# EARTHQUAKE EXPERIENCE IN PUERTO RICO AND THE CARIBBEAN: LESSONS AND WHAT WE HAVE LEARN FROM THEM IN THE LAST TWO DECADES[1]

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**ABSTRACT:** The Commonwealth of Puerto Rico, an unincorporated territory of the United States, and the smallest island of the Greater Antilles, is approximately 200 km by 60 km; it is also the island with the highest population densities within the Caribbean region. Several historical earthquakes have caused extensive damage to Puerto Rico and have generated Tsunami. There is a great concern to many geophysicists who believe that the subduction zone (Puerto Rico Trench) may be due for a major event because it has not ruptured in over 200 years. This research provides a description of the Peak Ground Acceleration (PGA) and instrumental Intensity (IMMI) distribution of significant moderate magnitude ($5.0 \leq M \leq 6.4$) earthquakes, the temporal-spatial patterns of the regional and local seismicity, within Puerto Rico Island (PRI) occurred during the last two decades, the lessons we have learned from them, and their association with the known mapped faults and the historical earthquakes ($M \geq 7.0$), as well as to the un-known faults and the earthquake epicentral clusters within the PRI and Caribbean region. In addition, the tectonic frame and faults of the region and the Puerto Rico Strong Motion Program (PRSMP) seismic network instruments coverage and distribution is provided. Finally, it was found the most recent Puerto Rico Seismic Hazard Map (2003), contained in the current building code, does not take into account the multiple partially studied active seismic faults that were found within the Island and that at least one of them could generate magnitude 7.5 earthquakes. Update the PRI Seismic Hazard Map considering the new identified active faults and the new findings of the seismic studies and the local site effects is plenty justified.

**Keywords:** 2020-Indios-earthquake, 2010-Moca-earthquake, 2014-Puerto-Rico-earthquake, Peak-Ground-Acceleration, Earthquake catalog

# EXPERIENCIA DE SISMOS EN PUERTO RICO Y LA REGIÓN DEL CARIBE: LECCIONES Y LO QUE SE HA APRENDIDO DE ELLOS EN LAS ÚLTIMAS DOS DÉCADAS

**RESUMEN:** El Estado Libre Asociado de Puerto Rico, territorio no-incorporado de los Estados Unidos de Norteamérica, es la isla más pequeña de las Antillas Mayores, mide aproximadamente 200 km por 60 km y es además la isla con la mayor densidad de población dentro de la región del Caribe. Varios sismos históricos de gran magnitud ($M \geq 7$) que han generado Tsunami, han causado graves y extensos daños a la isla. Existe una preocupación generalizada por la comunidad de geofísicos que consideran que la zona de subducción de la trinchera de Puerto Rico está propensa a la ocurrencia de un evento mayor porque no ha roto en más de 200 años. Esta investigación presenta la descripción de los valores máximos de aceleración e intensidades instrumentales (MMI) debido a sismos de magnitud moderada ($5.0 \leq M \leq 6.4$), el patrón de la distribución espacio-temporal de la sismicidad regional y local en la Isla de Puerto Rico (IPR) que ha ocurrido en las últimas dos décadas, las lecciones que se han aprendido de ellos, y su asociación con la fallas mapeadas y conocidas y los sismos históricos significativos ($M \geq 7$), así como las fallas estudiadas parcialmente o desconocidas y las concentraciones de epicentros en la IPR y la región del Caribe. En adición a lo anterior, se provee una descripción del marco tectónico, las fallas de la región y la distribución de la cobertura instrumental de la red sismológica de movimientos fuertes de Puerto Rico (PRSMP, por sus siglas en inglés). Es de hacerse notar que el mapa de amenaza sísmica más reciente de Puerto Rico data del 2003, mismo que está contenido en los códigos actuales de construcción para Puerto Rico, no contempla múltiples fallas sísmicas activas que han sido identificadas dentro de la isla y que al menos algunas de ellas son capaces de generar sismos de magnitud

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del orden de 7.5. Actualizar el mapa de amenaza sísmica para Puerto Rico que considere las recién identificadas fallas sísmicas activas y los nuevos hallazgos de estudios sísmicos y de la respuesta local del sitio está plenamente justificada.

**Palabras clave**: 2020-sismo de Indios, 2010-sismo de Moca, 2014-sismo de Puerto Rico, aceleración máxima del suelo, catálogo de sismos

## INTRODUCTION

The understanding of the earthquake phenomena has several issues not well understood due to the complexity of the wave propagation phenomena and the particular seismotectonic processes due to local and regional geological conditions. In particular, for the Puerto Rico Island (PRI) recent regional seismic data have recently been collected with state of the art seismic instrumentation, and historical earthquakes occurred nearby the PRI and the Caribbean region. However, local seismicity and precise earthquake locations are still needed for better understanding and identifying the occurrence of seismic patterns and their respective seismogenic zones. On the other hand, the most recent Puerto Rico Seismic Hazard Map (2003), contained in the current building code, does not take into account multiple partially studied active seismic faults that were found within the Island and that at least one of them could generate magnitude 7.5 earthquakes.

The Puerto Rico Strong Motion Program (PRSMP) seismic network in charge of the operation of 113 permanent seismic station instrumented with accelerometers deployed in the Puerto Rico Island (PRI), the US and British Virgin Islands and Dominican Republic. The deployed accelerometric stations are: (i) free-field (ff) strong motion stations, (ii) instrumented structures (STR) (Dams, Bridges, Buildings), and (iii) the data acquisition/monitoring and analysis of earthquakes considered strong from the point of view of their intensity and magnitude.

In the last two decades, Puerto Rico and the Caribbean Region has experienced and documented several moderate magnitude ($5.0 \leq M \leq 6.4$) occurred in PRI and its Caribbean neighborhood producing PGA as large as 0.40 of *g* and intensities of VIII in the Modified Mercalli Intensity (MMI) in several locations within PRI, causing several damage in strategic facilities and causing alarm among the inhabitants.

A Caribbean region earthquake catalog nearby of PRI was compiled in order to capture the big picture of the regional seismic activity within the last two decade, primarily the last sixteen (16) years and in particular at the epicentral regions of several historical and instrumentally recorded (during 2010-2020) large to moderate magnitude earthquakes occurred nearby PRI in onshore and offshore, which include the M6.4 earthquakes of 01/13/2014, and 01/07/2020, the largest earthquakes recorded instrumentally by PRSMP and the Puerto Rico Seismic Network. From the point of view of joint temporal-spatial distribution of epicenters, episodic temporal-spatial seismic activity is clearly seen as temporal-spatial concentrations during certain time intervals in different regions. These localized concentrations of epicenters that occur during certain time intervals in well localized/concentrated regions may suggest "apparent seismic gaps" that shows no regular time interval, neither spatial pattern.

## TECTONIC AND SEISMOTECTONIC FRAME OF CARIBBEAN REGION AND PRI

The most significant regional physiographic and tectonic features around Puerto Rico are: (i) the Puerto Rico Trench, to the north, (ii) the Muertos Through, to the south, (iii) the Anegada Passage, to the east, and (iv) the Mona Passage, to the west (Figures 1a and 1b).

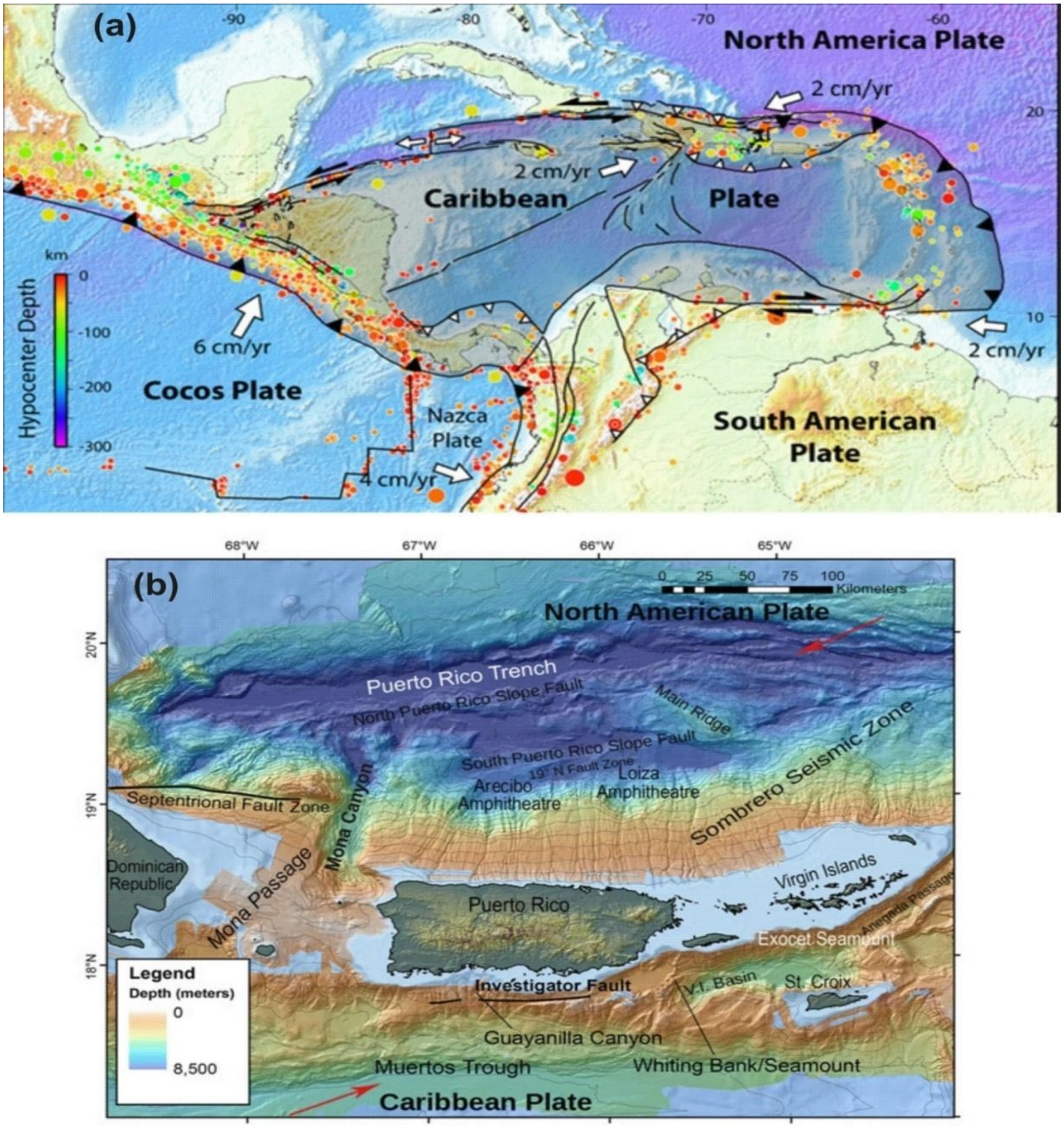

**Figure 1**: **Regional tectonic frame of Caribbean plate (a), (modified from: http://web.ics.purdue.edu/~ecalais/haiti/context/), and seismic zones in PRI vicinity (b). (Modified from https://soundwaves.usgs.gov/2015/06/fieldwork2.html).**

In addition to the off-shore active faults, PRI has several relevant mapped on-shore fault systems. Those of greatest concern for the engineering community are: (i) the Great Northern Puerto Rico Fault Zone (GNPRFZ), (ii) the Great Southern Puerto Rico Fault Zone (GSPRFZ), and (iii) the Lajas Fault Zone. Some of these structures have unknown potential for large magnitude events, as there is no evidence of Holocene rupture. These in-land fault segments of approximately 50-km can produce M7.0 events and can potentially extend to the south-southwest region of PRI as part of a longer fault zone (Figures 2a and 2b).

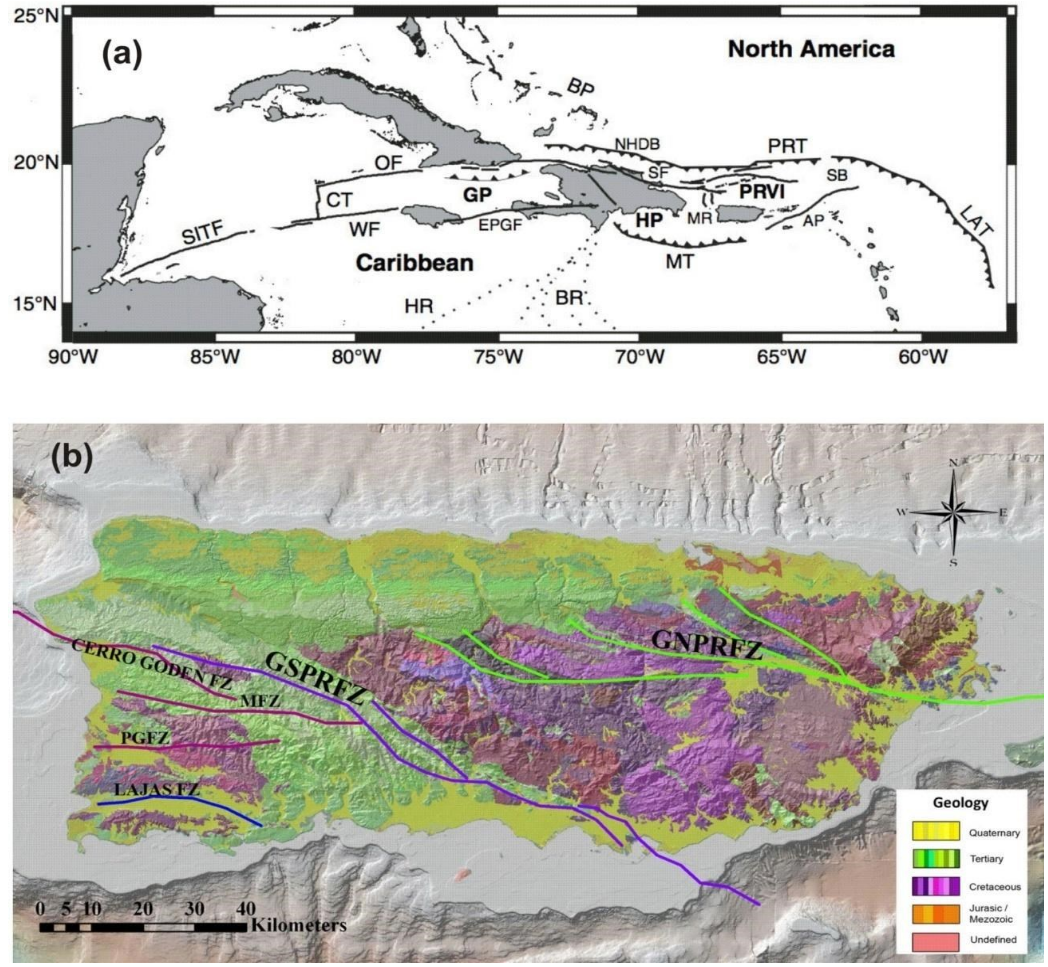

**Figure 2**:**Northern Caribbean plate boundary show microplates and structures of off-shore (a), and on-shore faults in Puerto Rico and Caribbean region (b) AP-Anegada Passage; BP-Bahamas Platform; BR—Beata Ridge; CT Cayman trough spreading center; EPGF-Enriquillo-Plantain Garden fault; GP-Gonave platelet; HP-Hispaniola platelet; HR-Hess Rise; LAT-Lesser Antilles Trench; MR-Mona Rift; MT-Muertos trough; NHDB-North Hispaniola deformed belt; OF-Oriente fault; PRT-Puerto Rico Trench; PRVI-Puerto Rico–Virgin. GNPRFZ-Great Northern Puerto Rico Fault Zone; GSPRFZ-Great Southern Puerto Rico Fault Zone; Cerro Goden FZ; MFZ-Mayaguez Fault Zone; PGFZ-Punta Arena-Guanajibo Fault Zone; Lajas FZ. (Modified from: GSA, Special Paper 385, 2005).**

The spatial seismic activity is mainly concentrated in eight zones: (i) Puerto Rico Trench, (ii) Slope faults in the North and South of Puerto Rico, (iii) Northeast of "Zona del Sombrero", (iv) the Mona Canyon, (v) Mona Passage, (vi) the depressions of Virgin Islands and Anegada Passage, (vii) Muertos Through, and (viii) Southeast of Puerto Rico. The magnitude threshold, the time interval, and the spatial limits for the sub-catalog were chosen in order to avoid any bias in the coverage and number of detected earthquakes, since improvements of sensitivity and spatial coverage of PRSN were gained over time from newer installed stations (Figure 3a). From the above, and the temporal earthquakes distribution for the period 2004/07/05 to 2020/12/10, shows concentrations of seismic sequences that may suggest apparent space-time gaps of seismic sequences (Figure 3b).

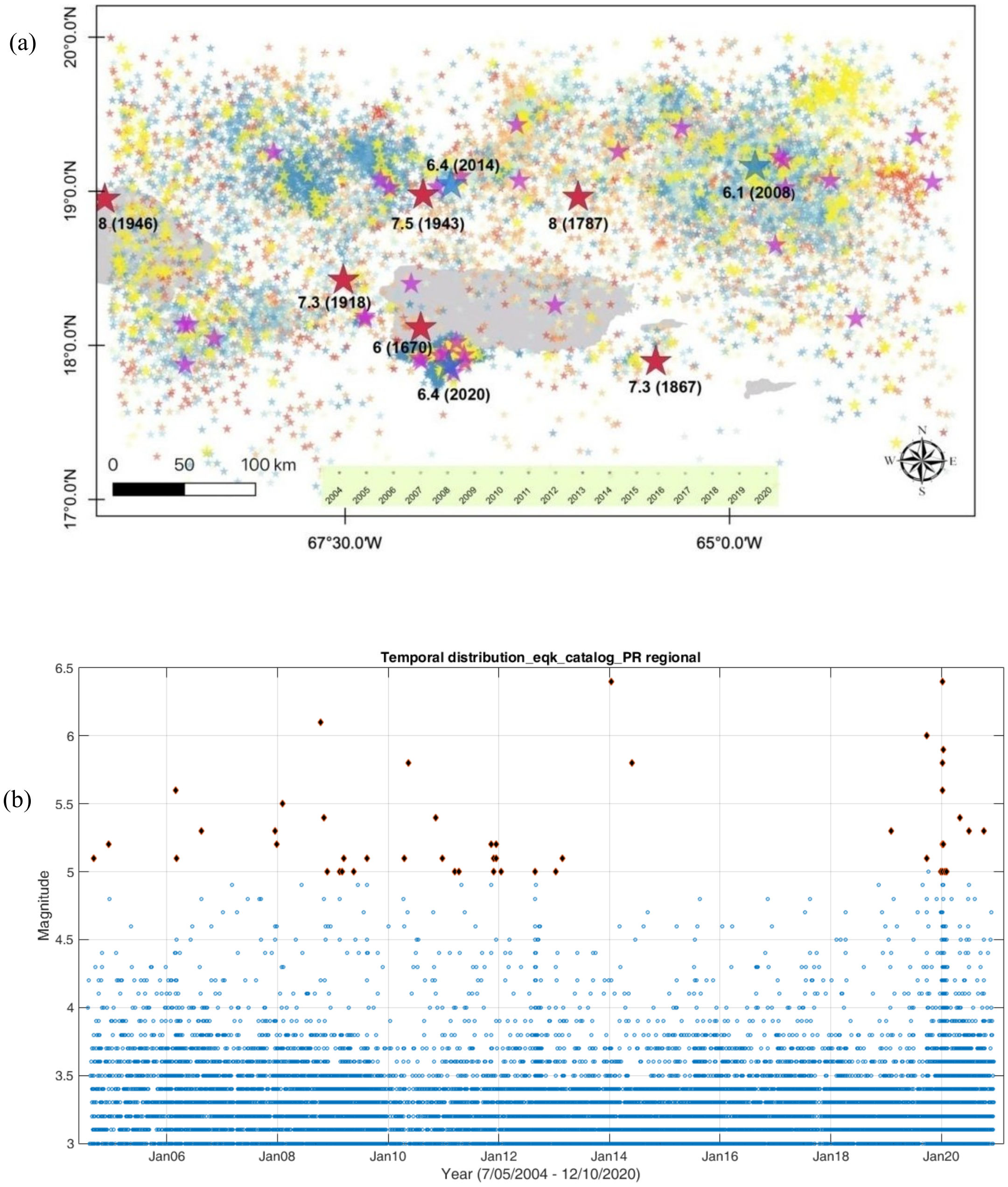

**Figure 3: Puerto Rico and Caribbean regional earthquakes distribution of the last 16 years: (a) space distribution (star symbols are: yellow 4.0≤M≤4.9; magenta 5.0≤M≤5.9; blue M≥6..0; small stars in different colors M≤3.9; stars in red with label are historical events), (b) time distribution (magnitudes of 5 and larger shown with brown diamonds).**

## PUERTO RICO STRONG MOTION PROGRAM

The PRSMP-SN is currently in charge of the maintenance/operation of strong motion stations of: (i) free-field (f-f), (ii) instrumented structures (st) (Dams, Bridges, and Buildings), and (iii) the data acquisition/monitoring/analysis of moderate-large earthquakes from the point of view of their intensity and magnitude. All instruments are deployed in the Puerto Rico Island (PRI), the USA-, and the British-Virgin Islands (USA-VI, B-VI), and the Dominican Republic (DR).

Currently, the Puerto Rico Strong Motion Program (PRSMP) includes 113 triaxial f-f stations and 19 engineering structures, instrumented with arrays of digital accelerographs as follows: PRI: 91 f-f, 17st; DR: 16 f-f; USA-VI and B-VI: 6 f-f, 2st. Figure 4 shows the distribution of the f-f strong motion stations and the instrumented structures. In addition to the regional monitoring of strong ground motions in PRI, small aperture urban strong motion arrays have been installed and operated by PRSMP in the cities of San Juan, Ponce and Mayagüez. Currently, these small aperture arrays have provided valuable information for the local site response/effects studies when using moderate magnitude earthquakes. Figures 5a, 5b, and 5c shows the distribution of the strong motion instruments within urban areas.

The PRSMP-SN is operated 24/7 by the Civil Engineering and Surveying Department of the University of Puerto Rico at Mayaguez (UPRM) with the mandate of monitoring, research, and education in the field of Earth Sciences strong motion seismology.

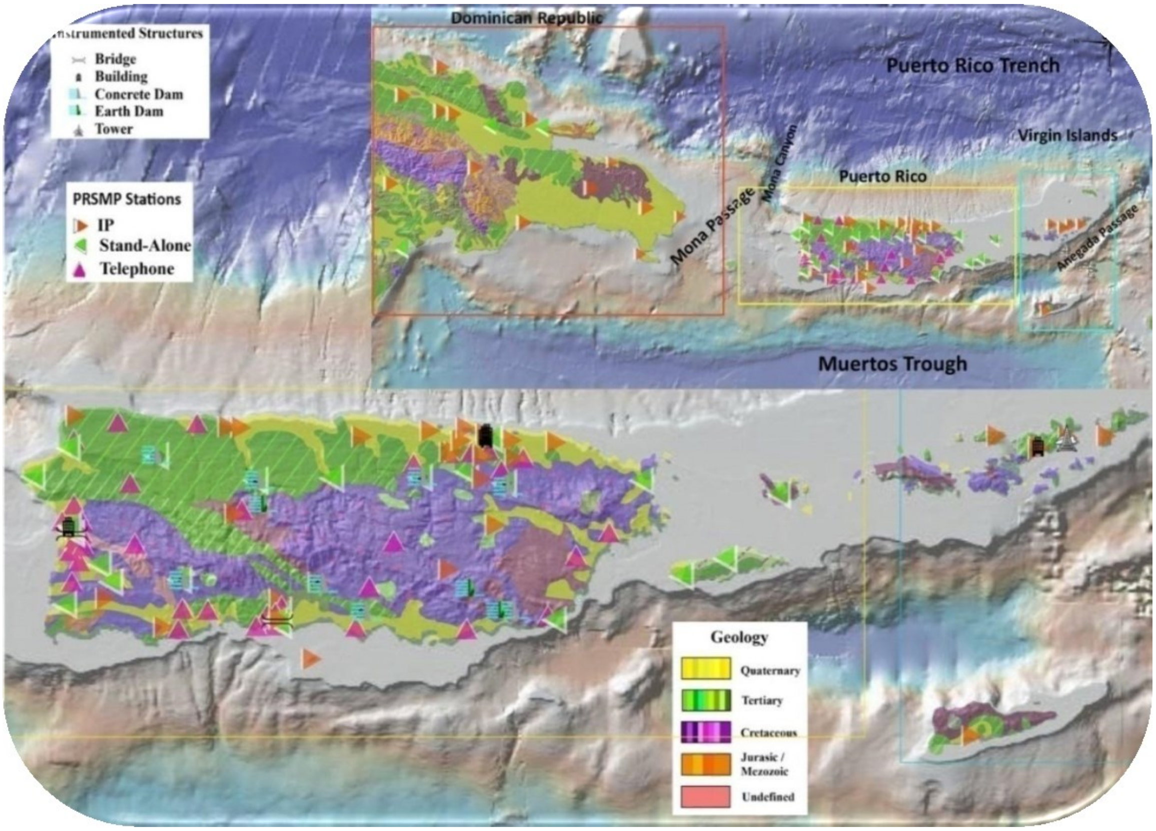

**Figure 4**: **Distribution of accelerographs, and instrumented civil structures with accelerometers operated by PRSMP.**

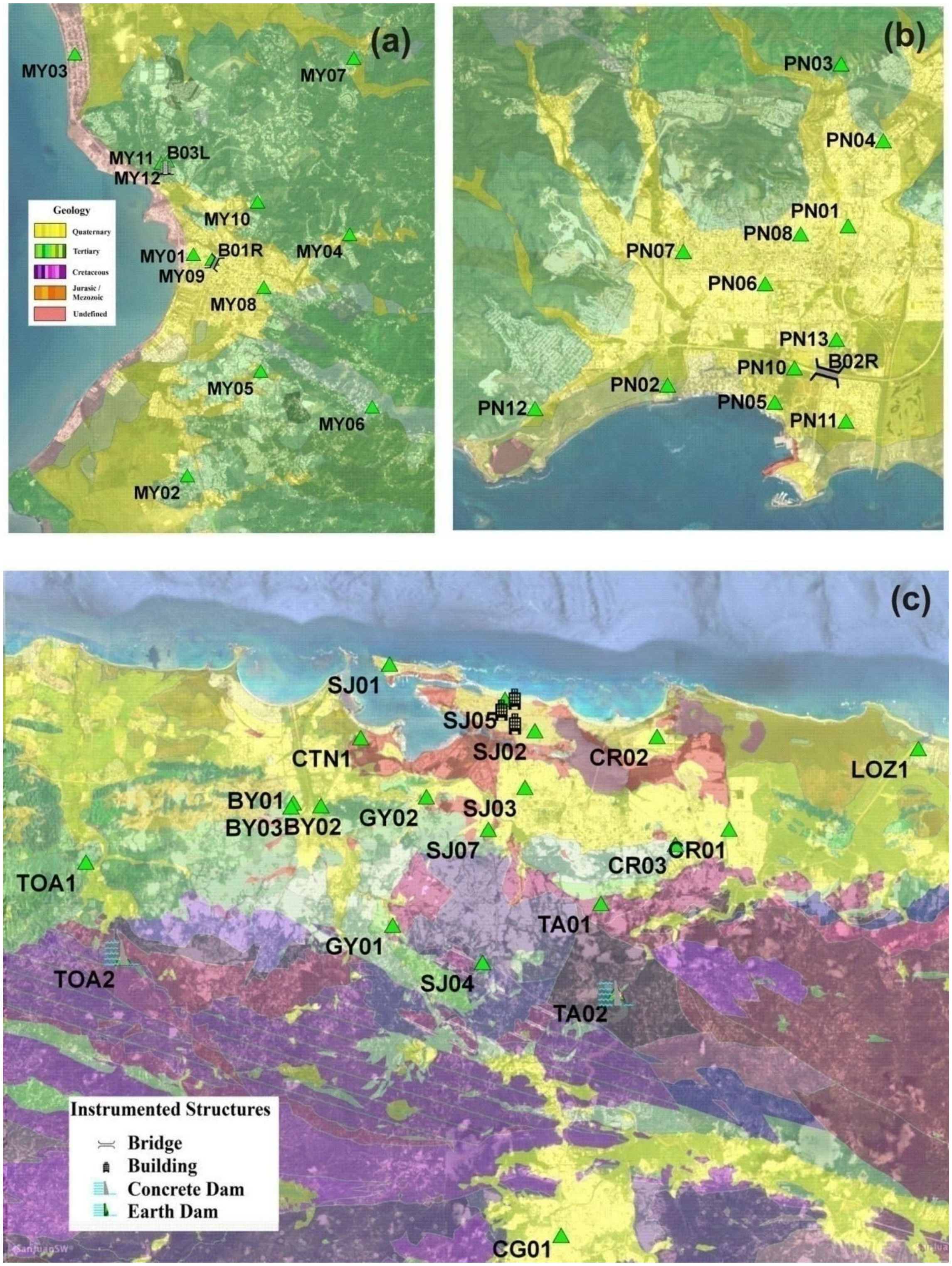

**Figure 5**: Small aperture urban arrays of accelerometers (solid triangles) in the cities of: (a) Mayagüez, (b) Ponce, and (c) San Juan Metropolitan Area.

## Data Studied Earthquakes

$M_W$5.8, 05/16/2010 Moca, Puerto Rico earthquake, $M_W$5.4, 12/24/2010, and $M_W$5.3, 12/17/2011 earthquake.

This first set of studied earthquakes dates from 2010 and 2011 are of special interest due to the irregular distribution of the peak ground acceleration (PGA) and spectral amplitudes (SA) within the PRI with respect to the expected typical decay of the PGA and the SA as the distance increase. The local site conditions (effects), as well as path effects are discussed in order to explain this observed behavior. The earthquake locations and focal mechanisms are shown in Figure 6, showing as well the regional surface geological conditions of the PRI.

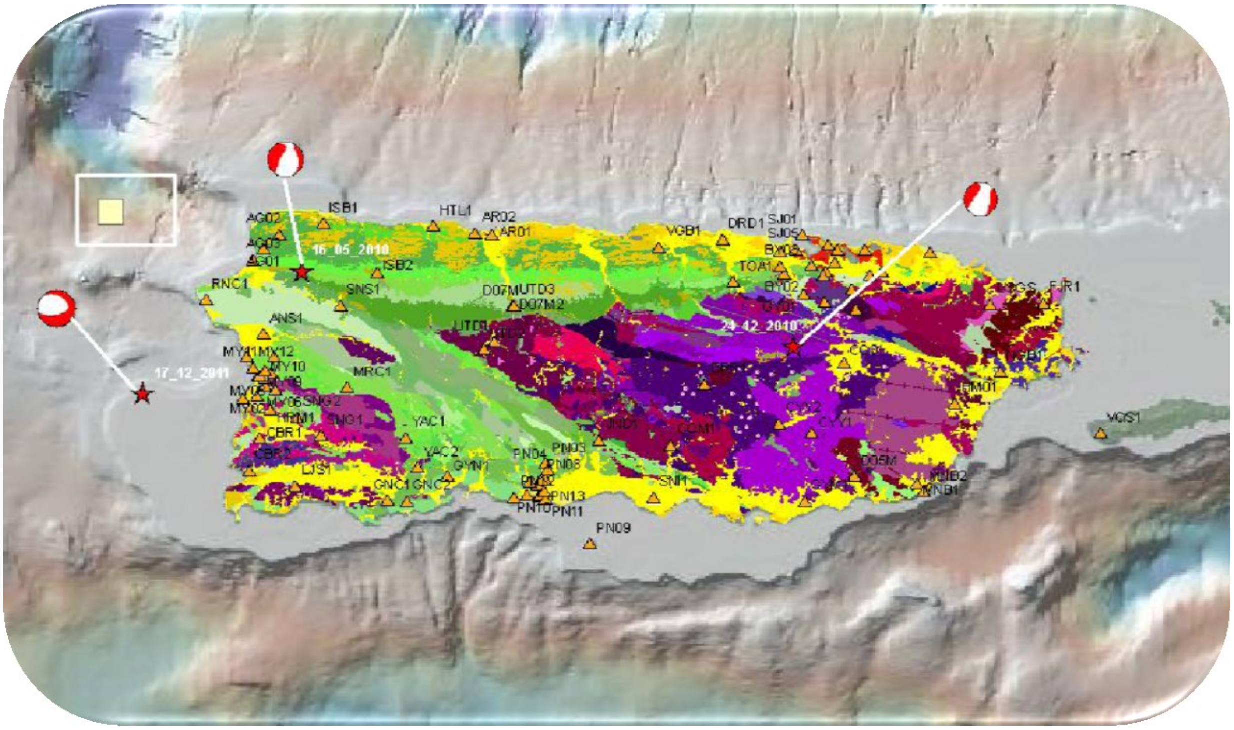

**Figure 6**: **2010-2011 studied earthquakes epicentral location (stars), focal mechanism (beach-balls), PRSMP seismic stations (triangles), and surface geology (yellow color young soft geological units, and green-brown-purple dark colors old hard geological units).**

From these earthquakes, the MW5.8 earthquake is of particular interest because is the largest magnitude earthquake occurred on-shore within the PRI. Its epicentral location was 18.4° Lat., -67.07° Lon., and focal depth 113.1 km, reporting an intensity of VI in the municipality of Añasco, which is located at approximately at 15 km from its epicenter, while in some cases the intensity hardly reach an intensity of III in towns located at closer epicentral distances. This earthquake was widely felt in Puerto Rico, the eastern Dominican Republic, and the Virgin Islands. It was recorded also by 59 stations of the PRSMP providing a reliable set of acceleration records distributed around the island. According to the USGS Centroid Moment Tensor solution, this earthquake occurred in an inclined seismic zone that dips south from the Puerto Rico Trench and that consists of subducted lithosphere of the North America plate. Earthquakes that have focal-depths between 70 and 300 km, are commonly termed "intermediate-depth" earthquakes and typically cause less damage on the ground surface above their foci than is the case with similar magnitude shallow-focus earthquakes. Large intermediate-depth earthquakes may be felt at great distance from their epicenters. In terms of the observed maximum peak ground acceleration it was: (i) 0.0651 of g at Añasco (ANS1 station, located at an epicentral distance of 15 km in alluvial soil), and (ii) 0.2301of g at station UTD2 located at an epicentral distance of 42 km on rock. The instrumental intensity (MMI) estimated with Wald et al., (1999) relationship was V and VII, respectively for these two previously described sites. From the analysis conducted, with the aim to explain the anomalous distribution of peak ground motions, we reached that the anomalous PGA distribution may be associated not only by local site effects due to the presence of soft soils, but by focusing of waves energy due to the physiographic conditions of the UTD2 region and apparent directivity effects. This earthquake caused light damage on buildings and houses, and caused alarm among the inhabitants of the area.

Standard strong motion signal processing was applied to the recorded data obtaining the .V1, .V2, and .V3 processed data, which correspond to the uncorrected acceleration records converted to physical units, the corrected acceleration record in physical units of acceleration, velocity and displacement, and the spectral representation of all above, respectively. In Figure 7, the map of the PGA distribution in the PRI is provided. The acceleration time series and the spectral characteristics for stations SJ04 and UTD2 are provided in Figure 8.

Figures 9 and 10 provide the graphical view of PGA distribution in PRI for the earthquakes of 12/24.2010 and 12/17/2011, respectively. Table 1 provides the estimated PGA at key stations for comparison purpose.

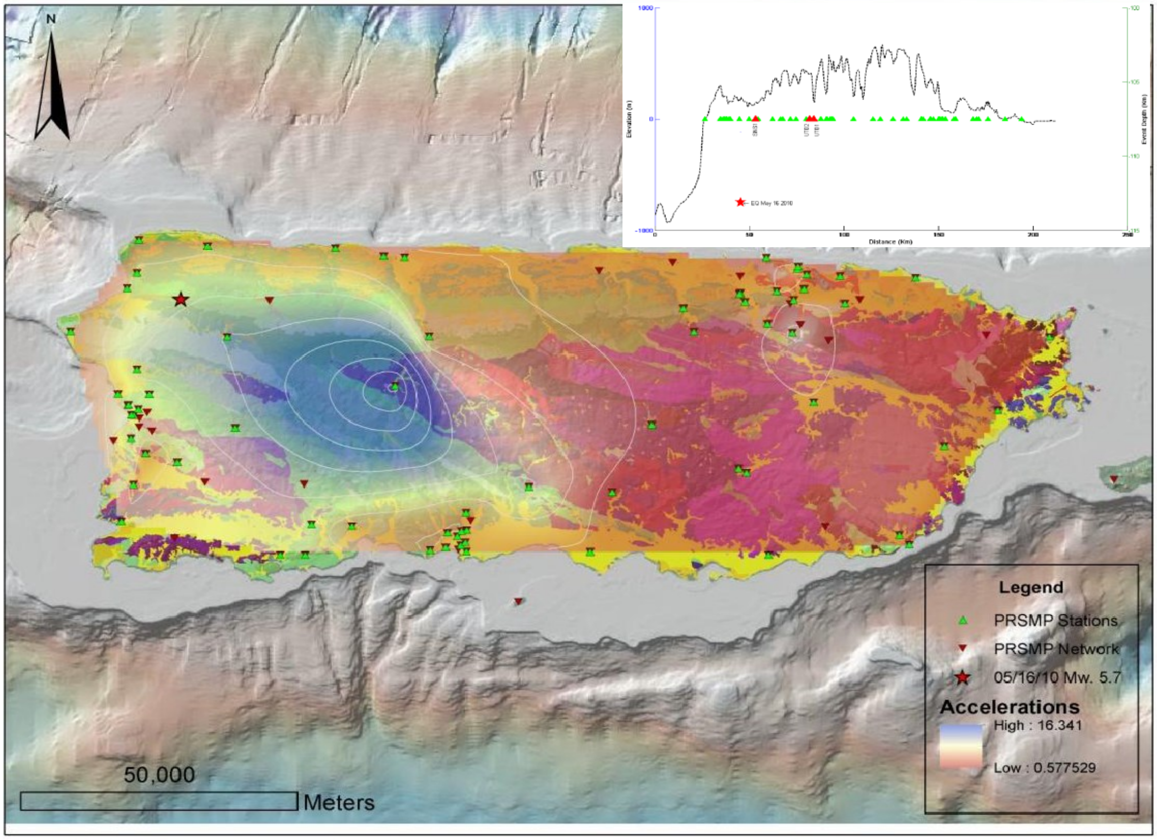

**Figure 7**: **PGA distribution of the Mw5.8, 05/16/2010 earthquake (star). Triangles in green indicate stations that recorded this earthquake. West-east topographic profile showing SNS1 and UTD2 stations (red triangles), and earthquake hypocenter (red star), all green triangles projected PRSMP stations along the profile.**

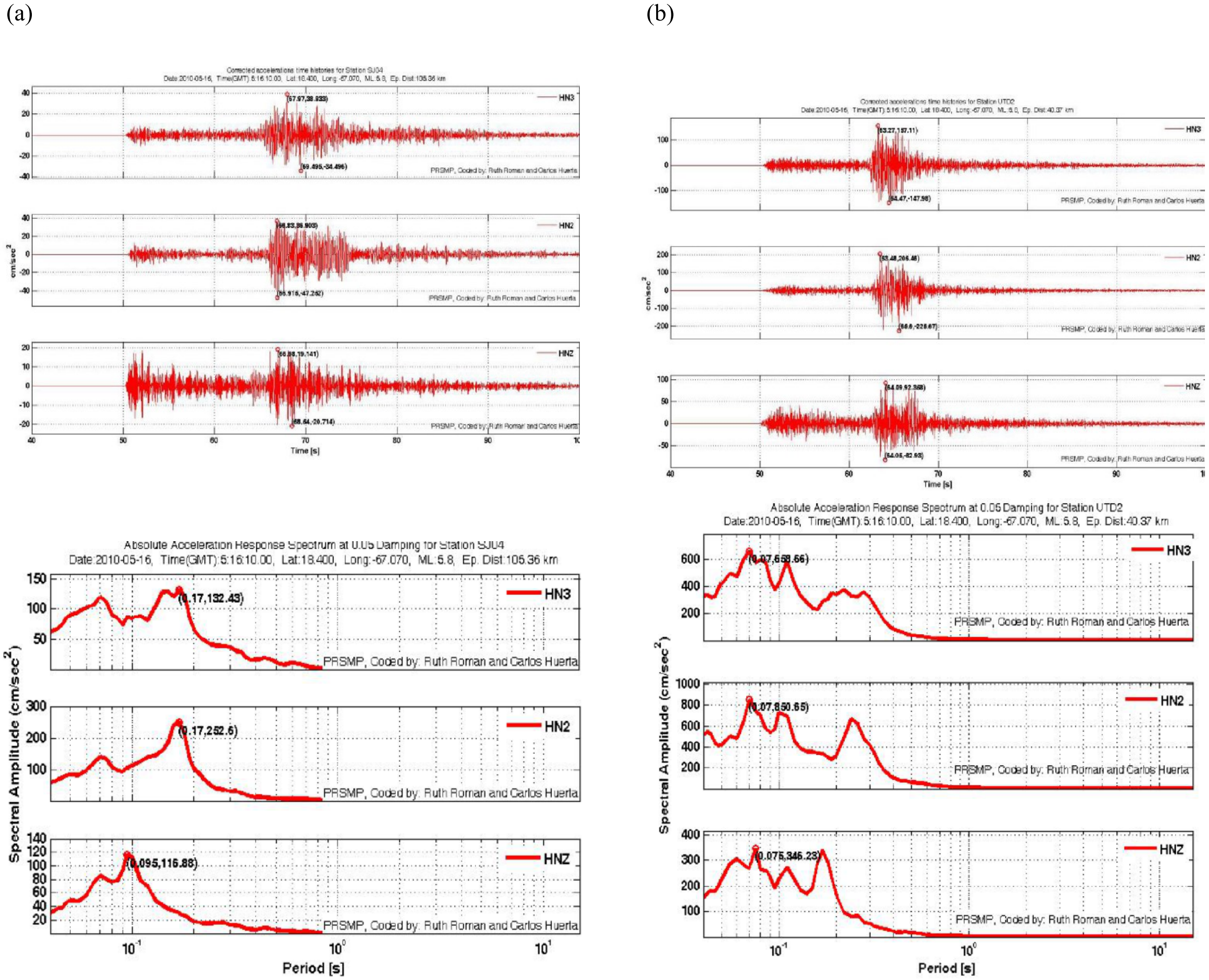

**Figure 8**: **Acceleration time series and response spectral characteristics for stations (a) SJ04 and (b) UTD2.**

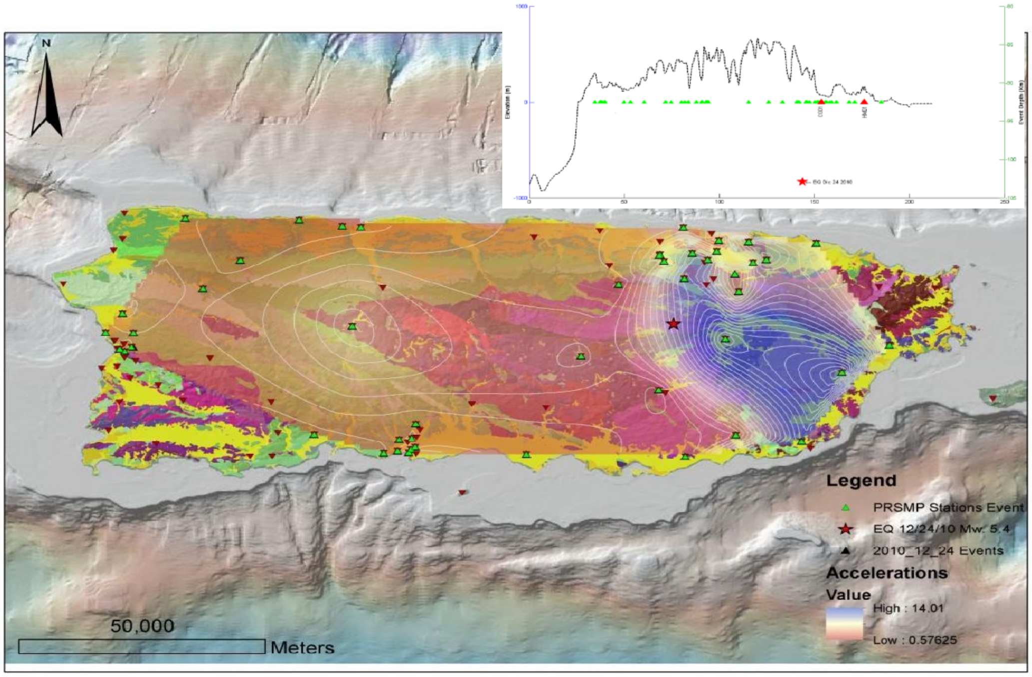

**Figure 9**: **PGA distribution of the Mw5.4, 12/24/2010 earthquake (star). Triangles in green indicate stations that recorded this earthquake. West-east topographic profile showing CG01 and HM01 stations (red triangles), and earthquake hypocenter (red star), all green triangles projected PRSMP stations along the profile**.

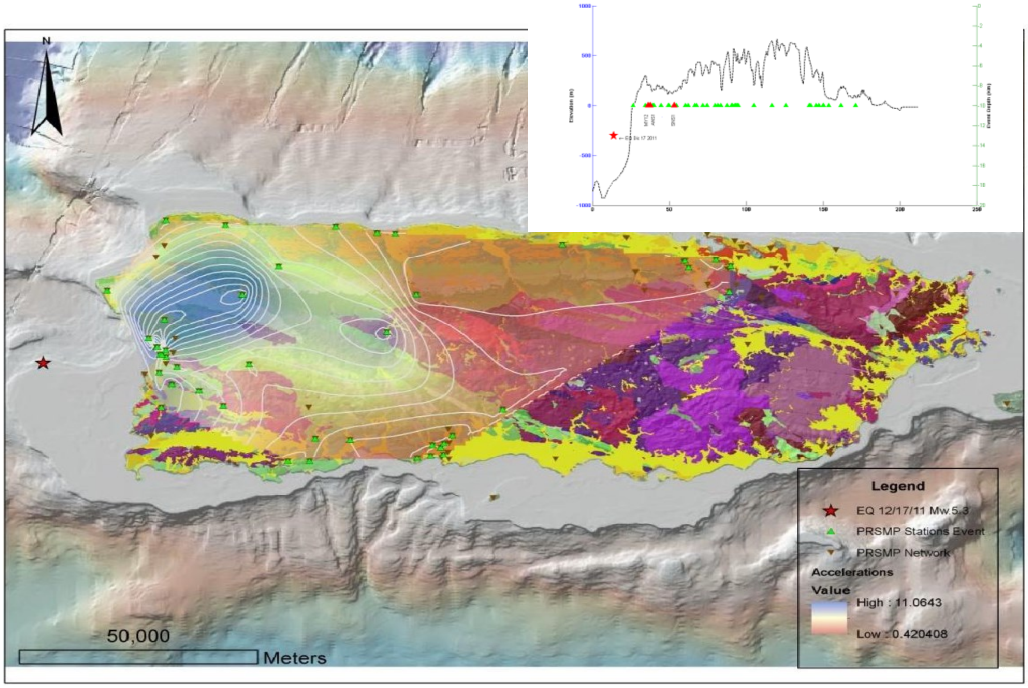

**Figure 10**: **PGA distribution of the Mw5.3, 12/17/2011 earthquake (star). Triangles in green indicate stations that recorded this earthquake. West-east topographic profile showing MY12, ANS1 and SNS1 stations (red triangles), and earthquake hypocenter (red star), all green triangles projected PRSMP stations along the profile.**

**Table 1: Comparison of PGA of 05/16/2010, 12/24/2010 and 12/17/2011 earthquakes at key stations.**

| Event date (Magnitude) | Max_PGA ($cm/s^2$) | Station | Distance (km) | Max_PGA ($cm/s^2$) | Station | Distance (km) |
|---|---|---|---|---|---|---|
| 05/16/2010<br>(5.8) | 23.01 | UTD2 | E=40.17<br>H=120.02 | 2.04 | AG02 | E=13.03<br>H=113.84 |
| 12/24/2010<br>(5.4) | 14.15 | HM01 | E=34.01<br>H=108.54 | 12.13 | CG01 | E-10.06<br>H=103.44 |
| 12/17/2011<br>(5.3) | 11.30 | MY12 | E=23.38<br>H=29.01 | 4.08 | UTD2 | E=69.3<br>H=71.3 |

E: Epicentral distance, H: Hypocentral distance, PGA: Peak Ground Acceleration

## $M_W$6.4, 01/13/2014 Puerto Rico Earthquake

On January 13 2014, 04:01:04.0 UTC, an $M_W$6.4 earthquake occurred in the Caribbean region just about 70 km out of the Northern coast of Puerto Rico. According to the USGS and PRSN the reported earthquake epicentral location were at Latitude/Longitude of: $19.001^0/-66.848^0$, and. $19.1385^0/-66.8231^0$, respectively. The focal depth estimated by both agencies was 28 versus 36 km, respectively. During the following 12 hours, 76 aftershocks (USGS source) of small magnitude ranging from 2.5 to 4.6 (2 of 4.6, and 2 of 4.5) occurred south of the epicentral region. No serious damage was reported. Falling objects were reported, which is usual to happen in moderate shaking. This earthquake, occurred as a result of oblique-thrust faulting, which is consistent with this subduction zone interface. Preliminary faulting mechanisms for the event indicate it ruptured either a structure dipping shallowly to the south and striking approximately east-west, or a near-vertical structure striking northwest-southeast.

The earthquake occurred in the deep Ocean Trench, is not the strongest earthquake occurred in the area. The 1918 M7.3, and the 1916 M7.2 earthquakes occurred in la Mona Passage and East coast of Dominican Republic are the largest ones occurred nearby. Results of the processing (the standard strong motion data processing procedure; .v1, .v2, .v3 was here adopted) and analysis of acceleration records collected by the Puerto Rico Strong Motion Program (PRSMP, 58 records) and the inclusion/processing of acceleration records of Puerto Rico Seismic Network (PRSN, 9 records) in terms of the PGA and estimated instrumental intensity IMM are presented in the PR map. The PGA/IMM distribution is discussed in terms of the local site, topographic and possible directivity effects. The site dominant vibration frequency distribution is also discussed.

At the location of this earthquake, the North America plate moves west-southwest with respect to the Caribbean plate at a velocity of approximately 20 mm/yr., and subducts beneath the Caribbean plate at the Puerto Rico Trench. The location, depth and mechanism of the earthquake are consistent with this subduction zone interface. While the Puerto Rico Trench is known to be a significant seismic hazard, and is capable of hosting M8+ earthquakes, moderate-to-large events on the subduction zone are rare.

Over the past century, three such events have occurred nearby to the January 13, 2014 earthquake – a M 6.6 event in 1915, just to the east of the 2014 event; a M 7.0 earthquake 70 km to the west in 1917; and a M 7.6 earthquake in 1943 just northwest of the 2014 earthquake. Two earthquakes occurred in the Mona Passage approximately 100 km to the southwest of the 2014 earthquake in 1916 (M 7.0) and 1918 (M 7.3), while the 1946 M 7.9-8.0 Hispaniola earthquake struck 230 km to the west, also on the North America slab interface. The July 1943 North Mona Passage earthquake did not cause significant damage in Puerto Rico, though it did spawn a small tsunami, and was the first in a series of large events in the broader northern Caribbean region between central Hispaniola and Puerto Rico over the following decade, including the larger 1946 earthquake. The 1946 event is known to have caused significant damage in both Hispaniola and Puerto Rico, including destruction from a subsequent tsunami.

In the epicentral region of the M6.4 01/13/2014 earthquake and the historical Mona Passage M7.5 earthquake of 10/11/1918, as previously described episodic concentrations in time and space of small magnitude earthquakes epicenters were evident, however do not show temporal pattern. Preliminary results of statistical analysis of an ongoing research in terms of the parameter b (Gutenberg-Richter relationship), and the Omori's law with the aim to relate the tectonic framework of the region (or sub-regions) such as structural heterogeneity stress have been estimated, showing no significant variation of these parameters.

A set of stations that recorded this earthquake (01/13/2014), were selected (63) to show the most evident differences of the PGA and SA distribution. Among these selected stations, the epicentral distances goes from 104 to 112 km (for the Mayaguez urban area), and from 123 to 130 km at the urban area of Ponce. In terms of the slant distance they are 109 to 116 km, and 126 to 133 km respectively. Figure 11 shows the regional PGA distribution within the PRI.

The surface geology varies from Cretaceous, Tertiary and Quaternary rocks/soils. In terms of their lithology, the rocks/soils varies from Limestone (K), Hard Clay, Rock, Sand-Cemented Silt, and Alluvial deposits (Qa). The variation of the PGA and SA on the selected stations, here presented, are easily observed on their graphs being the most significant difference between stations grouped for the Mayagüez versus Ponce urban areas, even though the variation/difference in epicentral distance is small among each group of stations. The PGA at stations group of Mayagüez area range from 0.3 to 3.2% of g, and 0.96 to 3.3% of g for Ponce metropolitan area. Figure 12 provide the graphical view of the PGA distribution in Mayagüez and Ponce urban areas. In terms of the period fundamental vibration mode, it ranged from 0.11-s to 0.7-s for Mayagüez urban area and 0.32-s to 0.9-s for Ponce.

The SA distribution showed spectral amplitude peaks with the shortest period at station: MY06 (0.11-s, 19.4_SA), and PN03 (0.32-s, 28.26-SA). The ones with the largest period are: station MY09 (0.7-s, 117.54-SA), and PN05 (0.9-s, 125.54-SA). The distribution of the estimated instrumental MMI shows three well localized anomaly spots (Mayagüez, Ponce and Utuado urban areas) with intensity values that reach up to IV; one at station MY01 (at epicentral distance of 112 km), other at station PN4 (at epicentral distance of 130 km), and the third one at stations UTD1, UTD2 (at epicentral distances of 97-, 98-km). Some other scattered sites (not grouped) as stations EMPR, VGB1, BY02, BY03, TOA1 (all nearby San Juan Metropolitan Area), LOZ1, CR01, and CBYP (at the eastern part of PRI) also reached intensity of IV. These estimated instrumental intensities are in good agreements with the ones reported in the news. Figure 13 shows the acceleration time series and spectra of 01/13/2014 earthquake of station LOZ1.

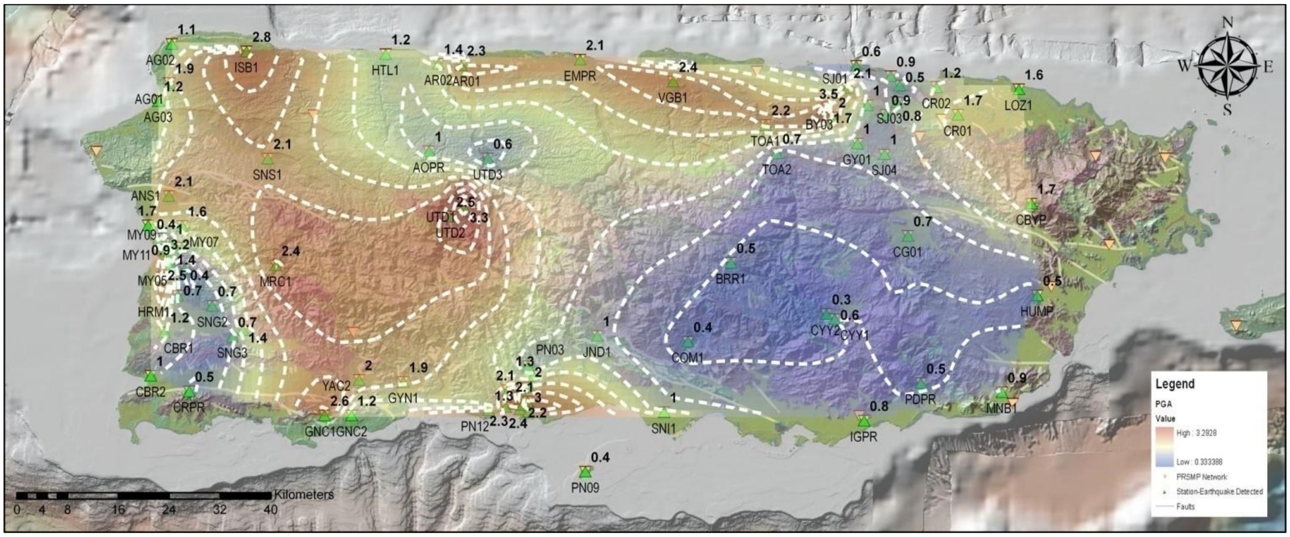

**Figure 11**: **Regional PGA distribution of the Mw6.4, 01/13/2014 earthquake. Triangles in green indicate stations that recorded this earthquake**.

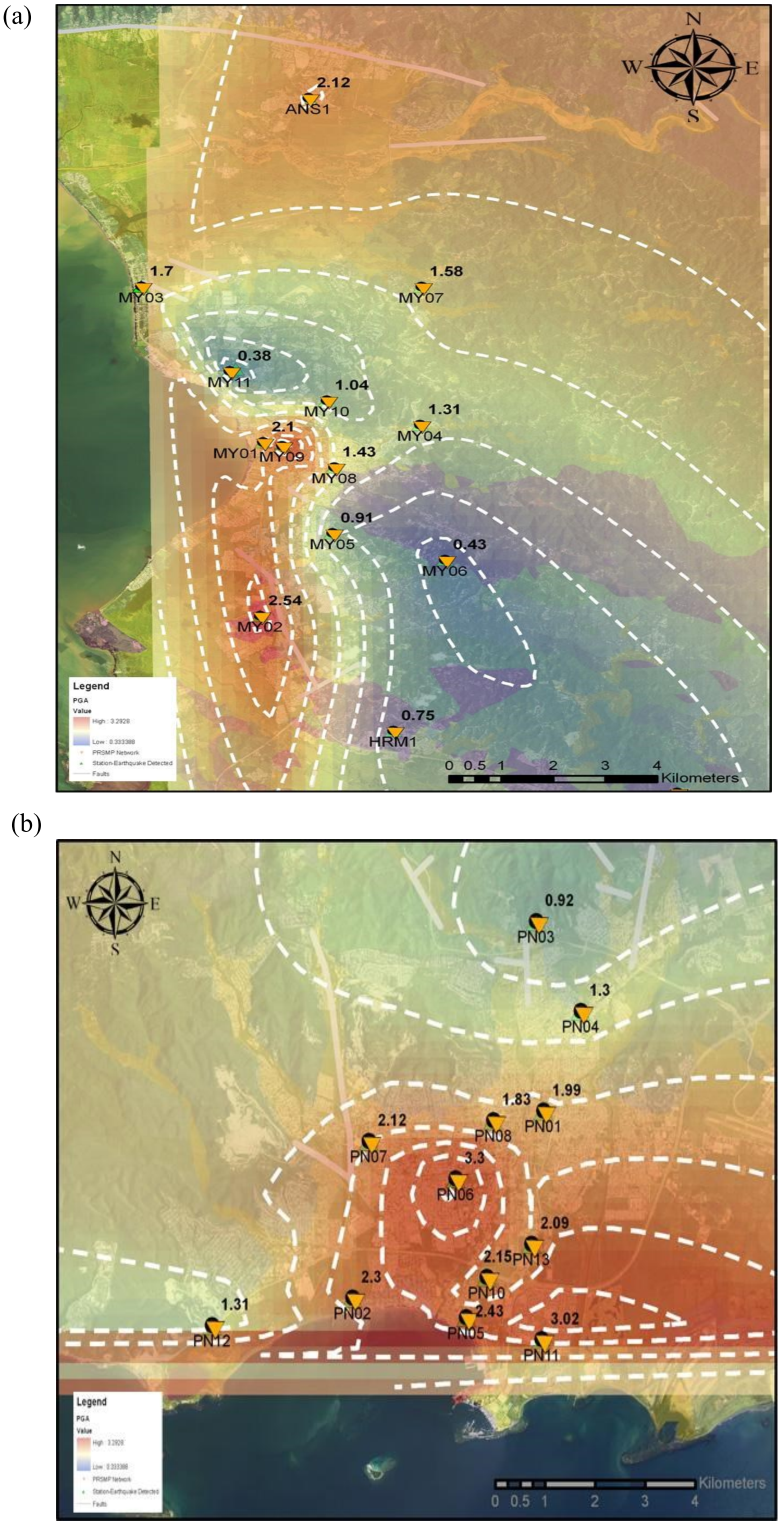

**Figure 12**: **PGA distribution of the Mw6.4, 01/13/2014 earthquake in urban areas of: (a) Mayagüez and (b) Ponce.**

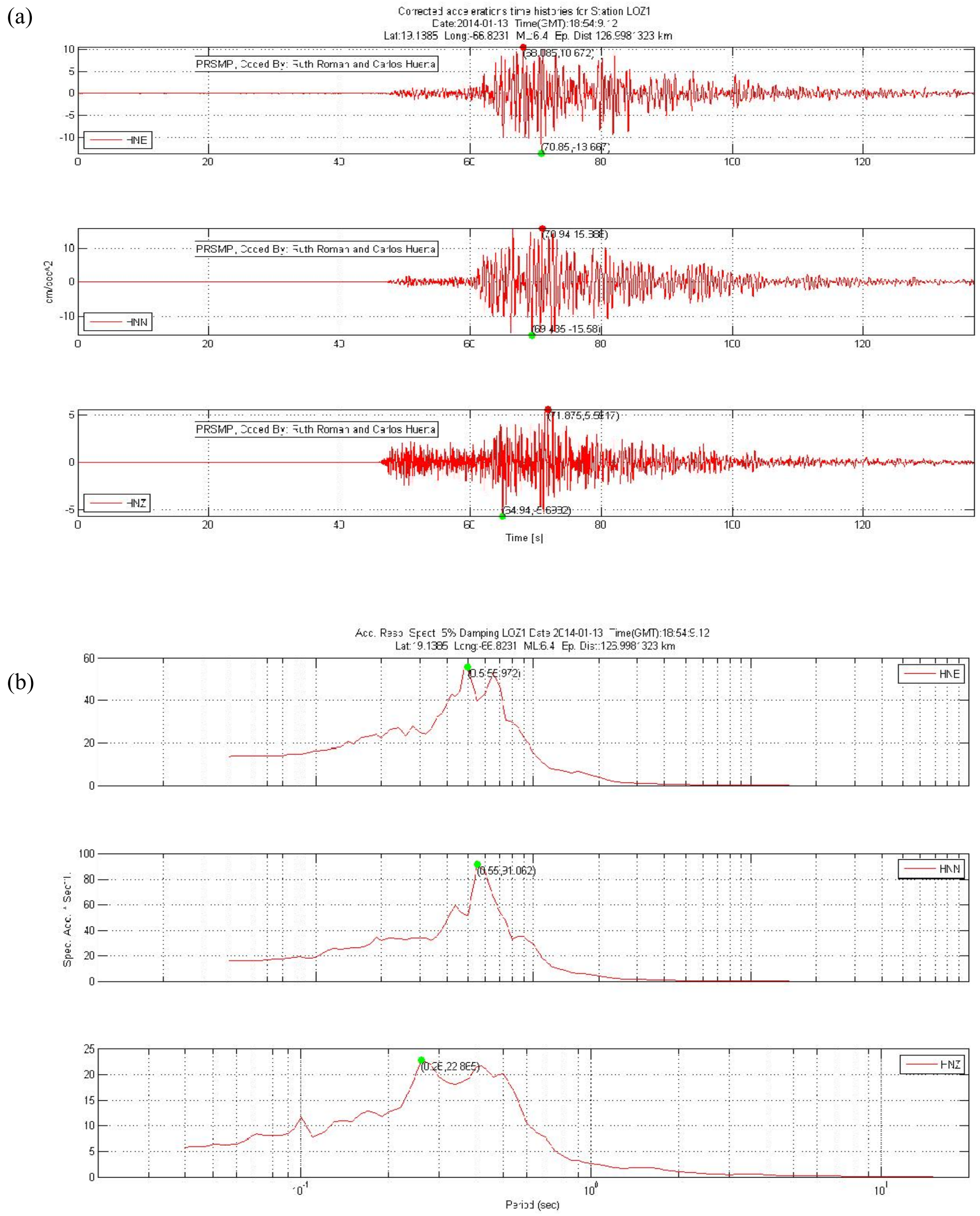

**Figure 13**: **Acceleration time series and response spectra of 01/13/2014 earthquake at station LOZ1**.

## $M_W$6.4, 01/07/2020 Indios Earthquake

South-west Puerto Rico earthquakes sequence of the January 2020, were recorded by the PRSMP seismic stations, being the largest of magnitude $M_W$6.4, the one occurred on January 7/2020. The above referred earthquake sequence, really started by late December of 2019. The $M_W$6.4 earthquake was located offshore at ~8 km south of Indios Town in the Municipality of Guayanilla (epicenter at Lat. $17.869^0$N and Lon $-66.827^0$, and focal depth 9.0 km). The closest and largest epicentral distances were ~9 km, and ~100 km (YAC2, and CR03, stations respectively). Focal mechanism solution, reported in https://earthquake.usgs.gov/earthquakes/eventpage indicate oblique normal faulting at shallow depth as the result of slip on either a moderately dipping plane striking just north of west, or on a moderately dipping plane striking just west of south. The location and focal mechanism solution are consistent with an intraplate tectonic setting within the lithosphere of the Caribbean plate. Results of regional distribution within the PRI of PGA within the PRI and instrumental intensity (MMI) distribution in the Puerto Rico Island are next described. The geometric mean of the largest PGA reached ~0.38g at YAC2, and 0.017g at CR03. Local site effects are evident, being ~0.35g at station UTD2 located at ~35 km, and 0.005g in SNG2 station located ~36 km. The estimated instrumental intensities varied from VIII, nearby YAC2, to III nearby CYY2 station. Figure 14 shows the PGA regional distribution within PRI, and Table 2 provides the largest PGA at the closest epicentral distance of PRSMP stations.

Extensive structural damage to public and private civil infrastructure that includes complete or partial collapse of schools, government buildings homes, bridges and churches were reported in the municipalities of Yauco, Guánica, Peñuelas, and Guayanilla. The largest city nearby (~20 km) the epicentral region of the seismic sequence is Ponce. In addition to the seismic faults recognized in the current building code, take into account these partially studied seismic faults and the eventual amplification of the seismic waves due to soft soils strata is an issue.

In addition to the effects on the civil infrastructure of the seismic sequence of January 2020, there was also reports of extensive ground deformation such us: lateral spreading, soil liquefaction and ground settlement. Landslides on precarious slope stability were not the exception.

The spatial (Figure 15) and the temporal (Figure 16) earthquakes distribution for the period 2019/11/01 to 2020/05/31, on the epicentral region of the M6.4 01/07/2020 Indios earthquake, shows a noticeable increase of the number of earthquakes of M≥2.5 starting on 01/03/2020 (see Figure 16).

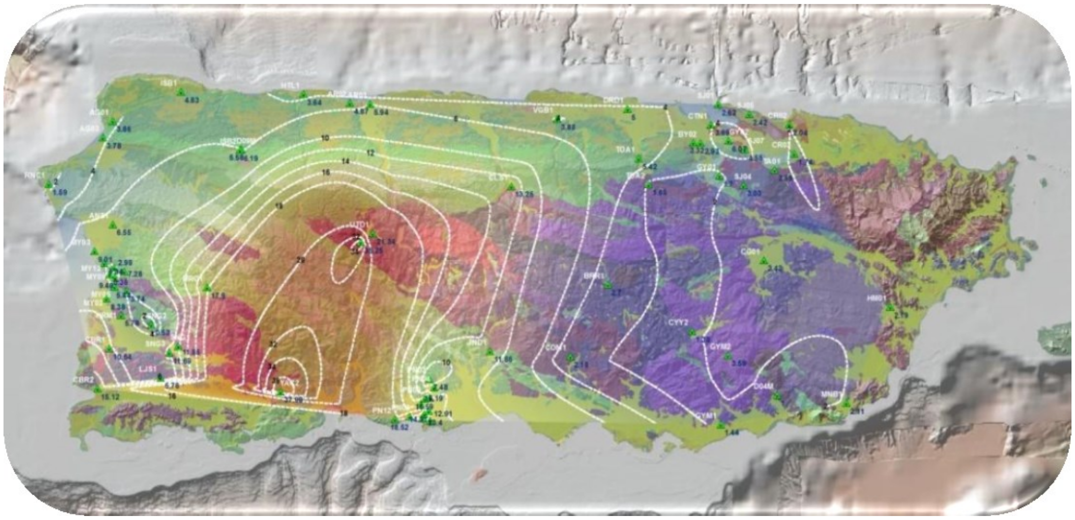

**Figure 14**: **$M_W$6.4 Indios earthquake of 01/07/2020 PGA regional distribution within PRI.**

**Table 2**: **M**W**6.4, Indios earthquake PGA at stations of PRSMP with epicentral distance ≤ 25 km.**

| Station ID | Epicentral Distance (km) | Max. PGA (%g) |
|---|---|---|
| YAC2 | 8.7 | 39.8 |
| PN02 | 18.5 | 21.2 |
| PN04 | 23.9 | 22.2 |
| PN06 | 20.8 | 15.2 |
| PN08 | 21.7 | 15.7 |
| PN10 | 21.1 | 24.4 |
| PN11 | 22.0 | 13.2 |
| PN13 | 21.9 | 17.5 |

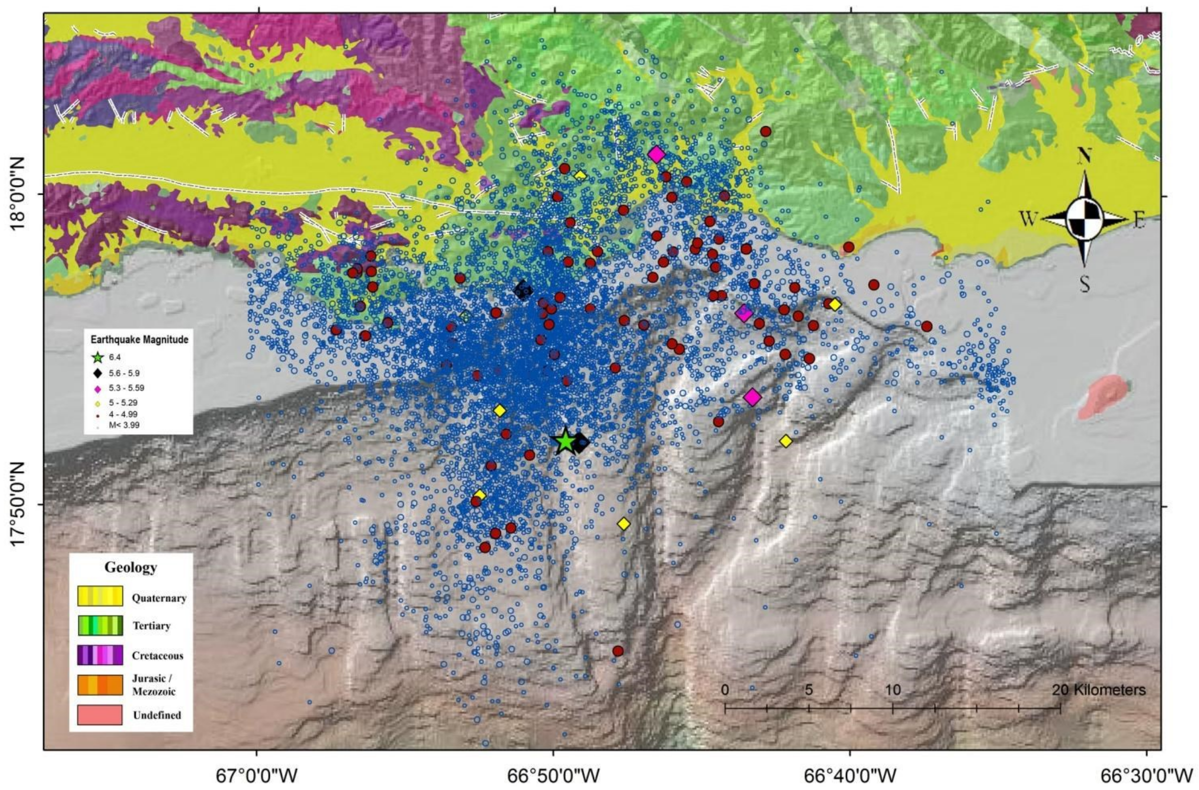

**Figure 15**: **Spatial distribution of the January/2020 earthquakes sequence for the time window of 11/01/2019 to 05/31/20.**

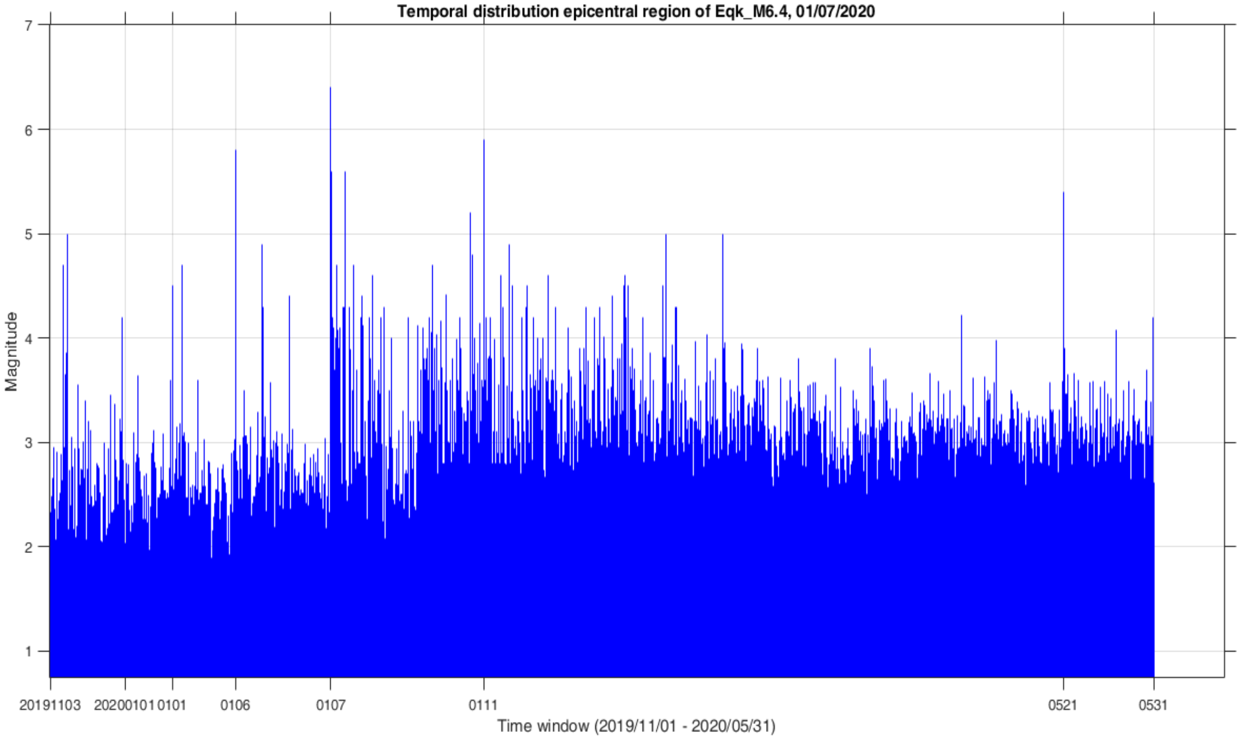

**Figure 16**: **Temporal distribution of the January/2020 earthquakes sequence for the time window of 11/01/2019 to 05/31/2020.**

## LESSONS LEARNED AND CONCLUSIONS

Based on the systematic studies of the earthquakes of moderate magnitude (5≤M≤6.4) carried out during the last 12 years, and the analysis of the homogeneous earthquakes catalogs for Puerto Rico and the Caribbean region, we have now a very solid evidence (based on observed/recorded time series of earthquakes) about the regions where the local site conditions (site effects) produce amplification effect on the ground response in which may be also associated the effect of energy focusing due to the topographical conditions of the site. The directivity effect due to the earthquake focal mechanism and its focal depth is also an issue to consider in the incoming research topics. The amplification effect seen from the studied M6.4 earthquakes confirmed the expected ground response stated by the studied 5≤M≤6.0, 2010-2011 earthquakes. From the point of view of the analysis of the earthquake catalogs the seismic sequences distribution, may suggest the association of the recent occurrence of earthquakes of magnitude greater than M5, may be associated where historical large magnitude have been occurred. The apparent seismic gaps is being still is an issue that requires more studies. The seismic sequence concentrations even though are located where not known mapped faults, are clear indication of the stress process is occurring at depth and earthquakes of moderate magnitude are plausible to occur.

The learning lesson, we may conclude base on the above, is that moderate magnitude (even small magnitude) earthquakes are useful data to better understand the wave propagation phenomena and the tectonic/seismotectonic process of the region, and the local site response. In layman words, we should not wait until the large magnitude earthquake (the big one) occur to know (or study) the conditions of the ground response upon an earthquake.

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