fig. 6a and Fig. 6b, respectively. An area of coastal subsidence that is much smaller than the Mw 6.4 signal was detected near Playa Santa that may be due to the pair of Mw 5.1 and 5.3 07/03 earthquake offshore (Fig. 6a). The subsidence was accompanied by westward horizontal component west of Playa Santa and an eastward component east of Playa Santa (Fig. 6b).

GPS time series relative to the Caribbean reference frame for 9 stations surrounding the study area (Fig. 1) were downloaded from the Nevada Geodetic Laboratory (Blewitt et al., 2018). We used the data that was processed with the final GPS orbits. The time series were used to evaluate relative plate motions within the region and encompassed available continuous observations for at least 4 years since 2008 and prior to the start of the seismic sequence.

Locations and focal plane solutions of Mw≥4.5 earthquakes in this sequence, published by the Advanced National Seismic System (ANSS) Comprehensive Earthquake Catalog (ComCat) (https://earthquake.usgs.gov/earthquakes/search/ accessed February 15, 2021) have been adopted for analysis here. Some alternative locations provided in the ANSS-ComCat appear to fit the other data better than the preferred ones in the catalog: The alternate epicenter of the 01/06/20 Mw5.8 earthquake, which was thought to trigger the Mw6.4 earthquake is located within the modeled Mw6.4 fault patch from the observed InSar subsidence (dotted blue rectangle in Fig. 2), discussed below, whereas the published preferred location is 5 km to the south. The alternate epicenter of the Mw5.6 earthquake is located within a cluster of relatively large earthquakes, which followed the Mw6.4 earthquake, whereas the preferred catalog epicenter is on land 14 km to the north, where there were no reports of significant damage (https://earthquake.usgs.gov/earthquakes/eventpage/pr2020007010/dyfi/intensity). The alternate locations of the 12/29/2019 Mw4.7, 01/03/20 Mw4.7, and the 01/10/20 Mw5.2 are also clustered better with other earthquakes on those dates.

The epicenter of small earthquakes in Fig. 2 were relocated using the HypoDD algorithm (Waldhauser & Ellsworth, 2000) using the Puerto Rico Seismic Network (PRSN) P and S arrival pick data between 12/15/2019-08/19/2020. The parameters applied in the relocation were as follows: maximum separation distance of 7 km, minimum observations per event 16, minimum number of pairs 12. With these constraints, 7130 earthquakes were retained for relocation (Vanacore et al., 2021).

4. Observations and modeling

4. 1 Seismic reflection

Seismic reflection profiles crossing the insular slope show patches of surficial sediment cover with a thickness of generally ≤0.05 s except where deposited in depressions on the flanks of canyon interfluves (purple horizon in Fig. 4). The underlying sediments appear more consolidated and are internally separated by unconformities, marked by green (shallower) and red (deeper) unconformities. The unconformities are discontinuous within individual lines, either because of poor acoustic penetration or due to collapse and tilting of small blocks, similar to observations on shore (Monroe, 1980; Renken et al., 2002; Mann et al., 2005). The ages and consistency of the unconformities within and among lines cannot be verified without borehole data. Extrapolation of the lithology encountered in the top 500 m of onshore boreholes (Renken et al., 2002; Trumbull and Garrison, 1973), provides a general guidance to the interpretation of these offshore horizons: Unconsolidated clastic sediments of Pleistocene to Holocene age overlie unconsolidated to poorly-consolidated boulder to clay-size detritus of marl and limestones of Pleistocene to Miocene age, which are in turn underlain by limestone deposited in a brackish to shallow marine environment. This limestone may be equivalent to the Miocene-Pliocene age Ponce Formation (Monroe, 1980). Late Oligocene Juana Diaz Formation of well-bedded shales and sandstones may also be encountered at the base of the seismic section (Monroe, 1980; Kennedy et al., 2015).

The insular shelf platform is typically < 20 m deep, is rimmed by fringing reefs at the shelf edge mantled by patch reefs, cays and pavement encrusted coralline algae, stony corals (Scleractinia) and sponges (Ballantine et al., 2008). The cays and shallow shoals were often hazard to navigation and interfered with data acquisition.

Faults were recognized by offsets of normally continuous sediments or lithified sedimentary units and by diffractions and opaque subvertical zones of reflectivity. The faults are concentrated is specific areas: Most of them are distributed 3.5-7 km seaward of the shelf edge between Guayanilla and Guanica (Fig. 2 and 4). Two additional fault groups were identified, one on the slope SW of Ponce Basin (Fig. 4e), and the second group at distances of 17-21 km from the shelf edge (Fig. 4c). Faults were not identified elsewhere in the survey area, i.e., closer to the shelf edge, and at distances of 7-17 km from the shelf edge. Apparent dips of the mapped faults range from ~45° to sub-vertical. Although fault dips were observed to be variable, adjacent ones may represent a single deep fault with hanging-wall antithetic deformation (e.g., Harding, 1985; Withjack et al., 1995).

Faults or stratigraphic disturbances, not attributable to reefs structures, were encountered on the shelf, cutting surficial sediments (<0.05 s) in several clusters (Fig. 2). Two parallel seismic lines offshore Punta Montalva appear to delineate two fault groups, one in the vicinity of the offshore continuation of Punta Montalva Fault (Fig. 2; Fig 4g, h), and a second one farther south (Fig. 2; Fig 4g, h). Faults on the shelf were also encountered in within (Fig. 4f) and seaward of Guayanilla Bay, as well as south of Playa Santa and La Parguera.

4.2 Surface subsidence and displacement

Subsidence due to the Mw6.4 January 7, 2020 with a maximum of 20 cm was estimated from the combined InSAR time-series fits as described above (Fig. 5). The long axis of the subsidence was oriented in a NE-SW- direction with amplitude increasing offshore. Eyewitnesses reported permanent flooding of parts of El Faro (Fig. 5), a coastal community in Guayanilla, immediately following the Mw6.4 event (C. von Hillebrandt-Andrade, NOAA, , Written Comm., 2020; Pérez-Valentín et al., 2021). Permanent flooding was also documented in other coastal locations in surveys conducted during the week following the earthquake (green dots in Fig. 5; Allstadt et al., 2020). The vertical subsidence was modeled with Coulomb 3.3 software (Toda et al., 2010) assuming an elastic half space and using the in the ANSS-ComCat fault parameters (strike, dip, and seismic moment of 268°, 43°, and 5.04e18 N-m, respectively) for the Mw6.4 earthquake. Modifying the rake, slip, rupture length and top and bottom depths by trial-and-error significantly improved the fit to the observations. The modified parameters include a rake of -72° (-58° in the event page), top and bottom depths of 2 and 10 km, rupture length of 11.3 km, and a uniform slip of 1.265 m. These values are close to Liu et al. (2020) estimated peak slip of 1.6 m and main slip patch between 3-13 km from kinematic inversion of GPS and strong motion data. We assumed a crustal shear modulus of μ = 3e10 Pa. Our model predicts a maximum subsidence of 0.45 cm offshore centered at the upper reach of Guayanilla Canyon (Fig. 5).

Our suggested fault plane also matches the relocated micro-seismicity by Vanacore et al., (2021) from 01/07-08 (the rupture day and the following day) (Inset in Fig. 5). Micro-seismicity on 01/07/20 prior to the Mw6.4 earthquake was <8.5 km depth but extended downward to ~15 km after the event, suggesting that the rupture continued to propagate deeper.

The U.S. Geological Survey (USGS) revised earthquake epicenter falls, however, outside the surface projection of the fault plane, but an alternate epicenter determined by the PRSN, listed in the ANSS-ComCat (17.9578°N, 66.8113°W, Table A1) is located near the bottom edge of the modeled slip patch (Star in Fig. 5 and in inset).

A second much smaller coastal subsidence (≤ 0.04 m) was detected near Playa Santa from the InSAR time-series fit for 07/03/2020 (Fig. 6). This subsidence may be due to the Mw5.3 07/03 and/or the 07/03 Mw5.1 earthquake offshore. The subsidence was accompanied by westward horizontal component west of Playa Santa and an eastward component east of Playa Santa with an amplitude ≤ 8 cm. GPS station PRMI recorded a step in the horizontal displacement components during the observation period with the north component being almost twice as large as the east component (Fig. 6b). We had to assume however, that the horizontal motion in the InSAR anomaly represents the E-W displacement component, because the satellite lines-of-sight are primarily east and west. The vertical and horizontal displacements were jointly forward-modeled using Coulomb 3.3 (Toda et al., 2010) by two crossing strike-slip models (rake=0°), one oriented 250° and dipping 50° and the other oriented 111° (parallel to the Punta Montalva fault) and dipping 85°. Both modeled faults are very shallow, from 0.5 to 3.5 km and from 0.5 to 5 km and have a small slip of 40 and 25 cm respectively. The fit to observations is not as good as that of the Mw6.4 earthquake subsidence despite numerous trials, because (a) the focal mechanism parameters of the 07/03/2020 earthquakes served as poor starting models, (b) the two datasets had to be fit simultaneously, and (c) because the north displacement component is unknown. The fit the subsidence and displacement amplitudes, shown in Fig. 6, required modeled seismic moments that are 4 and 2 times larger than the 8.22e16 N-m and 6. 62e16 N-m earthquakes, respectively of the two 07/03/20. Note also that one of the focal mechanisms is primarily normal whereas the modelled displacements have left-lateral strike slip. The discrepancy may perhaps be explained by additional aseismic deformation or by observational uncertainties in the InSAR data due to the small detected amplitudes.

5. Interpretation

5.1 Progression of seismic activity

Moderate-size (≥ Mw4.5) earthquake activity shows a complex temporal development of both strike-slip and normal faults. We grouped the activity into clusters based on adjacent earthquakes within a span 24 hours of each other. Fig. 2 shows the interpreted color-coded clusters, with their temporal progression following the color spectrum from purple to red (Fig. 2 inset) and the modeled fault planes from InSAR data.

Earthquake activity started SE of Guayanilla on 12/28/19 and advanced to the SE with M ≤5 left-lateral strike-slip focal mechanisms along one or more faults. It triggered an Mw5.8 strike-slip earthquake on 01/06/20. These faults were located at the upper end of the 01/07/20 Mw6.4 fault plane derived from modeling the InSar subsidence (Fig. 5). Additional normal and strike-slip ruptures that day extended the Mw6.4 fault patch to the SE, perhaps along a secondary fault(s). Normal and strike-slip fault ruptures, including an Mw5.9 earthquake, took place along the west and side of the Mw6.4 patch 3-6 days later (1/10-1/13/20) and were accompanied by intense micro-seismicity (not shown). Normal fault ruptures took place along the NE edge of the Mw6.4

rupture plane on 1/20 and east of it on 05/02/20. Strike-slip rupture also initiated 10-15 km west and southwest of the M6.4 patch between 01/14 and 02/04/20 (colored grey). Seismic activity intensified 10-15 km west of the Mw6.4 rupture plane during June-July 2020 with some ruptures probably occurring along the Punta Montalva Fault and others under the shelf. Small coastal subsidence and horizontal motion, detected by InSAR and northwestward motion registered at the GPS site PRMI in La Parguera, were probably caused by a pair Mw5.1 and Mw5.3 earthquakes on of 07/03/2020 (Fig. 6).

Several conclusions can be drawn from this sequence of events: First, the sequence is not a typical foreshock-mainshock-aftershock sequence. We base this inference on two lines of evidence: (a) The magnitudes of the seismic sequence did not follow Båth's Law (i.e., Båth's Law states the largest aftershock is 1-1.2 magnitude levels smaller than the main shock, e.g., Shcherbakov and Turcotte, 2004). (b) The energy released during the Mw6.4 earthquake was only 64% of the total energy released during the seismic sequence, assuming similar stress drop during all the earthquakes.

Second, the area may be crisscrossed by intersecting network of short faults, which were probably activated by the changing stress field caused by the progression of rupture along different faults. Third, the earthquake sequence was probably initiated by strikes-slip fault(s) SE of Guánica, and not by rupture on the Punta Montalva Fault as inititally proposed (López-Venegas et al., 2020), where moderate earthquakes occurred only 6 months later.

5.2 Associating mapped faults with seismic events and fault planes

The faults in the seismic reflection profiles show offsets of tens of meters, which are much larger than the offset expected from the moderate earthquakes in the recent seismic activity, suggesting that they represent long-term displacements. However, the nature of these displacements, such as the exact fault location, dip, strike, and rake, cannot be deduced from the profiles, because shallow deformation in relatively poorly consolidated sediments is often not indicative of fault parameters at depth (e.g., Harding, 1985; Withjack et al., 1995). Nevertheless, we can try to associate the locations of observed faults with specific clusters of earthquakes and with fault planes derived from the InSar data.

Faults were observed on and close to the shelf edge, but rarely on not in deeper water. Their spatial distribution is similar to the spatial distribution of the 2020 seismic sequence, suggesting that earthquake activity in the region is probably limited to the nearshore area. More specifically, the belt of observed faults 3-7 km south of the shelf edge in the seismic data could correspond to the surface projection of the fault plane responsible for the Mw6.4 normal rupture (blue rectangle in Fig. 2) and/or the rupture of subsequent earthquakes within ±24 hours. The faults on the shelf south of Guayanilla Bay could have been caused by displacements along the fault plane responsible for Mw6.4 earthquake (blue rectangle) or by a fault that was reactivated during the 01/20/2020 earthquake cluster (green). The fault in the middle of Guayanilla Bay (Fig. 4F) may be the extension of one of the faults crossing the bay from west to east (Grossman, 1963; J. Joyce, University of Puerto Rico, Written Comm., 2020). A better delineation of this fault is needed because of its location under a population center and critical industrial facilities.

However, the association of other observed faults in the seismic reflection data with the locations of moderate or large earthquakes is less straight forward. Several faults were observed SW of Caja de Muertos Fault and Ponce Basin, but moderate-size seismic activity did not extend to that area. Whether this area is still seismically active, is unknown. One possibility is that these no longer active faults undergo shallow creep induced by nearby large earthquakes existing faults. An example of such phenomenon (although in an active fault) is the observed shallow creep deformation on the Garlock Fault, California, following the Ridgecrest earthquake 5-20 km away (Ross et al., 2019).

On the other hand, observed faults on the seismic data in the western part of our study area were eventually associated with moderate earthquake activity, although not at the time of our data acquisition. For example, with the exception of one Mw5.2 strike-slip earthquake (grey in Fig. 2), seismic activity on the shelf south of Playa Santa and Punta Montalva took place three months after the completion of our survey. Fault mapping is therefore a useful tool to assess the locations of future seismic activity in the area.

5.3 The role of Punta Montalva Fault in the seismic sequence

The Punta Montalva Fault (Roig-Silva et al, 2013) appears to have had a little role in the initiation of the 2020 seismic sequence. The seismic sequence started several km ENE of the southeastern end of the fault (Fig. 2). Moderate-sized strike-slip earthquakes and micro-seismicity took place along the southeastern-most 5-km of the fault during June 2020 (Fig. 2), five months after the largest event. Adames-Corraliza (2017) studied this part of the fault in detail using LIDAR and Ground Penetrating Radar and interpreted it to be active. However, the rest of the 33-km-long proposed fault was not associated with either moderate or micro seismicity during this seismic sequence (e.g., Fig. 2). There was also no seismic reflection evidence for an extension of the fault farther to the SE beyond the shelf edge, a distance of 5-km from the headland (Fig. 2). Hence, the role of the Punta Montalva fault in accommodating the differential block model in SWPR is unknown. An evaluation of the potential seismic activity along the entire 33-km-long strike-slip fault is important because rupture of the entire length can generate an M6.9 earthquake (Wells and Coppersmith, 1994).

6. Discussion

6.1 Longer term tectonic activity

Several lines of evidence indicate that the seismic sequence in SWPR is but the latest episode of a repetitive earthquake cycle, whose recurrence interval is unknown. The extension directions indicated by the T-axis analysis of moderate (M≥4.5) earthquakes from the ANSS-ComCat (329°±10°; Table A1) are similar to those derived by Mann et al. (2005) from the study of terrestrial fault striations in the area (Fig. 7). The extension direction of the terrestrial faults is NW-to NNW, similar to the NW-SE to NNW-SSE (303°-344°) orientation of the T-axis of all the earthquakes. The age of the terrestrial faults is estimated at post-early Pliocene based on cross-cutting relationships with older faults (Mann et al., 2005).

The offsets of many of the mapped faults is at least several tens of meters (Fig. 4). Given the moderate magnitude of earthquakes, the observed slip on these faults cannot be the result of the latest earthquakes alone. Instead, they were likely activated repeatedly accumulating their offsets over many earthquake cycles.

The area of seismic activity is the only part of southern Puerto Rico where the shelf is indented northward, and the shelf edge becomes as narrow as 1 km (Fig. 7). The subsidence model for the Mw6.4 earthquake predicts the location of maximum subsidence to be at the headwaters of this canyon (Fig. 7), and recurrent rupture of this fault could have helped create the shelf indentation in this area.

The bathymetry also shows two NE-oriented bathymetric lineaments that are deeper to the NW despite the general southward dip of the insular slope (dashed blue lines in Fig. 7). These lineaments, and the down-to-the-NW normal displacement of many of the earthquakes' focal mechanisms, including the largest Mw6.4 event, suggest relative subsidence close to shore and relative uplift farther away from shore toward the SE.

The area of seismic activity is the located at the headwaters of the only large submarine canyon along southern Puerto Rico, the Guayanilla Canyon. Given the lack of major terrestrial rivers feeding the canyon system, the canyon system has likely developed to evacuate the sediments of the collapsing shelf edge by repeated normal faulting. The canyon system itself might have partially been affected by the repeated seismic activity, as is evident by the curious right-angle meandering of the eastmost tributary of the canyon. These abrupt meanders may be controlled by subsurface faults (dashed blue lines in Fig. 7). Since submarine morphology typically develops over a long geological time, the presence of the shelf indentation, unique lineaments and meanders are other indicators for a long-term history of seismic activity.

6.2 Diffuse tectonic boundary

The convergence rate and azimuth of the North American Plate with the Caribbean Plate are relatively constant across the span of the 800 km of the Puerto Rico Trench with deviations arising only from local variability in plate boundary orientation (Fig. 1). Nevertheless, seismic coupling appears to vary significantly across the plate boundary. The sector from the longitude of Mona Rift westward (Henceforth, Hispaniola) is associated with several large 20th century earthquakes (e.g., ten Brink et al., 2011), with partitioning of the GPS motion between sub-perpendicular convergence and sub-parallel strike slip, and with the accumulation of large strains on the upper plate (Symithe et al., 2015). The sector east of the longitude of Mona Passage (henceforth, Puerto Rico) is associated with smaller earthquakes, many of them showing oblique slip sub-parallel to the convergence direction (ten Brink, 2005; ten Brink et al., 2011). GPS velocities in Puerto Rico relative to the Caribbean plate are 1/5 those in Hispaniola and show northwestward motion toward the trench (Fig. 1) (ten Brink and Lopez, 2012; Symithe et al., 2015).

The difference in azimuth and magnitude of the GPS velocity between Puerto Rico and Hispaniola suggests the presence of a boundary between the upper plate blocks of Hispaniola and Puerto Rico. This boundary crosses the island arc, but its location and nature are poorly defined. GPS block models provide a relative block motion estimate of 1-5 mm/y (e.g., Symithe et al., 2015). Mann et al., 2002, Manaker et al., 2008, and others suggested that the boundary connects Mona Rift to Yuma Basin. Detailed multibeam bathymetry and seismic reflection mapping show a system of WNW-ESE normal faults with a nested fault-system oriented NW-SE, which indicates NE-SW motion across the boundary (Chaytor and ten Brink, 2010). Ten Brink and

Lopez (2012) using GPS measurements between 2008-2011 noted that stations PRMI in SWPR and MOPR on Mona Island (see Fig. 1 for location) move in the direction of Hispaniola whereas stations farther to the north and to the east move with the direction of the Puerto Rico block. They also noted a seismicity belt extending from Mona Rift to the SE through southwest PR. Solares-Colon (2019) used the F-test to verify the independent motion of SWPR recorded by GPS with respect to the Puerto Rico block, and its similar direction to Mona Island and eastern Hispaniola. The width of the accretionary wedge of Muertos Trough changes significantly at the longitude of the SW corner of PR (Granja-Bruña et al., 2009). The change in the width of the accretionary prism may correspond to the location of the block boundary, assuming that the Muertos accretionary prism is a back-arc wedge of the Puerto Rico-Hispaniola subduction zone (ten Brink et al., 2009).

We propose that the Western Puerto Rico Deformation Boundary (Fig. 1) is driven by variations in seismic coupling on the Puerto Rico subduction interface, with high coupling north of Hispaniola and Mona passage and almost no coupling north of Puerto Rico (Symithe et al., 2015). The deformation boundary may have several deformation domains: Mona rift in the north is a classical rift graben bounded by a fault on its east side and perhaps another one on its west side. Mona Passage farther south exhibits NW-SE series of faults, many of them not organized in a uniform fashion (Chaytor and ten Brink, 2010). Some of these faults may extend eastward on land (Grindlay et al., 2005). SWPR is characterized by subdued topography and east-west valleys (e.g., Lajas Valley) and faults (Prentice, 2005). The recent seismic activity, reported here, describes a NW-SE extension offshore SWPR. It may connect to the Muertos back-arc accretionary wedge, which is significantly wider west of the deformation boundary.

We suggest that the Western Puerto Rico Deformation Boundary is similar to a diffuse zone of deformation observed in the Middle America arc (Marshall et al., 2000), where smooth subducting seafloor offshore Nicaragua and northern Costa Rica changes to a rough seafloor in southern Costa Rica and Panama (Fig. 8). The change affects the rate of convergence and the development of a back-arc accretionary wedge north of Panama, known as the Northern Panama Deformation Belt (NPDB), which overthrusts the Caribbean plate. The Central Costa Rica Deformation Boundary (Marshall et al, 2000) exhibits several faulting domains with different faulting styles, recurring cycles of small and moderate earthquakes, and a change in the magnitude and orientation of the GPS velocity vectors from the Caribbean plate across the zone of diffuse deformation and to the Panama Block. Some of the seismic cycles there have been triggered by large subduction or back-arc earthquakes.

Similar elements are found in Puerto Rico. The smooth sea floor is analogous to the low-coupling trench north of Puerto Rico whereas the rough seafloor is analogous to the trench west of Mona Rift and in Hispaniola. Differential coupling across the subduction zone creates an irregular boundary across the volcanic arc, which exhibits diffuse deformation. The NPDB is a bivergent thrust wedge similar to Muertos Trough (ten Brink et al., 2009).

Alternatively, the seismic sequence of SWPR may perhaps be explained in the context of a slight north-south extension across the island arc, driven by strong coupling between the arc and the interior Caribbean plate and a weak coupling of the arc across the subduction zone to the north (Fig. 9), leading to tilting and collapse of the forearc (ten Brink, 2005). Extension in the southern part of the arc is evident by the basin morphology of Virgin Island Basin and Whiting Basin SE of Puerto Rico, and the possible extension across the Investigator Fault south of Puerto Rico. SWPR also has a unique valley and range-like topography, indicating a relative north-south extension. The continuous pre-2020 high-resolution terrestrial GPS data (Table A2) also appear to indicate opposing roughly N-S motion between pairs of stations across the two blocks in question. The relative motion between western Puerto Rico's GPS station pairs PRMI versus PRLT, MAYZ, and PRJC and between station pairs PRGY and PRJC (Fig. 1) is 1.7±0.6 mm/y N7E° ± 11°.

6.3 Why doesn't the deformation zone mature?

The recent seismic activity shows that despite being subjected to this tectonic/structural regime since perhaps post Early Pliocene, deformation continues to be accommodated along many small faults and has not coalesced into a mature boundary. We can offer several hypotheses to explain this observation. First, the rate of deformation at this boundary is low, perhaps 1-2 mm/y (1-2 km per Ma), and therefore, the coalescence of many faults into one or a couple of major faults may take a lot longer. The slow deformation rate is likely due to the slow rate of convergence between the North American and Caribbean plates. It is worth noting, however, that the Central Costa Rica Deformation Boundary is also considered an immature block boundary despite having more than an order of magnitude faster convergence rate across the Middle America Trench (Marshall et al., 2000). A second and perhaps more plausible hypothesis is that the inherited island arc structure and composition, such as in Puerto Rico (Fig. 3) are anisotropic because the accretion process that built these arcs is fundamentally two dimensional. The anisotropic composition of the arc may promote long along-arc faults, such as strike-slip faults in oblique convergence regimes, and short faults with chaotic orientations at block boundaries across the arc.

7. Conclusions

The Southwestern Puerto Rico (SWPR) seismic sequence ruptured multiple short normal and strike-slip faults along the insular shelf and upper slope of southwest Puerto Rico. The seismic activity included many moderate-size earthquakes over a span of a year and did not follow a typical main shock-aftershock sequence. InSAR-detected coastal subsidence, earthquakes clustered in time and space, and sub-seafloor faults, detected in high-resolution seismic reflection survey, attest to the existence of multiple rupturing faults at different orientations. Despite morphological and structural indicators of a long-term deformation history of similar nature, the deformation does not seem to center on one or more mature fault, perhaps because of the heterogenous composition and structure across the arc. The seismic sequence may be the southernmost domain of a diffuse deformation boundary between the Hispaniola and Puerto Rico blocks, which also includes the domains of SWPR, eastern Mona Passage, and Mona Rift. The diffuse zone, which we name the Western Puerto Rico Deformation Boundary may be analogous to the Central Costa Rica Deformation Boundary and may be driven by variations in subduction coupling along the Puerto Rico Trench.

Acknowledgements and Data

The logistical support of the University of Puerto Rico Department of Marine Sciences in carrying out a rapid response seismic reflection survey only two months after the largest earthquake in the sequence is greatly appreciated. The logistical support included the use of the

R/V Sultana and shore support at the department's shore lab in Isla Magueyes at no cost. We thank Prof. Ernesto Otero, director, and Aldo Acosta, communication specialist, and Captain Orlando Espinoza and his crew for all their generous help. Christa von Hillebrandt, and Victor Huérfano helped facilitate logistical issues. This work contains modified Copernicus data from the Sentinel-1A and -1B satellites provided by the European Space Agency (ESA). Original ALOS-2 data and products are copyright JAXA and provided under JAXA ALOS Research Announcement 6 (RA6). Part of this research was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration and supported by the Earth Surface and Interior focus area. We thank Kate Allstadt and Claudia Flores, USGS, for thorough and helpful reviews. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Earthquake data can be found in ANSS-ComCat https://earthquake.usgs.gov/earthquakes/search/. Supplemental Table A1 lists the catalog parameters of earthquakes with Mw $\geq$ 4.5 including alternative locations, plotted in Fig. 2. GPS data can be found at http://geodesy.unr.edu/magnet.php. Supplemental Table A2 lists the parameters of the stations appearing in Fig. 1. Processed InSAR data can be found in https://aria-share.jpl.nasa.gov/20200106-Puerto_Rico_EQ/Displacements/. Original Copernicus Sentinel-1 data is available at no charge from the Copernicus Sentinels Scientific Data Hub (https://scihub.copernicus.eu/) and is mirrored at the NASA Alaska Satellite Facility archive center https://search.asf.alaska.edu/. Original ALOS-2 data is available from JAXA (https://auig2.jaxa.jp/ips/home). Bathymetry data can be found in https://doi.org/10.25921/ds9v-ky35 and Andrews et al. (2014). For further details see Appendix A3. The seismic reflection data is being prepared for release by the USGS -Woods Hole Science Center.

References

Adames-Corraliza, Á. R. (2017). Geomorphic and geophysical characterization of the north Boquerón Bay-Punta Montalva fault zone: A capable fault system in southwestern Puerto Rico, M.Sc. thesis, 147 pp., Univ. Puerto Rico, Mayaguez.

Allstadt, K.E., Thompson, E.M., Bayouth García, D., Irizarry Brugman, E., Hernandez, J.L., Schmitt, R.G., Hughes, K.S., Fuentes, Z., Martinez, S.N., Cerovski-Darriau, C., Perkins, J.P., Grant, A.R., and Slaughter, S.L., 2020, Field observations of ground failure triggered by the 2020 Puerto Rico earthquake sequence: U.S. Geological Survey data release, https://doi.org/10.5066/P96QNFMB.

Andrews, B.D., U.S. ten Brink, W.W. Danforth, J.D. Chaytor, J-L Granja-Bruna, P. Llanes Estrada, and A. Carbo-Gorosobel (2014) Bathymetric terrain model of the Puerto Rico Trench and Northeast Caribbean for marine geological investigations, USGS OFR 2013-1125.

Ballantine, D. L., R. S. Appeldoorn, P. Yoshioka, E. Weil, R. Armstrong, J.R. Garcia, ... and C. Lilyestrom (2008). Biology and ecology of Puerto Rican coral reefs. In *Coral Reefs of the USA*, pp. 375-406. Springer, Dordrecht

Blewitt, G., W. C. Hammond, and C. Kreemer (2018), Harnessing the GPS data explosion for interdisciplinary science, *Eos,* **99**, https://doi.org/10.1029/2018EO104623

Chaytor, J.D., and U.S. ten Brink (2010). Extension in Mona Passage, Northeast Caribbean, *Tectonophys.* **493** 74-92.

Dascher-Cousineau, K., Lay, T., & Brodsky, E. E. (2020). Two foreshock sequences post Gulia and Wiemer (2019). *Seismol. Soc. Am.* **91** 2843-2850.

DeMets, C., Jansma, P.E., Mattioli, G.S., Dixon, T.H., Farina, F., Bilham, R., Calais, E., Mann, P. (2000). GPS geodetic constraints on Caribbean-North America plate motion. *Geophys. Res. Lett.,* **27** 437–440.

Fielding, E. J., S. S. Sangha, D. P. S. Bekaert, S. V. Samsonov, and J. C. Chang (2017). Surface Deformation of North-Central Oklahoma Related to the 2016 Mw 5.8 Pawnee Earthquake from SAR Interferometry Time Series, *Seism. Res. Lett.* **88** 971-982.

Fielding, E.J., E. Vanacore, and A. López-Venegas (2020) SAR imaging of the coseismic and postseismic deformation from the 2020 southwest Puerto Rico seismic sequence, Geo. Soc. Am. Annual meeting 2020, presentation 139-4.

Garrison, L. E. (1969) Structural geology of the Muertos insular shelf, Puerto Rico US Geological Survey OFR 69-103.

GEBCO Compilation Group. (2020). GEBCO 2020 grid https://doi.org/10.5285/a29c5465-b138-234d-e053-6c86abc040b9

Geist, E.L. and ten Brink, U.S., (2021) Earthquake Magnitude Distributions on Northern Caribbean Faults from Combinatorial Optimization Models, *J. Geophys. Res.,* in Review.

Granja-Bruña, J. L., U. S. ten Brink, A. Carbó-Gorosabel, A. Muñoz-Martín, M. Gómez Ballesteros (2009). Morphotectonics of central Muertos thrust belt and Muertos Trough (northeastern Caribbean), *Mar. Geol.* **263** 7-33. doi:10.1016/j.margeo.2009.03.010.

Grindlay, N. R., L. J. Abrams, L. Del Greco, and P. Mann (2005). Toward an integrated understanding of Holocene fault activity in western Puerto Rico: constraints from high-resolution seismic and sidescan sonar data. Active Tectonics and Seismic Hazards of Puerto Rico, the Virgin Islands, and Offshore Areas, *Geol. Soc. Am Spec. Pap.* **385**, 139-160.

Grossman, I. G., 1963, Geology of the Guanica-Guayanilla Bay area, southwestern Puerto Rico: Art. 29 in *U.S. Geol. Survey Prof. Paper* **475-**B, p. B114-B116

Harding, T. P. (1985). Seismic characteristics and identification of negative flower structures, positive flower structures, and positive structural inversion. *AAPG Bulletin*, ***69***, 582-600.

Kay, C.A. (1957), Notes on the structural geology of Puerto Rico, *Bull. Geol. Soc. Am.* **68** 103-118.

Kennedy, B.R.C., K. Cantwell, D. Sowers, A.M. Quattrini, M. J. Cheadle, and L. McKenna (2015). EX1502 Leg 3 Océano Profundo 2015: Exploring Puerto Rico's Seamounts, Trenches, and Troughs, Expedition Report, NOAA Office of Ocean Exploration and Research, Silver Spring.

Liang, C., and E. J. Fielding (2017), Measuring Azimuth Deformation With L-Band ALOS-2 ScanSAR Interferometry, *IEEE Trans. Geosci. Remote Sensing* **55** 2725-2738, doi:10.1109/TGRS.2017.2653186.

Liu, C., T. Lay, T., Z. Wang, and X. Xiong (2020). Rupture process of the 7 January 2020, MW 6.4 Puerto Rico earthquake. *Geophys. Res. Lett.* **47** e2020GL087718.

López-Venegas, A.M., E. Vanacore, S. K. Hughes (2020a), Puerto Rico's Winter 2019-2020 Seismic Sequence Leaves the Island On Edge, *Temblor*, http://doi.org/10.32858/temblor.064.

López-Venegas, A.M., E. Vanacore, S. K. Hughes, G. Báez- Sánchez, and T. R. Hudgins (2020b), Response and initial scientific findings from the southwestern Puerto Rico Seismic Sequence" (2020), *Temblor*, http://doi.org/10.32858/temblor.068.

Manaker, D. M., E. Calais, A. M. Freed, S. T. Ali, P. Przybylski, G. Mattioli, P. Jansma, C. Prépetit, and J. B. De Chabalier (2008), Interseismic Plate coupling and strain partitioning in the Northeastern Caribbean, *Geophys. J. Int.* **174** 889-903 246X.2008.03819.x.

Mann, P., E. Calais, J.-C. Ruegg, C. DeMets, and P.E. Jansma, (2002) Oblique collision in the north-eastern Caribbean from GPS measurements and geological observations. *Tectonics* **21** 7-1.http://dx.doi.org/10.1029/2001TC0011304.

Mann, P., J. C. Hippolyte, N. R. Grindlay, and L. J. Abrams, (2005). Neotectonics of southern Puerto Rico and its offshore margin. Active tectonics and seismic hazards of Puerto Rico, the Virgin Islands, and offshore areas, *Geol. Soc. Am Spec. Pap.* **385**, 173-214.

Marshall, J.S., D.M. Fisher, and T.W. Gardner (2000) Central Costa Rica deformed belt: Kinematics of diffuse faulting across the western Panama block. *Tectonics* **19** 468-492.

Miranda, E. et al. (16 authors) StEER Puerto Rico M6.4 earthquake 7 January 2020 preliminary virtual reconnaissance report (PVRR), NHERI DesignSafe Project ID: PRJ-2670,Released: January 10, 2020

Monroe, W. H. (1980). Geology of the middle Tertiary formations of Puerto Rico U.S. Geological Survey Prof. Pap 953.

Morales-Velez, A.C., J. Bernal, K.S. Hughs, M. Pando, J.C. Perez, L.A. Rodriguez, and L.E. Suarez, Geotechnical Reconnaissance of the January 7, 2020 M6.4 Southwest Puerto Rico Earthquake and Associated Seismic Sequence, Geotechnical Extreme Event Reconnaissance Report (GEER)-066. June 26, 2020.

Pérez-Valentín, K., Barreto-Orta, M., Castro, A., Montañez-Acuña, A., and Cabrera-Valentín, N. (2021). Revealing geomorphic changes after the occurrence of a seismic event on the south coast of Puerto Rico (2020), *Shore and Beach*, **89**, 22-33.

Piety, L. A., J. R. Redwine, S. A. Derouin, C. S. Prentice, K. I. Kelson, R. E. Klinger, and S. Mahan (2018) Holocene Surface Ruptures on the Salinas Fault and Southeastern Great Southern Puerto Rico Fault Zone, South Coastal Plain of Puerto Rico, *Bulletin of the Seismological Society of America*, **108** 619–638, doi: 10.1785/0120170182

Prentice, C. S., and P. Mann (2005). Paleoseismic study of the South Lajas fault: First documentation of an onshore Holocene fault in Puerto Rico, *Geol. Soc. Am. Spec. Pap.* **385** 215–222.

Renken, R. A., B. A. Black, W. C. Ward, I. P. Gill, F. Gómez-Gómez, and J. Rodríguez-Martínez (2002). Geology and hydrogeology of the Caribbean islands aquifer system of the commonwealth of Puerto Rico and the US Virgin Islands. US Geological Survey Prof. Pap. 1419.

Roig-Silva, C. M., E. Asencio, and J. Joyce (2013). The northwest trending North Boquerón Bay-Punta Montalva fault zone—A through going active fault system in southwestern Puerto Rico, *Seismol. Res. Lett.* **84** 538–550.

Rosen, P. A., E. Gurrola, G. F. Sacco, and H. Zebker (2012), The InSAR Scientific Computing Environment, paper presented at 9th European Conference on Synthetic Aperture Radar, Nuremberg, Germany, 23-26 April.

Ross, Z. E., B. Idini, Z. Jia, O. L. Stephenson, M. Zhong, X. Wang, ... and J. Jung (2019). Hierarchical interlocked orthogonal faulting in the 2019 Ridgecrest earthquake sequence. *Science* ***366*** 346-351

Shcherbakov, R. and D.L. Turcotte (2004). A modified form of Bath's law. Bull. Seismol. Soc. Am. ***94*** 1968-1975.

Solares-Colón, M.M., (2019), New Constraints on Crustal Deformation Within the Puerto Rico-Virgin Islands Microplate Using Two Decades of GPS Data, Ms.C. thesis, University of Puerto Rico, Mayaguez.

Symithe, S., E. Calais, J. B. de Chabalier, R. Robertson, and M. Higgins (2015), Current block motions and strain accumulation on active faults in the Caribbean, *J. Geophys. Res.: Solid Earth*, **120** 3748-3774 https://doi.org/10.1002/2014JB011779.

ten Brink, U.S. (2005). Vertical motions in the Puerto Rico trench and Puerto Rico and their cause, *J. Geophys. Res.* **110**, B06404, doi:10.1020/2004JB003459.

ten Brink, U.S., S. Marshak, and J.-L. Granja Bruña, (2009). Bivergent thrust wedges surrounding oceanic island arcs: Insight from observations and sandbox models of the northeastern Caribbean plate, *Geol. Soc. Am. Bull.* **121** 1522-1536. doi:10.1130/B26512.1.

ten Brink, U.S., W.H. Bakun, and C.H. Flores (2011). Historical perspective on seismic hazard to Hispaniola and the NE Caribbean, *J. Geophys. Res.* **116**, B12318, doi:10.1029/2011JB008497.

ten Brink, U.S., and Lopez-Venegas, A.M. (2012). Plate interaction in the NE Caribbean subduction zone from continuous GPS observations, *Geophys., Res. Lett*. **39**, L10304, doi:10.1029/2012GL051485.

Toda, S., Stein, R.S., Sevilgen, V., and Lin, J., 2011, Coulomb 3.3 Graphic-rich deformation and stress-change software for earthquake, tectonic, and volcano research and teaching—user guide: U.S. Geological Survey Open-File Report 2011–1060, 63 p.

Trumbull, J. V. and L.E. Garrison (1973) Geology of a system of submarine canyons south of Puerto Rico. *J. Res. U.S. Geol. Sur.* **1** 293-299.

Vanacore, E. A., Joyce, J., ten Brink, U., Fielding, E. J., Lopez-Venegas, A. (2021) Double Difference relocations of the Southwestern Puerto Rico Seismic Sequence, *Seis. Res. Lett.,* 92, 1444.

von Hillebrandt-Andrade, C. G, A. López, E. Vanacore (2020), 2019-2020 Southwestern Puerto Rico Seismic Sequence, *TsuInfo Alert*, **22**, no. 1.

Waldhauser, F., & Ellsworth, W. L. (2000). A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, California. Bulletin of the Seismological Society of America, 90(6), 1353-1368.

Wells, D.L., and K.J. Coppersmith (1994) New Empirical Relationships among Magnitude, Rupture Width, Rupture Area, and Surface Displacement, Seismol. Soc. Am. 84 974–1002.

Withjack, M. O., Q. T. Islam and P.R. La Pointe (1995). Normal faults and their hanging-wall deformation: an experimental study. *AAPG bull.* **79** 1-17.

Wright, T. J., B. E. Parsons, and Z. Lu (2004). Toward mapping surface deformation in three dimensions using InSAR, Geophysical Research Letters **31** L01607.

Yunjun, Z., H. Fattahi, and F. Amelung (2019), Small baseline InSAR time series analysis: Unwrapping error correction and noise reduction, *Computers & Geosciences* **133** 104331, doi:10.1016/j.cageo.2019.104331.

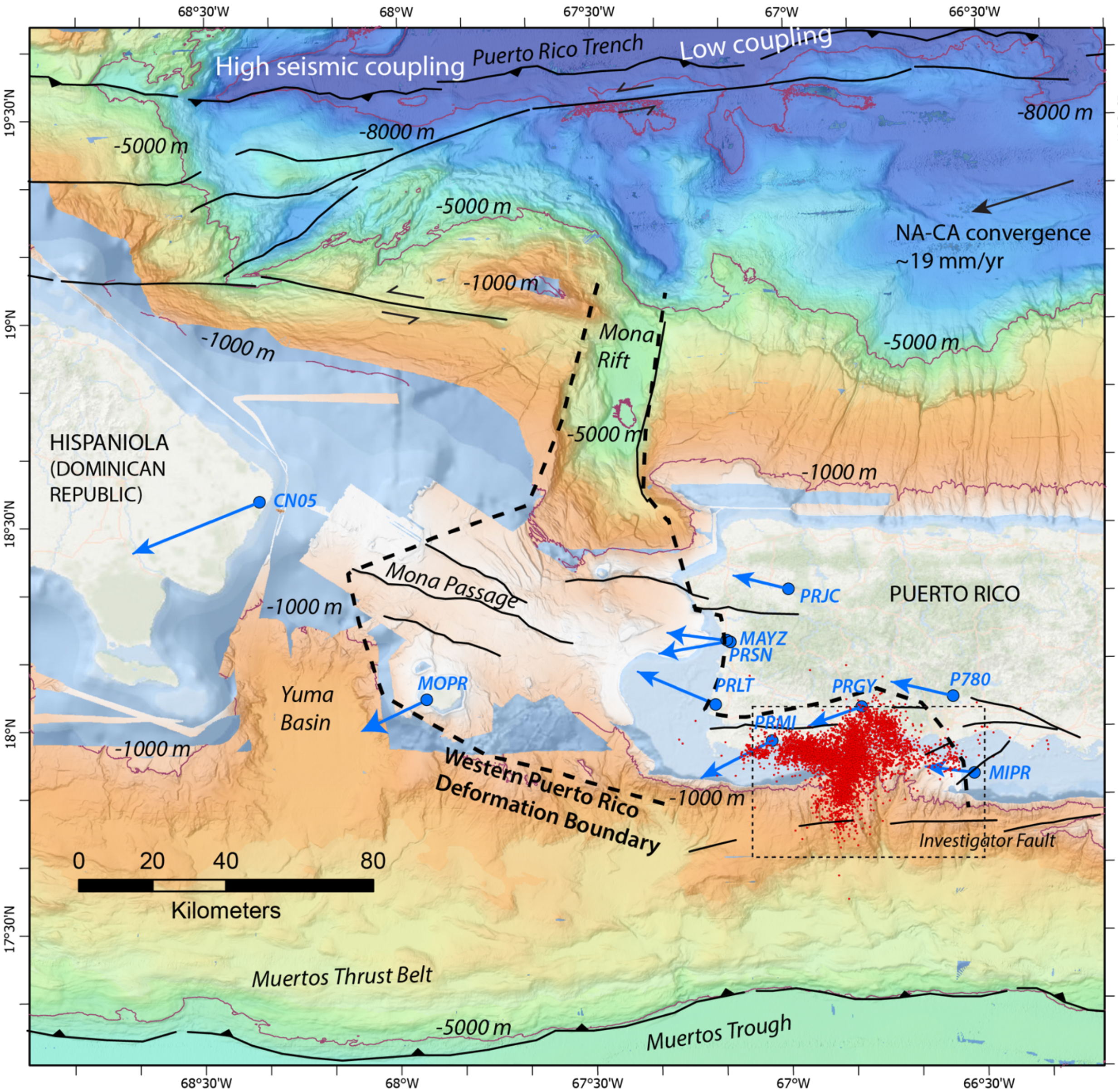


Figure 1. *Regional map. Shaded multibeam bathymetry (Andrews et al., 2014) colored by water depth with selected depth contours (thin purple lines. Areas without multibeam bathymetry from GEBCO global bathymetry and are shaded light blue. Red dots – M ≥ 2.5 earthquakes in the SWPR seismic sequence from ANSS-ComCat. Black lines – Major faults after Geist and ten Brink, 2021). Blue lines- GPS vectors with length proportional to long-term displacement rate relative to fixed Caribbean plate (Table A2). Area between dashed lines is our proposed Western Puerto Rico Deformation Boundary. dotted black rectangle – Location of Fig. 2.*

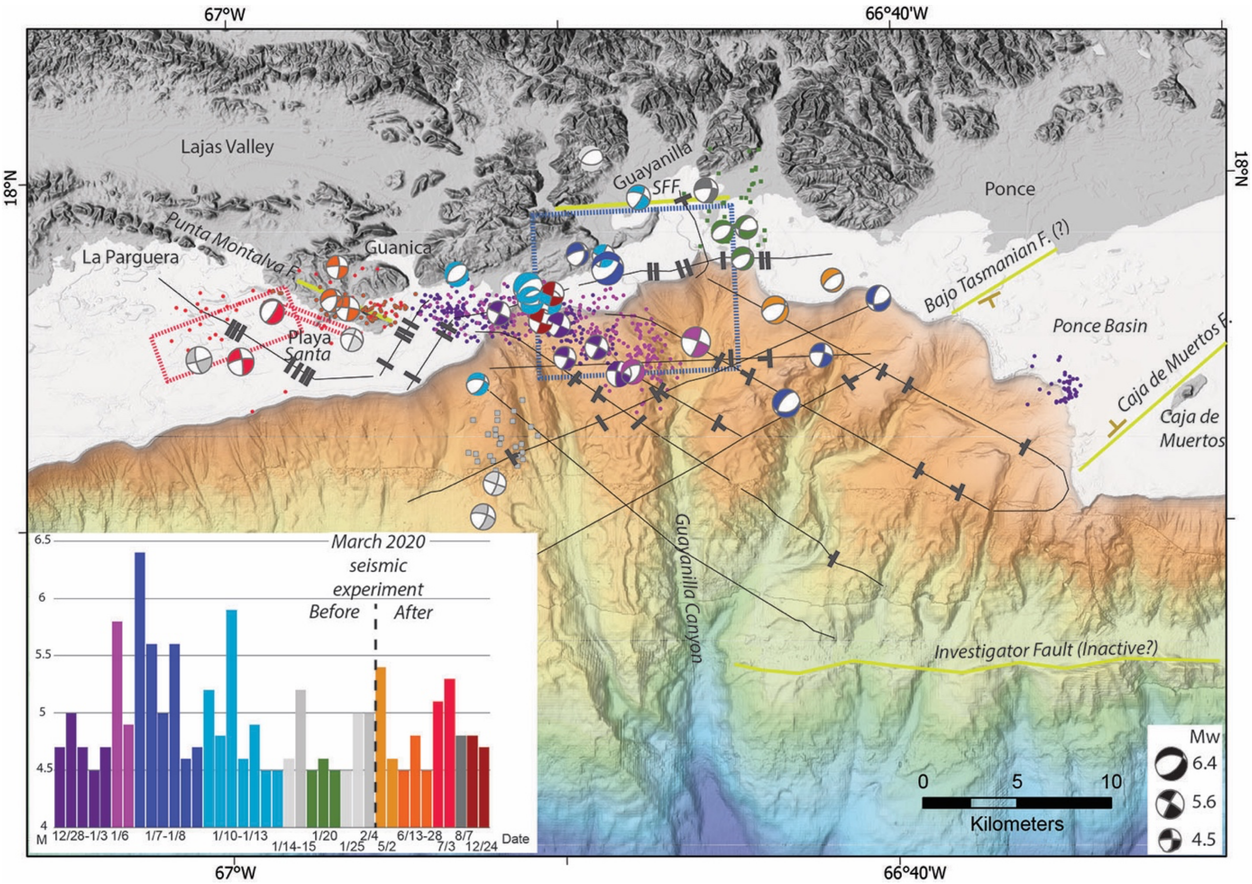


Figure 2. *Locations and focal mechanisms of Mw≥4.5 earthquake clusters (from ANSS-ComCat) colored by date. Inset shows dates of the clusters and color code. Grey earthquakes are moderate earthquakes not associated with a cluster. Some alternate epicenters from the catalog are shown, as discussed in the text and listed in Table A1. Colored dots – Relocated microseismicity using HypoDD (Vanacore et al, 2021) for a few selected dates, with colors matching the dates of focal mechanisms and the inset. Thin lines – locations of seismic reflection profiles collected between 03/07-03/13/2020, Heavy black marks – Faults interpreted from the seismic reflection profiles with small perpendicular marks denoting apparent dip direction. Dotted rectangles – Modeled fault planes from the InSAR observations (Fig. 5 and 6) with colors matching the dates of the focal mechanisms and inset. Yellow lines – published faults.*

Background – Shaded bathymetry colored by depth (white -1 0m to blue – 2000 m) and SRTM hill-shaded topography (grey). SFF – San Francisco Fault.

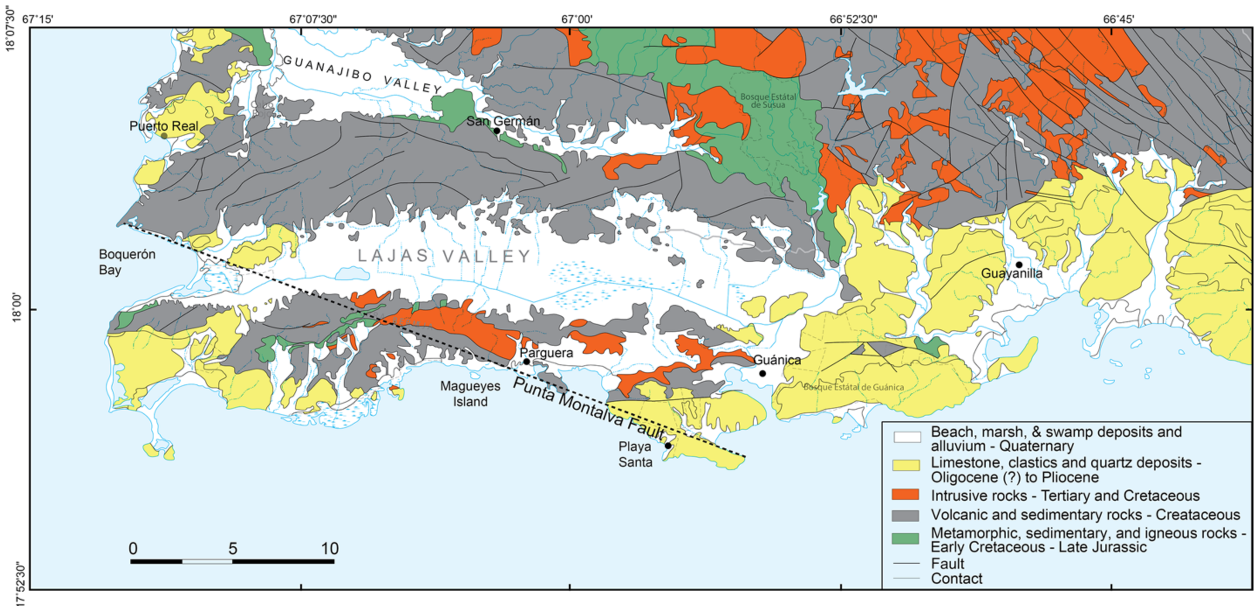


Figure 3. *Simplified geological map of SWPR modified from Renken et al., (2002). Note that basement rocks (orange, grey and green) do not align along a N-S axis. Dotted line – proposed 33-km-long Punta Montalva Fault by Roig-Silva et al., (2013).*

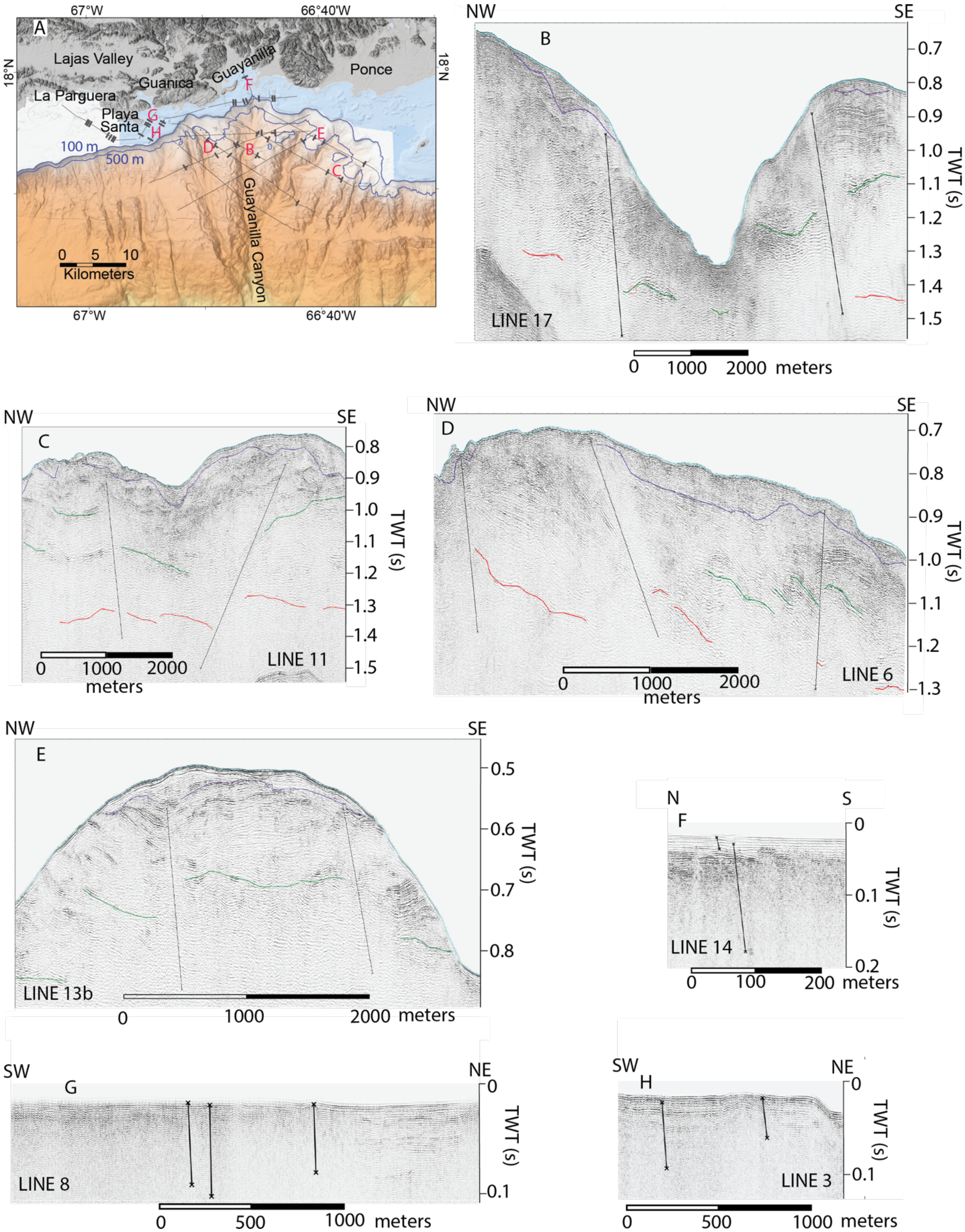

A
67°W
66°40'W
18°N
Lajas Valley
Guanica
Guayanilla
Ponce
La Parguera
Playa
Santa
G
H
F
D
B
E
C
100 m
500 m
Guayanilla Canyon
0 5 10
Kilometers
NW
SE
B
LINE 17
TWT (s)
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
0 1000 2000 meters
C
LINE 11
0 1000 2000
meters
D
LINE 6
E
LINE 13b
N
S
F
LINE 14
0 100 200 meters
SW
NE
G
LINE 8
0 500 1000 meters
H
LINE 3

Figure 4. *A – Location map of the seismic records. Thin lines – locations of seismic reflection profiles. Heavy black marks – Faults identified on the seismic reflection profiles with small perpendicular marks denoting dip direction. Blue lines – 100 and 500 m contours of water depth, above which limited sound source output was limited. B, C, D, E - Portions of selected high-resolution seismic profiles on the insular slope. F, G, H - Same on the shelf. Colored horizons are interpretation of unconformities. Purple horizon separates a possible unconsolidated Pleistocene and Holocene sediment from the underlying consolidated Late Oligoene(?) to Pleistocene limestones and perhaps sandstone and shale. Assuming a sub-seafloor seismic velocity of 2000 m/s, 100 milliseconds of two-way travel time (TWT) corresponds roughly to 100 m in the sub-seafloor.*

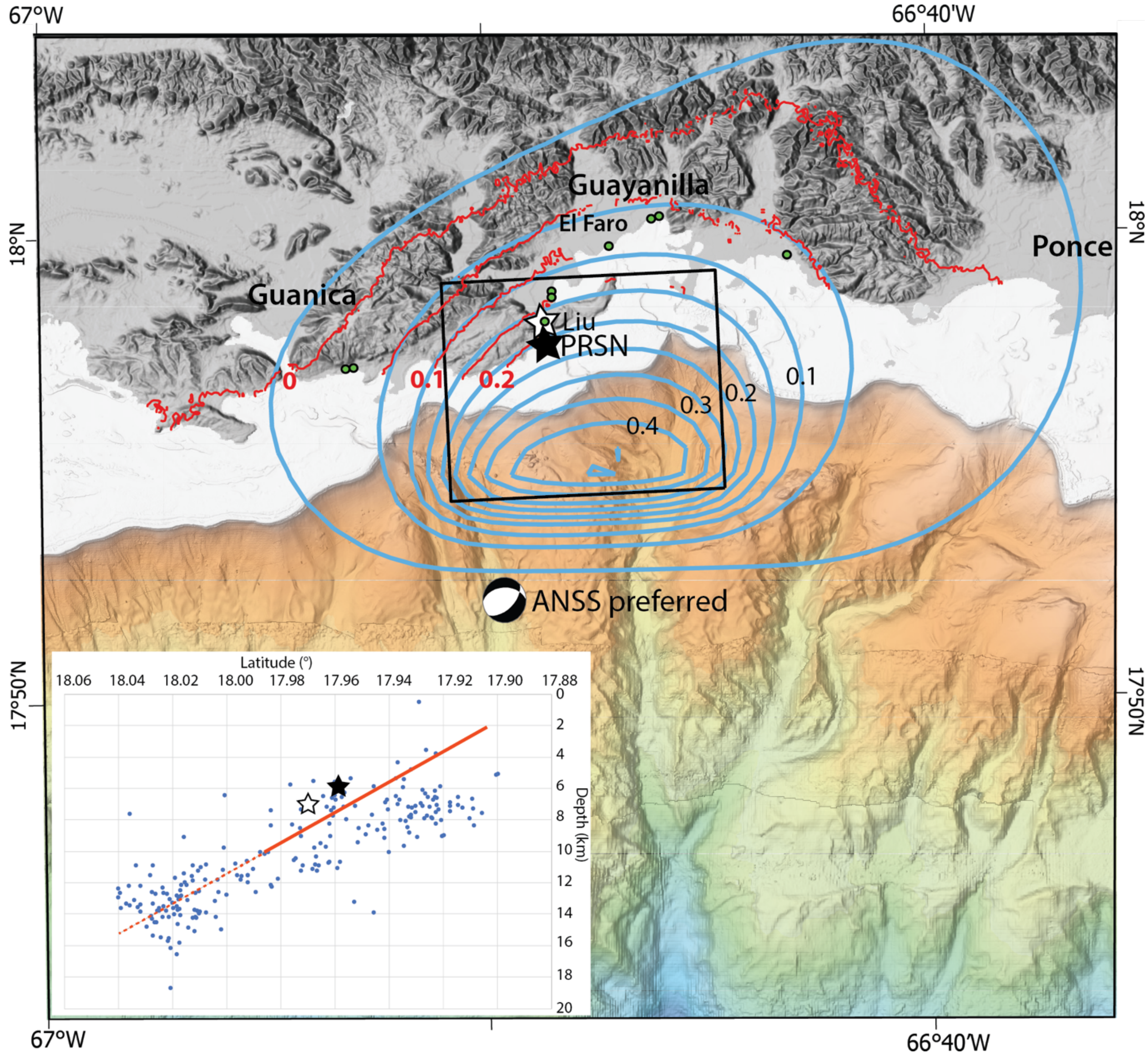
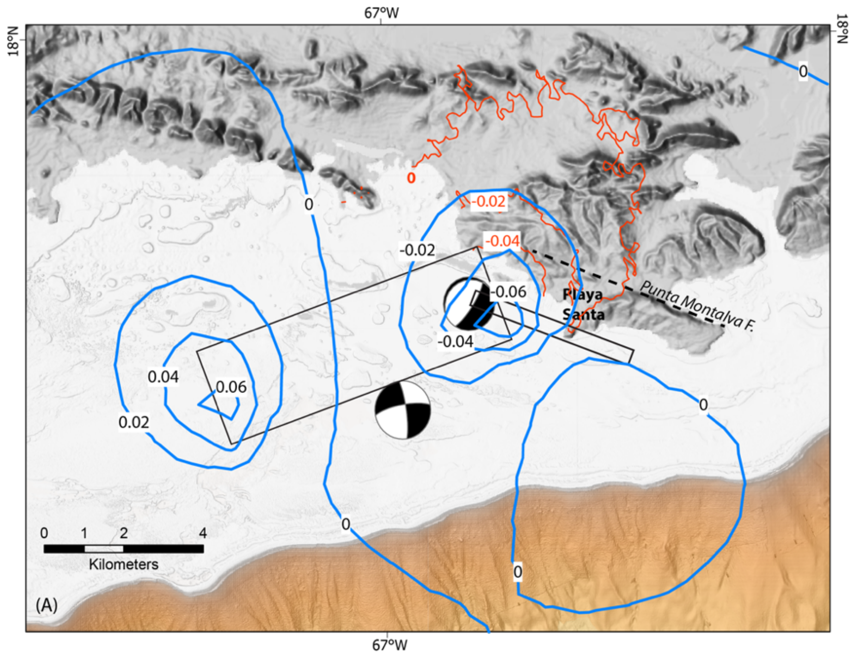


Figure 5. *Comparison between InSAR subsidence observations for the period* 01/02-01/14/2020 ***(****red contours) and subsidence modeling (blue contours). Contour interval for both is 0.05 m. Black rectangle -Surface projection of the modeled fault plane. The fault plane dips 43° to the north. See text for modeled fault parameters. Note that the preferred epicenter in the ANSS-ComCat is 5 km south of the updip edge of the fault plane, whereas the PRSN epicenter is located toward the bottom of the fault patch. Liu – Liu et al. (2020) epicenter (*17.97°N, 66.81°W). *Green dots – reported locations of coastal subsidence following the earthquake. Inset*

-*Projection of relocated small earthquakes by* Vanacore et al. (2021) *occurring within the longitudes of the modeled fault patch during 01/07-01/08/2020. Red line is our modeled fault plane. Dashed red line is an extrapolation to deeper depths. Black and white stars - Projected hypocenters of PRSN and Liu et al. respectively.*



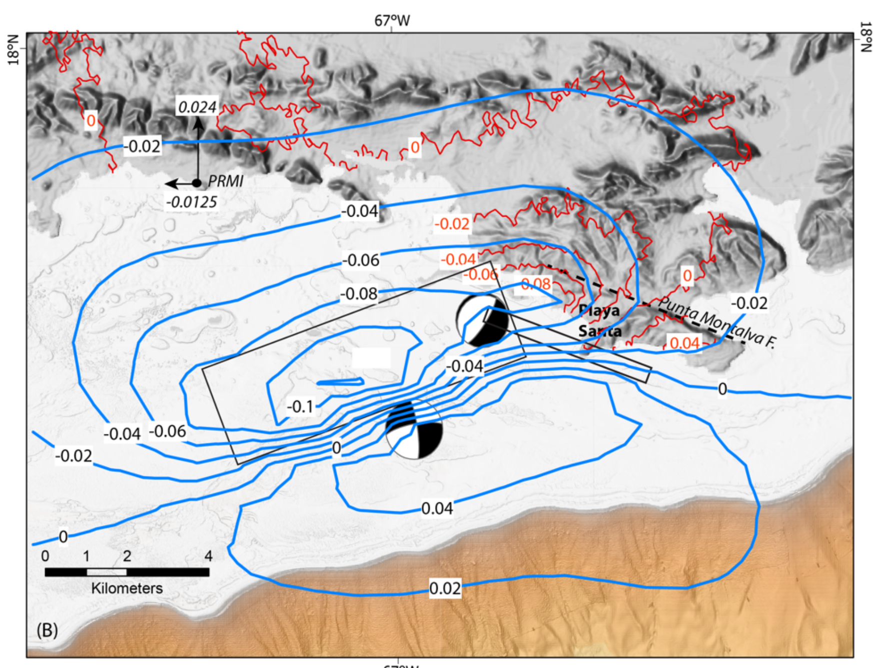


Figure 6. *(A) Comparison between InSAR subsidence observations possibly related to the 07/03 Mw5.1 and 5.3 earthquakes* **(***Red contours) and modeled subsidence (blue contours). Contour interval for both is 0.02 m. Black rectangles - Surface projection of the modeled fault planes. Fault planes dip to the NW and the NE. See text for modeled fault parameters. Focal mechanisms for the two* 07/03/2020 *earthquakes are from ANSS-ComCat. The catalog's preferred locations are outside the modeled fault planes, about 1.5 km away, and the locations plotted here are Pacific Tsunami Warning Center epicenters listed in the catalog. (B) Same for the east component of displacement (east is positive). Estimated horizontal displacement was assumed to represent the east component of the displacement, because of the Line-of-sight orientation of the satellites at this latitude. Abrupt displacement on 07/03 recorded at GPS station PRMI shows that the north component is almost twice as large as the east component (B), which we did not model.*

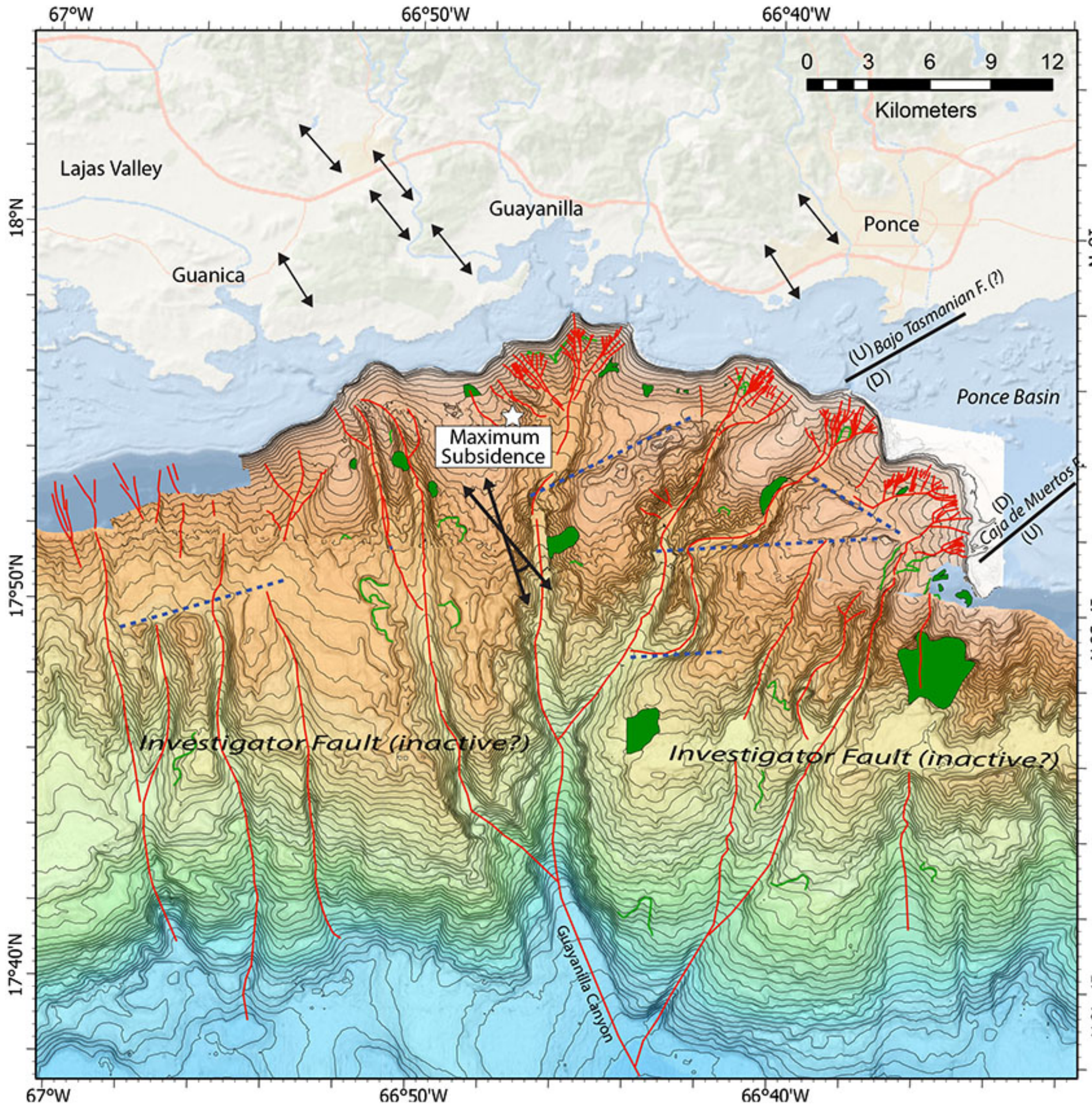


Figure 7. Compilation of evidence suggestive of long-term seismic activity in the study area. Dark double-sided arrows – Extension directivity of a range of T-axes for Mw>4.5 earthquakes in the seismic sequence (shown offshore) (See Table A1), and terrestrial post Early-Pliocene faults (Mann et al., 2005). Star - Center of modeled subsidence in Fig. 5. Blue dashed lines - Seafloor lineaments disrupting drainage on an otherwise general southward slope indicating possible tectonic control. Red lines – Thalwegs of the drainage system. Green areas – Landslide

scars. Green lines – Landslide scarps. Guayanilla Canyon is the only large submarine canyon along southern Puerto Rico, and it eroded the shelf to within 1 km from shore. Black lines – published faults and their sense of motion (after Garrison, 1969).

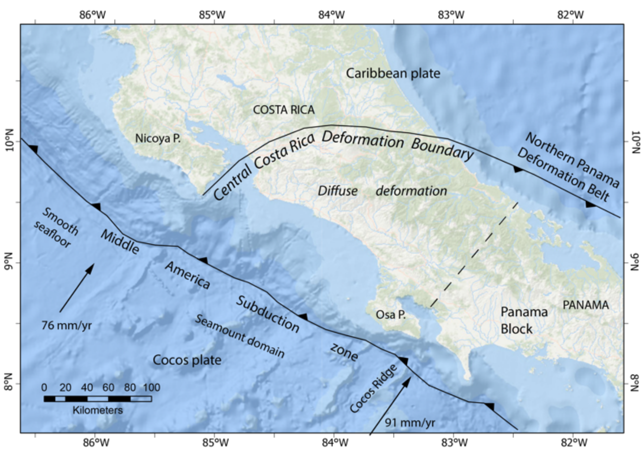


Figure 8. *Simplified map of the Central Costa Rica Deformation Boundary (Marshall et al, 2000), a diffuse block boundary, an analogous setting to the Western Puerto Rico Deformation Boundary.*

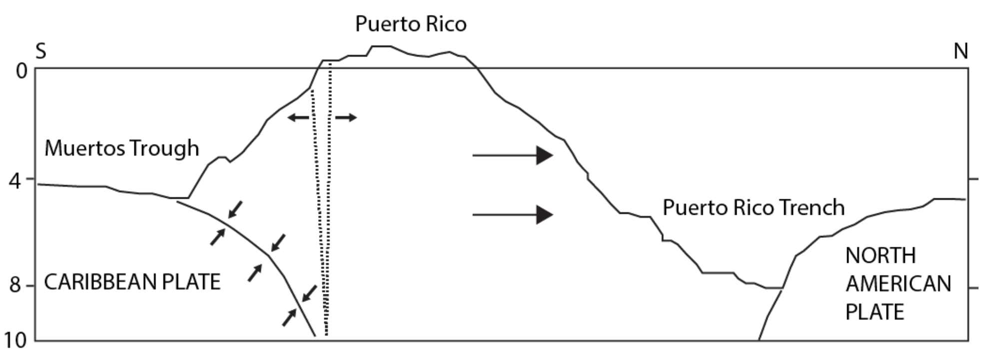


Figure 9. *An alternative explanation to the recent seismic activity in which fusion of the southern edge of the Puerto Rico block with the Caribbean plate may cause extension to develop along southwest Puerto Rico.*

Supplemental material for the article

Mature diffuse tectonic block boundary revealed by the 2020 southwestern Puerto Rico seismic sequence

By U.S. ten Brink, L. Vanacore, E.J. Fielding, J.D. Chaytor, A.M. López-Venegas, W. Baldwin[1], D. Foster, B.D. Andrews

The supplemental material includes lists of earthquake and GPS data plotted in Figures 1 and 2 and a list of bathymetry sources used to make the background bathymetry in Figures 1, 2, 4A, 5, 6, and 7.

Table A1 Mw≥4.5 from the ANSS-ComCat (https://earthquake.usgs.gov/earthquakes/search/) shown in Figure 2

yrmodayhrmin	Pref. lon (°W)	Pref. lat (°N)	Alt lon (°W)	Alt Lat (°N)	Moment (N-m)	Mw	Depth (km)	T axis (°)
201912282235	66.866	17.937			1.15E+16	4.7	6	340
201912290106	66.864	17.885	66.806	17.907	2.29E+16	5	6	156
201912290121	66.836	17.931			1.46E+16	4.7	3	341
202001022042	66.833	17.915			6.84E+15	4.5	7	333
202001030341	66.826	17.901	66.817	17.920	1.68E+16	4.7	2	161
202001061032	66.819	17.868	66.767	17.922	3.17E+17	5.8	6	156
200001061451	66.799	17.908			8.71E+15	4.9	6	318
202001070824	66.827	17.869	66.811	17.958	5.04E+18	6.4	9	156

202001070834	66.722	17.892			3.11E+17	5.6	10	325
202001070850	66.675	17.942			3.54E+16	5	10	313
202001071118	66.776	18.022	66.747	17.919	3.63E+17	5.6	9	164
202001071627	66.826	17.965			4.52E+15	4.6	8	320
202001082004	66.704	17.915			6.38E+15	4.7	6	147
202001102226	66.883	17.935	66.850	17.943	5.82E+16	5.2	9	161
202001110228	66.795	17.992			1.15E+16	4.8	4	158
202001111254	66.851	17.949			1.06E+18	5.9	5	339
202001112349	66.840	17.942			7.85E+15	4.6	8	325
202001120759	66.887	17.956			7.33E+15	4.9	8	143
202001121055	66.877	17.903			2.52E+15	4.5	7	335
202001130520	66.813	17.964			6.60E+15	4.5	9	335
202001141226	66.869	17.855			1.87E+16	4.6	10	336
202001151536	67.017	17.916			4.87E+16	5.2	5	123
202001200526	66.741	17.977			5.76E+15	4.5	7	157
202001200936	66.753	17.975			3.43E+15	4.6	7	149
202001201514	66.743	17.962			4.52E+15	4.5	14	327
202001250800	66.940	17.925			2.25E+15	4.5	6	152
202001252020	66.819	18.011			1.41E+16	5	13	164
202002041455	66.875	17.839			2.92E+16	5	7	153
202005021113	66.727	17.937			1.38E+17	5.4	9	332
202005021119	66.698	17.951			5.76E+15	4.6	7	325
202006130552	66.947	17.960			3.09E+15	4.5	9	317

202006280642	66.942	17.940			2.04E+16	4.8	11	322
202006282248	66.950	17.944			2.79E+15	4.5	13	315
202007031354	67.004	17.944	66.980	17.939	6.62E+16	4.9	6	129
202007032049	67.005	17.900	66.996	17.915	8.22E+16	5.3	3	126
202008070327	66.761	17.995			1.11E+16	4.8	12	325
202012241656	66.845	17.933			1.23E+16	4.8	6	334
202012241733	66.839	17.946			3.42E+15	4.7	9	328

Note: Pref. longitude and latitude are the preferred location provided in the catalog. Alt lon and lat are alternative locations listed for these events

Table A2. GPS motion relative to a fixed Caribbean plate from the MAGNET GPS network (http://geodesy.unr.edu/magnet.php) shown in Figure 1

Station	Long (°W)	Lat (°N)	speed (mm/y)	Azimuth (°)	East	North	SD East	SD North	Start & end dates
CN05	68.359	18.564	4.641	248	-4.310	-1.721	1.64	1.64	2014-2020
MOPR	67.931	18.077	2.508	245	-2.268	-1.071	2.16	2.05	10/08-8/11 11/14-8/16
PRMI	67.045	17.97	2.728	243	-2.432	-1.236	1.59	2.12	2016-2015
PRGY	66.814	18.051	1.907	251	-1.804	-0.618	2.57	3.24	2011-2019
MAYZ	67.159	18.218	2.042	278	-2.023	0.276	1.88	3.13	2010-2015
PRSN	67.145	18.217	2.528	261	-2.493	-0.417	2.20	2.92	2015-2019
PRLT	67.189	18.060	2.885	293	-2.604	1.126	2.05	2.41	2010-2019

PRJC	66.999	18.342	1.936	284	-1.876	0.479	2.22	2.23	2010-2019
MIPR	66.527	17.886	1.679	278	-1.663	0.228	1.52	1.68	2008-2016
P780	66.579	18.075	2.159	284	-2.099	0.509	1.94	2.17	2008-2018

Notes: 1. Data from 2020 was excluded from the stations in Puerto Rico, because of an observed displacement step(s) in response to the seismic sequence.

2. SD – Standard Deviation

Appendix A3 – Bathymetry sources used to plot Figures 1, 2, 4A, 5, 6, and 7

Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado, Boulder. 2014: Continuously Updated Digital Elevation Model (CUDEM) - 1/9 Arc-Second Resolution Bathymetric-Topographic Tiles. [customized subset download bound by coordinates 67.125 W, 18.166 N, 66.125 W, and 17.751 N]. NOAA National Centers for Environmental Information, accessed March 16, 2021, at https://doi.org/10.25921/ds9v-ky35.

National Oceanic and Atmospheric Administration, 2006, Descriptive report, habitat and hydrographic mapping survey WH00200, Puerto Rico, Northeast Caribbean Sea, vicinity of La Parguera: National Oceanic and Atmospheric Administration descriptive report, variously paged, accessed March 16, 2021, at https://www.ngdc.noaa.gov/nos/W00001-W02000/W00200.html.

National Oceanic and Atmospheric Administration, 2016, Descriptive report, navigable area mapping survey H12935, Puerto Rico, Caribbean Sea, southeast coast of Puerto Rico: National

Oceanic and Atmospheric Administration descriptive report, variously paged, accessed March 16, 2021, at https://www.ngdc.noaa.gov/nos/H12001-H14000/H12935.html.

National Oceanic and Atmospheric Administration, 2018a, Descriptive report, habitat mapping survey WH00468, Puerto Rico, Northeast Caribbean Sea, vicinity of Guanica and Ponce: National Oceanic and Atmospheric Administration descriptive report, variously paged, accessed March 16, 2021, at https://www.ngdc.noaa.gov/nos/W00001-W02000/W00468.html.

National Oceanic and Atmospheric Administration, 2018b, Descriptive report, navigable area mapping survey H13143, Puerto Rico, San Juan and Ponce vicinities, Bahia de Ponce: National Oceanic and Atmospheric Administration descriptive report, variously paged, accessed March 16, 2021, at https://www.ngdc.noaa.gov/nos/H12001-H14000/H13143.html.

National Oceanic and Atmospheric Administration, 2018c, Descriptive report, navigable area mapping survey H13144, Puerto Rico, San Juan and Ponce vicinities, 8.5 NM SE of Bahia de Ponce: National Oceanic and Atmospheric Administration descriptive report, variously paged, accessed March 16, 2021, at https://www.ngdc.noaa.gov/nos/H12001-H14000/H13144.html.