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ASSESSMENT OF THE TSUNAMIGENIC POTENTIAL ALONG THE NORTHERN CARIBBEAN MARGIN

Case Study: Earthquake and Tsunamis of 12 January 2010 in Haiti.

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ABSTRACT

The potential tsunami risk for Hispaniola, as well as for the other Greater Antilles Islands is assessed by reviewing the complex geotectonic processes and regimes along the Northern Caribbean margin, including the convergent, compressional and collisional tectonic activity of subduction, transition, shearing, lateral movements, accretion and crustal deformation caused by the eastward movement of the Caribbean plate in relation to the North American plate. These complex tectonic interactions have created a broad, diffuse tectonic boundary that has resulted in an extensive, internal deformational sliver slab - the Gonâve microplate – as well as further segmentation into two other microplates with similarly diffused boundary characteristics where tsunamigenic earthquakes have and will again occur. The Gonâve microplate is the most prominent along the Northern Caribbean margin and extends from the Cayman Spreading Center to Mona Pass, between Puerto Rico and the island of Hispaniola, where the 1918 destructive tsunami was generated. The northern boundary of this sliver microplate is defined by the Oriente strike-slip fault south of Cuba, which appears to be an extension of the fault system traversing the northern part of Hispaniola, while the southern boundary is defined by another major strike-slip fault zone where the Haiti earthquake of 12 January 2010 occurred. Potentially tsunamigenic regions along the Northern Caribbean margin are located not only along the boundaries of the Gonâve microplate's dominant western transform zone but particularly within the eastern tectonic regimes of the margin where subduction is dominant - particularly along the Puerto Rico trench. The Haiti earthquake of 12 January 2010 and its focal mechanism are examined, as they provide additional clues of potential tsunami generation that can occur along transform zones and, more specifically, from interplate and intraplate seismic events and subsequently induced collateral hazards, such as aerial or submarine landslides triggered by strong surface seismic waves.

Key Words: Tsunami, Haiti, Hispaniola, Caribbean northern margin, Seismotectonics.

1. INTRODUCTION

A major earthquake struck Haiti in the early evening of January 12, 2010. It resulted in extensive destruction and thousands of deaths and injuries in the capital city of Port-au-Prince and surrounding areas. It was the worst earthquake to strike the country in the last 200 years. The quake generated a local tsunami in the Gulf of Gonâve and triggered landslides along the southern coast of the island of Hispaniola - which also generated local tsunamis. To understand the12 January 2010 earthquake as well as the specific geotectonic processes that affect Hispaniola, the adjacent Greater Antilles Islands and the potential for tsunami generation in the region, we examine the seismotectonics of the Eastern and Northern Caribbean margin. The present study provides background on the seismotectonics of Hispaniola and of the rest of the Greater Antilles Islands, reviews past destructive earthquakes and tsunamis, documents both the earthquake and tsunami in Haiti and assesses the potential risk of future tsunami generation from seismic events along convergent, divergent and transform tectonic boundaries of the diffuse Northern Caribbean margin.

2. SEISMOTECTONICS OF THE CARIBBEAN REGION - Brief Overview

The Caribbean is a region of considerable tectonic complexity. The Caribbean tectonic plate is surrounded on three sides by the much larger North and South American plates, both of which are moving approximately westward at an estimated rate of about 20 to 30 millimeters per year. There is a moderate level of inter-plate seismicity and interplate and intraplate seismic and volcanic activity. The region is characterized by three main types of plate boundaries: convergent, divergent and transform (Figure 1).

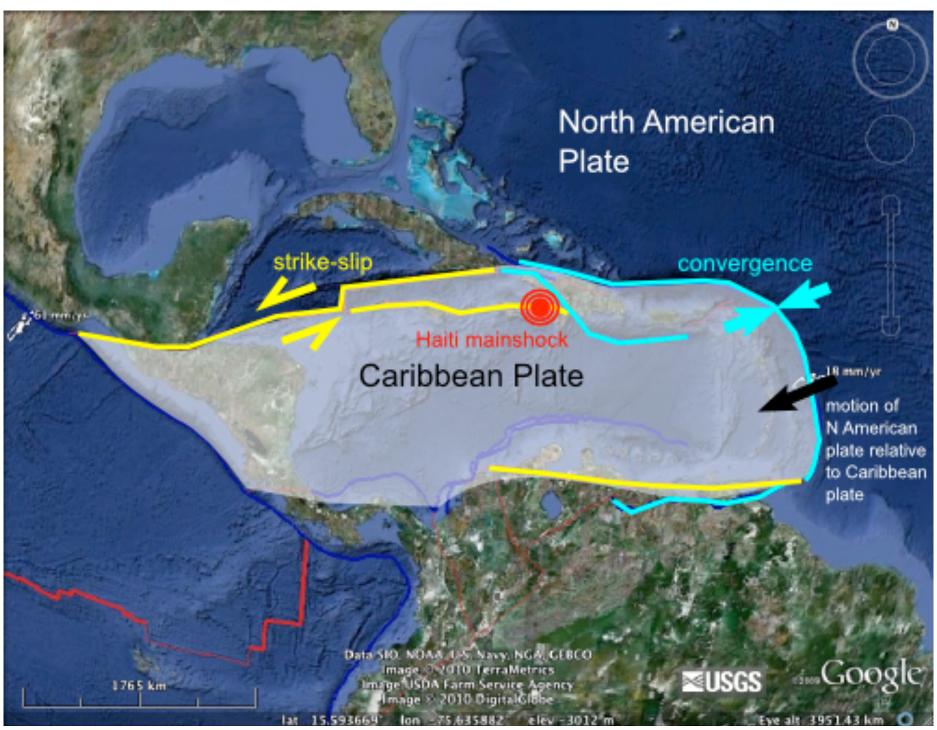

Figure 1. The Caribbean tectonic plate (USGS/Google graphic)

This tectonic activity results in frequent earthquakes, volcanic eruptions, landslides and mass edifice failures of volcanic island flanks. Most of the destructive events occur near or along the geo-tectonically active plate boundaries and are associated with complex mechanisms characteristic of each source. Generally, active seismic source mechanisms in regions of subduction in the Caribbean involve relatively small crustal blocks (Pararas-Carayannis, 2006). The present study examines the tsunamigenic potential along the segment of the Northern Caribbean margin extending from the Anegada Trough in the east to the Cayman Trough Spreading Center in the west (Fig. 2).

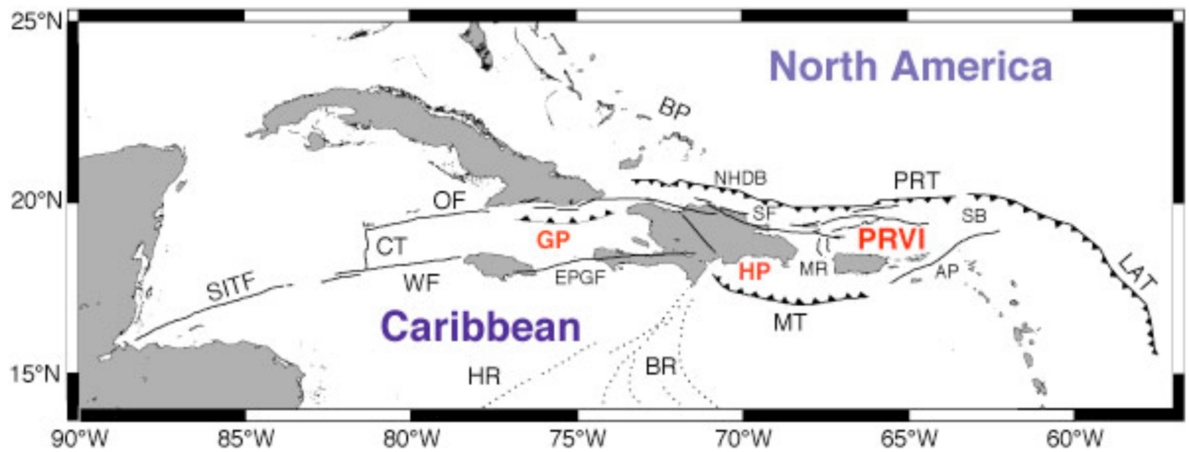

Figure 2. Northern Caribbean Margin (AP: Anegada Trough; BP: Bahamas Platform; BR: Beata Ridge; CT: Cayman Trough Spreading Center; EPGF: Enriquillo-Plantain Fault zone; GP: Gonave Microplate; HP: Hispaniola Microplate; HR: Hess Rise; LAT Lesser Antilles Trench; MR: Mona Pass Rift; MT: Muertos Trench; PRVI: Puerto Rico-Virgin Islands block; SITF: Swan Islands Transform Fault; SF: Septentrional Fault Zone; WF: Walton Fault zone (modified internet graphic).

2.1 Geotectonics of the Eastern Caribbean Margin -- Brief Overview

In the Eastern Caribbean, the interactions between the larger tectonic plates and the Caribbean plate are responsible for zones of subduction and the formation of the West Indies Volcanic Island Arc on the overlying plate. Seismic events are principally associated with a subduction zone along a north-south line, just east of the main island arc where the North American Plate dips from east to west beneath the Caribbean Plate. Additionally, the down-dip compression on the North American plate has created a tensional volcanic back-arc (Fig. 3), which is characterized by spreading and shallower seismic activity (Pararas-Carayannis, 2006).

As the fore-arc is driven by the mantle drag toward a trench – the zone of subduction - the resulting compression is balanced with the slab pull. This flow in the mantle causes back-arc spreading (Seno and Yamanaka, 1998). Arc stresses and such back-arc spreading result in increased volcanic activity in the Lesser Antilles region. Also, the inter-plate tectonic interaction near or along the marginal boundaries often results in moderate to large earthquakes. Superimposed on the inter-plate tectonic interaction is a pattern of intra-plate activity - which is more pronounced in the Leeward Islands region where subduction by the Barracuda Rise adds additional strain on both the "subducted" North American Plate and the overlying Caribbean Plate. In this region earthquakes are generally shallow and potentially tsunamigenic (Pararas-Carayannis, 2006).

Figure 3. The West Indies Volcanic Island Arc (after Pararas-Carayannis, 2006)

In the region northwest of Trinidad there is another concentration of earthquake activity where the strike of the plate boundary changes direction. The earthquakes in this region are of intermediate depth and thus not tsunamigenic. However, the potential for local tsunami generation from individual, active volcanic sources and active shallow seismic regions is relatively high (Pararas-Carayannis, 2006a). Examples of tsunamigenic volcanic activity include recent events related to the eruptions of Soufriere Hills volcano on Montserrat island (Pararas-Carayannis, 2006).

2.2. Geotectonics of the Northern Caribbean Margin

A review of geotectonic processes along the northern Caribbean margin can help assess the tsunami risk for Haiti and the Dominican Republic on Hispaniola, as well as for the other Greater Antilles Islands. Along the Northern Caribbean margin, including areas in the vicinities of Jamaica, Hispaniola and the Virgin Islands, convergent, compressional and collisional tectonic activity - caused primarily from the eastward movement of the Caribbean plate in relation to the North American plate - is also responsible for the creation of zones of subduction and the formation of volcanic island arcs on the overlying plate. The island of Hispaniola where Haiti is located, lies along the eastern Northern Caribbean margin, within the transition zone between different tectonic regimes, with subduction dominant to the east and a transform zone dominant to the west (Mann et al., 1998).

The two tectonic plates meet mainly through a combination of strike slip and interplate thrust faulting (Calais et al., 2002). As the Caribbean plate moves eastward with respect to the North American plate along the Northeastern margin at about 20 mm/yr, the oblique convergence is distributed between the subduction interface and major strike-slip faults within the overriding plate (Syed et al., 2008). In the last 250 years, this northeastern region has experienced eleven large ($M \geq 7.0$) earthquakes. Most of the significant historical tsunamis were generated along the dominant, eastern subduction regime.

The inter-plate tectonic interaction near or along these northern marginal boundaries results in moderate seismic and volcanic activity. Most of the earthquakes are of shallow depth. However, near the plate boundaries moderate, deeper, intra-plate earthquakes can also occur. The intra-plate earthquakes are caused primarily by internal deformation in a slab of the North American Plate. Concentrations of these earthquakes can occur to focal depths of up to 200 kilometers. The deformation within the North American-Caribbean plate boundary zone has resulted in what appears to be a segmentation of the Caribbean plate into three major microplates with diffused boundaries, each requiring an individual pole of rotation to describe its motion relative to the North American plate (Heubeck & Mann, 1991). The three microplates are the Gonâve (GP) and Hispaniola (HP) microplates and the Puerto Rico-Virgin Islands block (PRVI) (Fig. 2).

2.2.1 The Gonâve Microplate

The existence of the postulated Gonâve sliver microplate on the Northern Caribbean margin has been confirmed from GPS measurements of lateral movements, seismic data and patterns of folding, faulting, and tectonically-induced, Quaternary uplift of coral reefs in Western and Central Hispaniola (Dixon et al., 1998; DeMets & Wiggins-Grandison, 2007). Further west, the northern boundary of the Gonâve microplate is defined by the Oriente strike-slip fault south of Cuba (Calais and Mercier de Lepinaya, 2003), which appears to be an extension of the Septentrional fault system along northern Hispaniola. On the south the Gonâve is bounded by the Walton fault, the Jamaica restraining bend and the Enriquillo-Plantain Garden fault zone. The east boundary of the microplate is defined by faults in Hispaniola and the west boundary by the Cayman Spreading Center (CSC) (Fig. 4). The motion relative to the North American Plate is to the east. The elongated Gonâve microplate occupies an area of about 190,000 square kilometers of the northeastern Caribbean plate, which is in the process of shearing off and accreting to the North American plate (DeMets & Wiggins-Grandison, 2007; Mann, et al., 2008). Earthquakes mainly occur along the boundaries of the Gonâve microplate and some, along the subduction zone north of the Septentrional fit, have the potential to generate local tsunamis, particularly in the region along Northeast Hispaniola and closer to Puerto Rico.

Along the southern margin of the Gonâve microplate, earthquakes near the Muertos Trench also have the potential to generate local tsunamis on Hispaniola and Puerto Rico, with lesser effects on the Virgin Islands.

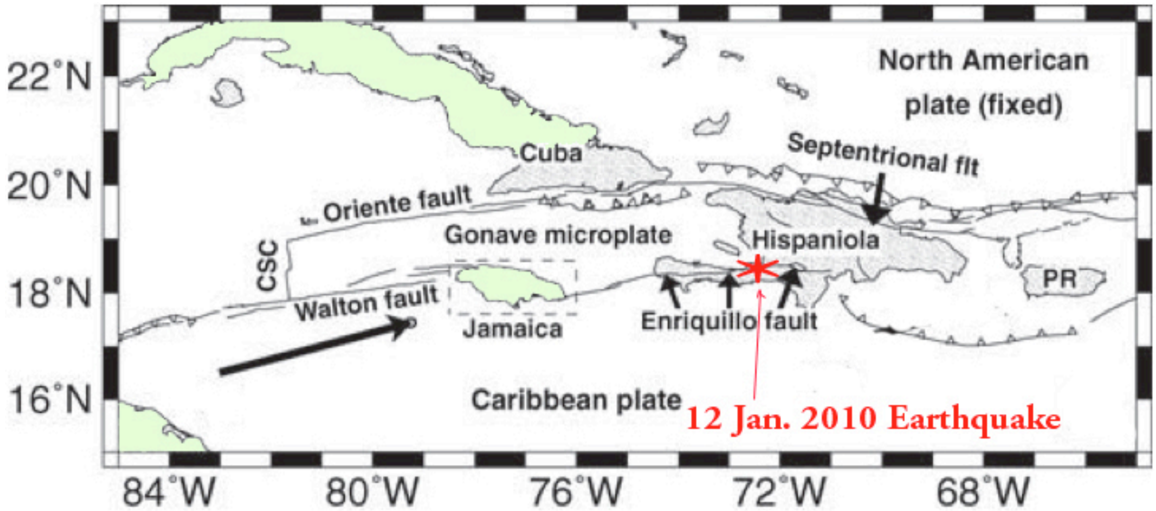

Figure 4. Location map and tectonic setting of the Gonâve microplate on the North-Central Caribbean margin. The arrows indicate the relative motion of the Caribbean plate in relation to the North American as predicted by a model (DeMets et al., 2006). CSC: Cayman spreading center and PR: Puerto Rico (Modified after DeMets and Wiggins-Grandison, 2007)

2.2.2 Hispaniola's Major Fault Zones

Part of the island of Hispaniola is within the Gonâve microplate. Active major plate-boundary structures affecting Haiti and the rest of Hispaniola, include two major left-lateral strike-slip faults and an offshore fold and thrust belt known as the North Hispaniola Deformation Belt, which is part of the subduction zone that extends beneath the northeastern Dominican Republic (Dolan and Wald, 1998; Tuttle et al., 2003). The two major, left lateral, strike-slip fault systems, which traverse Hispaniola in an approximate east-west direction, are the Enriquillo-Plaintain Garden (EPGFZE) along the southern part and the Septentrional (SFZ) along the north (Mann et al., 1995). Between the major fault zones there are a series of interconnected fault lines. Strike-slip faults are clearly visible on satellite imageries as lineaments (Thielen, 2010).

The two fault systems are part of the broader, diffuse boundary that has resulted in an extensive, internal deformational slab of the North American Plate by the aforementioned interaction, collision and subduction with the Caribbean tectonic plate. Tectonic motions are accommodated on the two faults and their offsets, which are located a little bit away from the actual plate boundary, further inside the plate's interior. However, most of the seismic activity on the Gonâve microplate is concentrated in Jamaica rather than Haiti - as shown by the epicenters of earthquakes shown in Figure 5.

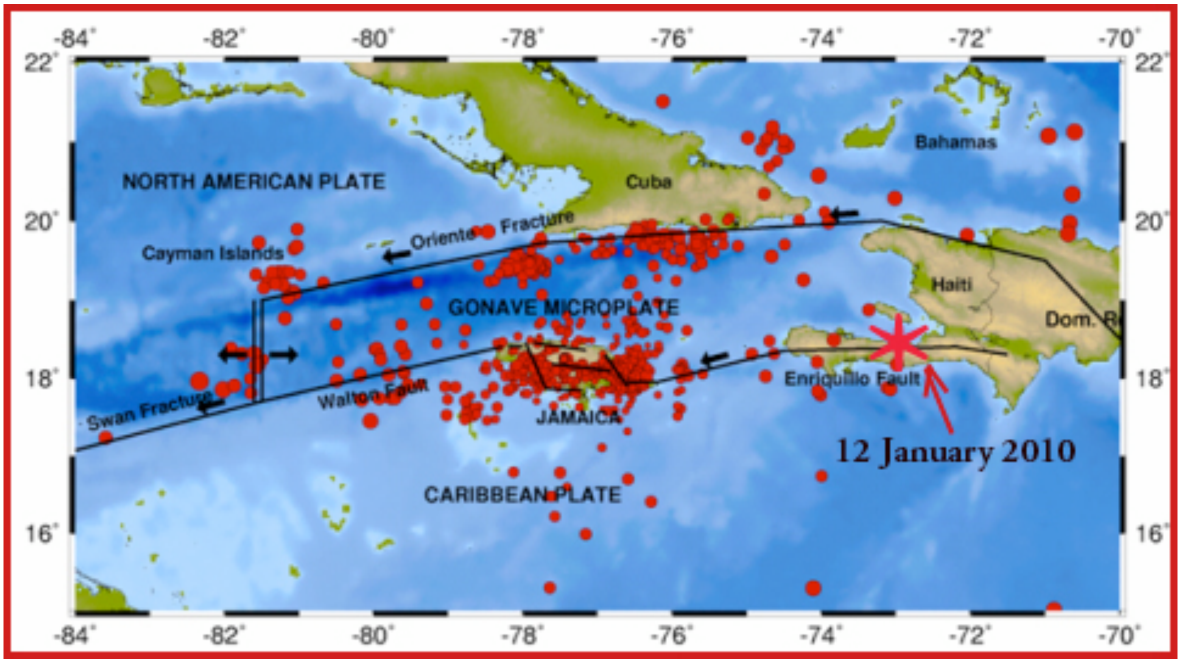

Figure 5. Seismicity of the Northern Caribbean Margin *(modified University of West Indies graphic)*

Between the EPGFZE and SFZ strike-slip fault systems, the central part of Haiti shows a diffused fractured deformational zone. The most recent phase of tectonism in this zone involves strong uplifts and broad open folding along NW-striking axes.

The Enriquillo-Plaintain Garden Fault System (EPGFZE) - The 1200-km-long EPGFZE is the southern moving edge of the Gonâve microplate (Mann et al., 1995). It provides a "bypass", strike-slip fault system which has allows continued, unimpeded eastward motion of the smaller Caribbean plate in southern Hispaniola - past zones of blocking convergence from the north. Satellite imagery and field observations indicate that the fault zone extends onshore from central Hispaniola east of Lake Enriquillo in the Dominican Republic to the westernmost end of Hispaniola, where it has a total offset of 30-50 km along Haiti's southern peninsula – considered to be a fragment of the Caribbean oceanic crust of the "Late Cretaceous Caribbean plateau basalts" (Mann et al., 1998)(Fig. 6).

The EPGFZE is similar in structure and character to the San Andreas fault of California and the Northern Anatolian fault system in Asia Minor, in that it involves strike-slip displacements, although along portions of its offsets there is evidence of transpression (compression and shear) and seismic events can include small vertical displacements that can generate local tsunamis. To the west, the fault zone crosses beneath the 50-km wide Jamaica Passage and continues west to eastern and central Jamaica where there is an apparent increase in seismicity. To the east, it extends into the Muertos Trench, a zone of subduction where earthquakes can potentially generate local tsunamis on Hispaniola and the adjacent Caribbean islands.

The earthquake of January 12, 2010 - as most of past destructive earthquakes in Haiti- occurred on an offset segment of EPGFZE, associated mostly with shallow earthquakes having left lateral strike slips (Fig. 6). However there is evidence that both vertical and lateral movement occurred - as when the 1701 earthquake struck. This segment of the EPGFZE had been locked for almost for 250 years. The last major earthquake in this particular segment had occurred in 1770. However, in 2008 there was some precursory seismic activity in the area.

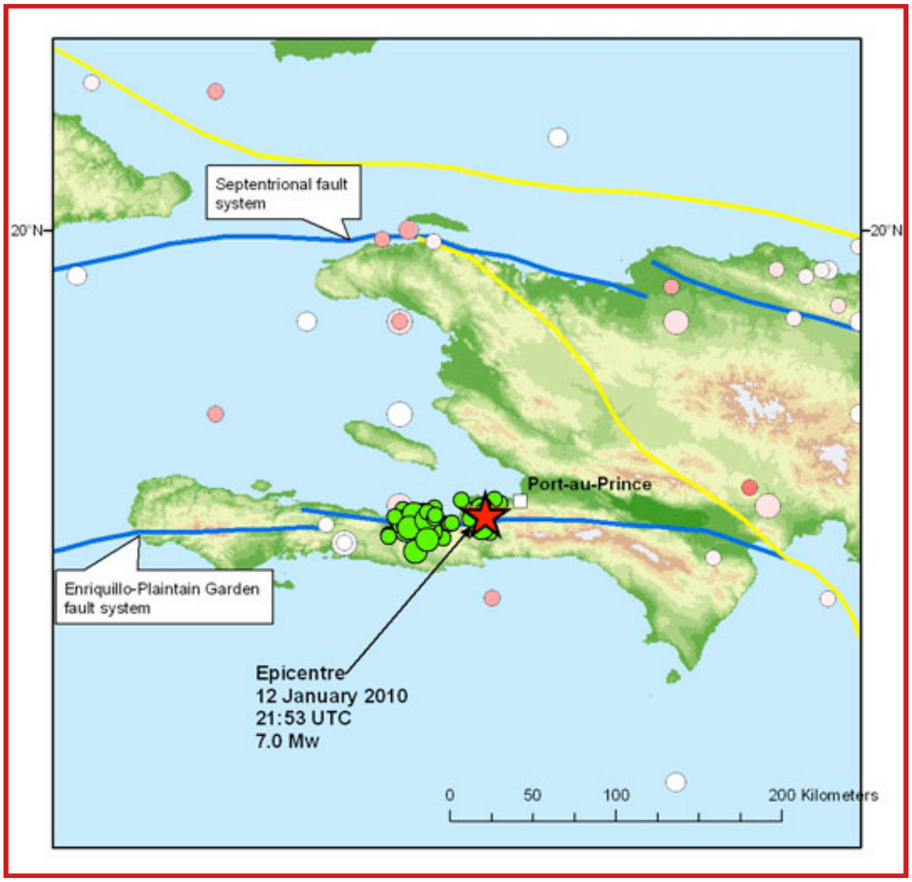

Figure 6. EPGFZE and SFZ in Haiti. Aftershock Distribution of 12 January 2010 Earthquake (modified graphic of the British Geological Survey)

The Septentrional Fault Zone (SFZ) - The Septentrional Fault Zone (SFZ) is a left-lateral fault zone located north of Hispaniola between the Caribbean and the North American plates (Fig. 6). This is a highly seismic zone. It forms part of the diffused north boundary on the Gonâve microplate and the Northern Caribbean margin. It runs through the Cibao valley in the northern Dominican Republic. To the east, it extends into the Puerto Rico subduction zone. To the west, its offset crosses northern Haiti and extends to the southern part of Cuba. There is a high probability that a strong, destructive earthquake on the SFZ could occur in the near future and impact both Haiti and the Dominican Republic.

Haiti's Regional Deformation Patterns - Between the two major strike-slip fault systems (the EPGFZE and the SFZ) the central part of Haiti shows a diffuse fracture zone that trends at N130. The most recent phase of tectonism in Haiti involves strong uplifts and broad, open folding along NW-striking axes, which is consistent with the regional maximum deformation pattern predicted for E-W left-lateral shear along the North America—Caribbean plate boundary (Pubellier et al, 2003).

3. CASE STUDY: EARTHQUAKE AND TSUNAMIS OF 12 JANUARY 2010 IN HAITI.

The traditional belief is that tsunamis are mainly generated from earthquakes along regions of subduction and not from seismic events in regions of lateral fault zones. However, as the 1999 tsunami in the Sea of Marmara indicated, transitional deformation associated with lateral faulting - such as that of the North Anatolian Fault (NAF), can result in earthquakes that can generate destructive tsunamis either by inducing sea floor uplift and subsidence by compression or by strong ground motions triggering sub aerial, submarine landslides or large scale coastal ground liquefaction. The following is a review of the earthquake of 12 January 2010 in Haiti as an interesting case of how local tsunamis can be generated along transitional segments of the Northern Caribbean margin from convergent, compressional and collisional tectonic activity.

3.1 The Earthquake of 12 January 2010 in Haiti

Haiti is on the western side of the Island of Hispaniola, one of the Greater Antilles Islands situated between Puerto Rico and Cuba. The 12 January 2010 earthquake in Haiti was an exceptional episode of sudden strain release over a wide area along a lateral offset segment of the strike-slip EPGFZE zone, which had been locked for 250 years and had accumulated great stress. There had been several minor precursor tremors in 2008 at Petionville, Delmas, Croix des Bouquets and La Plaine, which were indicative of stress increase along this segment of EPGFZ and that a large, long overdue, earthquake was highly probable. Unfortunately, not much attention was given to the precursor events, as the last major, destructive earthquake in the Port-au-Prince region had occurred in 1770. In the past major earthquakes had occurred in 1554, 1701, 1751, 1770, 1783, 1842, 1860 and 1887 along both the southern (EPGFZ) and northern zone (SFZ) (Fig. 6).

The 12 January 2010 earthquake was an extremely destructive shallow event with a focal depth of 13 km and a Moment Magnitude Mw = 7.0 (Fig. 7). It occurred at 21:53:10 UTC (04:53:10 PM local time) and its epicenter was at 18.457 N, 72.533 W (USGS), about 25 km (15 miles) WSW of PORT-AU-PRINCE; 130 km (80 miles) E of Les Cayes, 150 km (95 miles) S of Cap-Haitien, Haiti 1125 km (700 miles) SE of Miami, Florida (USGS data). Its strong ground motions lasting for 35-40 seconds were felt as far away as Jamaica. As in 1751, there was extensive ground cracking and liquefaction in the wide Cul-de-Sac plain - a rift valley that extends eastwards into the Dominican Republic.

Following the main shock up to January 25, 2010, there were at least 24 aftershocks ranging in magnitude from 5.0 to 5.9. Most of the aftershocks occurred to the west of the main earthquake in the region known as the Mirogoane Lakes, which is a basin formed by a 5 km pull-apart displacement from EPGFZ (Mann et al., 1995).

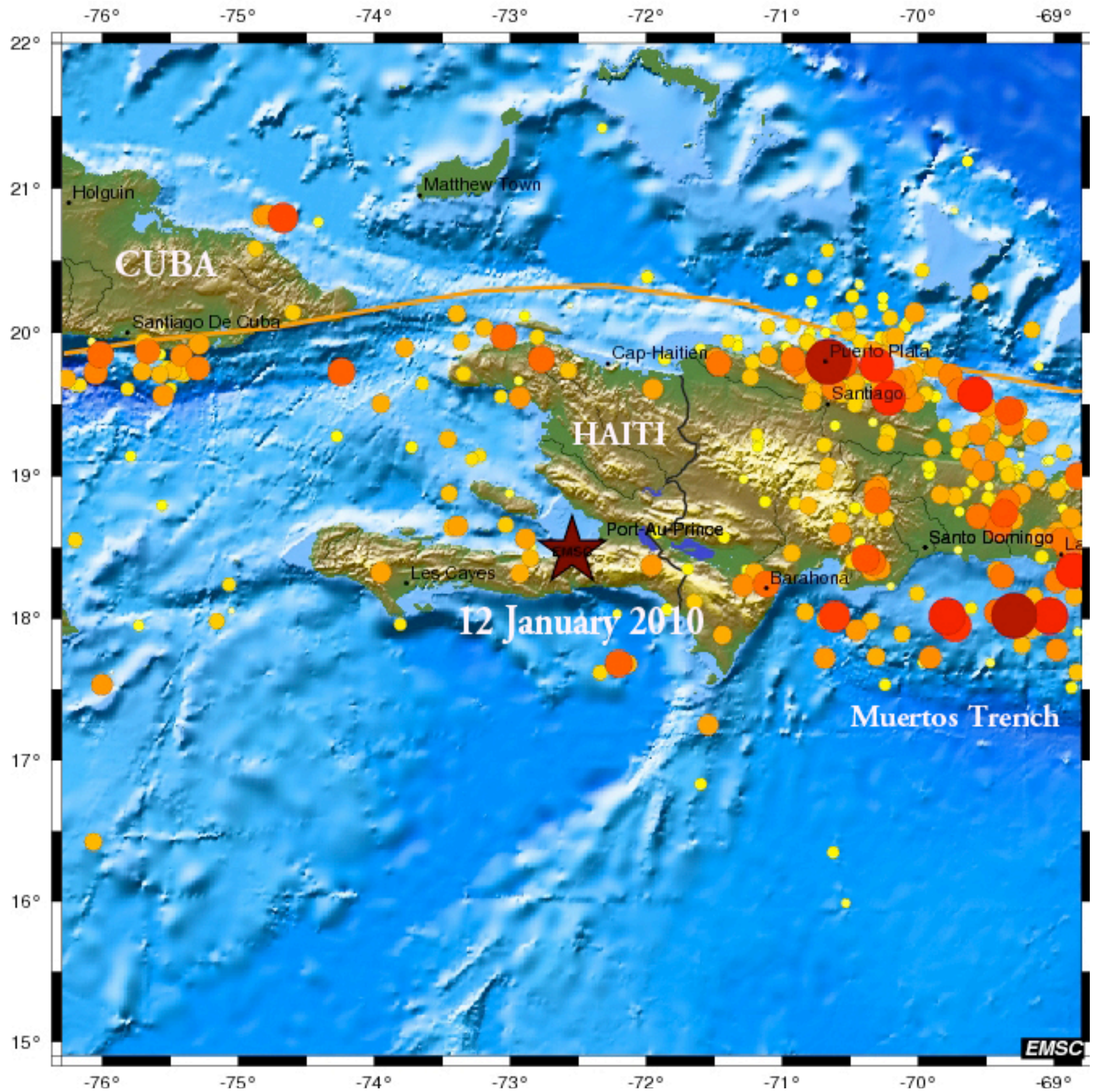

Figure 7. Seismicity from 1964 to 12 January 2010. Earthquakes ranging from M4 to M7.5, including the 12 January 2010, M7.1 earthquake. (Modified graphic of EMSC)

Based on the distribution of the aftershocks it appears that the earthquake's rupture was relatively short and estimated at about 75 km (Fig. 8). However, field investigations around the epicentral area found no clear evidence of rupture on the surface above the plate-boundary fault (Bilham, 2010), which is consistent with satellite radar images taken before and after the earthquake which indicate that the rupture started more than 8 kms in depth but ended at least 2 k below the earth’s surface. The significance of such absence of clear rupture is discussed in a subsequent section as it relates to estimates of earthquake recurrence frequencies and potential remaining stress in the region that could result in significant earthquakes and the generation of local tsunamis.

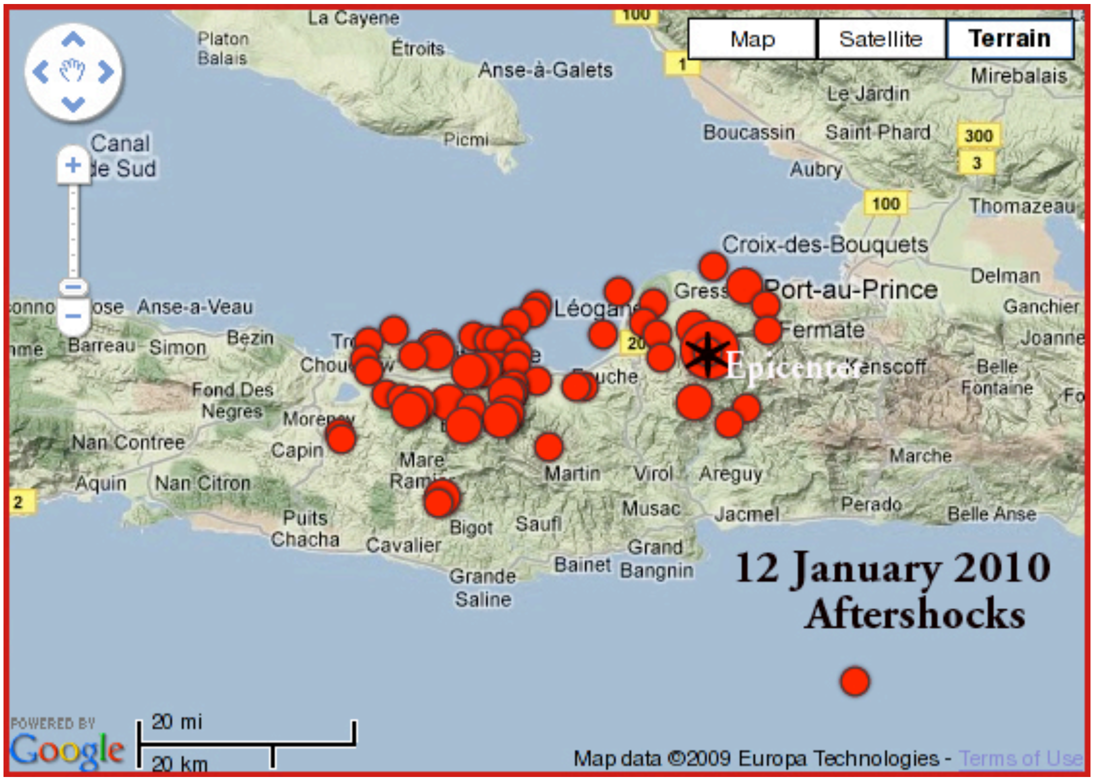

Figure 8. Aftershocks up to January 25, 2010 (modified after Europa Technologies)

3.1.1 Focal Mechanism

The earthquake's focal solution indicates that crustal movements resulted mainly from strike-slip shear. However, the focal mechanism solution (Fig. 9) shows evidence of transtension (extention & shear) as small vertical displacements – both uplift and subsidence - occurred along a portion of the coastline of the region known as the Mirogoane Lakes in the Gulf of Gonave, which as mentioned is a basin formed by a 5 km pull-apart displacement from EPGFZ (Mann et al., 1995).

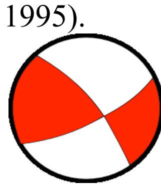

Figure 9. Focal Mechanism of the 12 January 2010 Earthquake.

3.2.2 Remaining Stress

It appears that not all the stress has been released on the EPGFZ. Coulomb stress is evident along both the east and west segments adjacent to that affected by the 12 January 2010 earthquake (Fig. 10). The segment to the east appears to have undergone the greater change in Coulomb stress, thus an earthquake with epicenter closer to Port Au Prince is very possible. Stress transference may also result in strong earthquakes or aftershocks in southern Haiti (east and west) along segments of EPGFZ – and as far west as Jamaica. The significance of the remaining stress for future earthquakes and tsunamis is evaluated in a subsequent section.

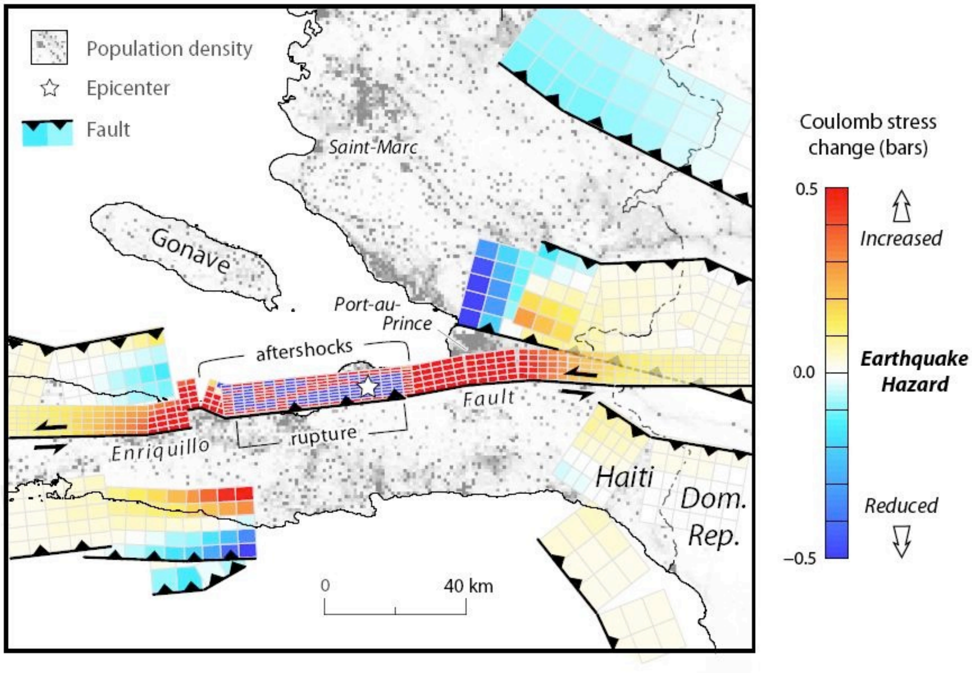

Figure 10. Coulomb stress change after the 12 January 2010 Earthquake (web graphic)

3.3 The Tsunamis of 12 January 2010 in Haiti

An overview of tsunami events in the region was provided by NOAA's Satellite and Information Service (NESDIS). Accordingly, the earthquake generated a local tsunami in the Gulf of Gonâve with a height of 3.3 meters at Petit Paradis - about 62 miles (100 kilometers) away from the earthquake's epicenter. The waves run 70 meters inland causing damage (Lovett, 2010). Seven people were swept out to sea. Trees in the water provided evidence of ground subsidence, as in 1770.

3.3.1 Tsunami Generation Mechanisms

As a general rule, strike-slip earthquakes do not generate tsunamis of any significance as motions involve primarily lateral crustal movements. However, the January 12, 2010 earthquake involved pull-apart motions, as well as small offshore uplift and coastal subsidence, similar to those caused by the 1770 quake. The tsunami was generated mainly by vertical changes of up to 50 cms. Figure 11, below shows the tsunami generating area. However, there is also evidence that the observed tsunami waves were caused by landslides in the Gulf of Gonâve. Both satellite imagery and on-the-ground photos show drastic changes in inland as well as coastal configuration. For example, a field survey found that a palm tree had slid from the shore to a water depth of 7 meters (Fritz, 2010). Waves with 15-second period arrived almost immediately after the quake, which also supports generation by landslides, and localized uplift and subsidence along the coast.

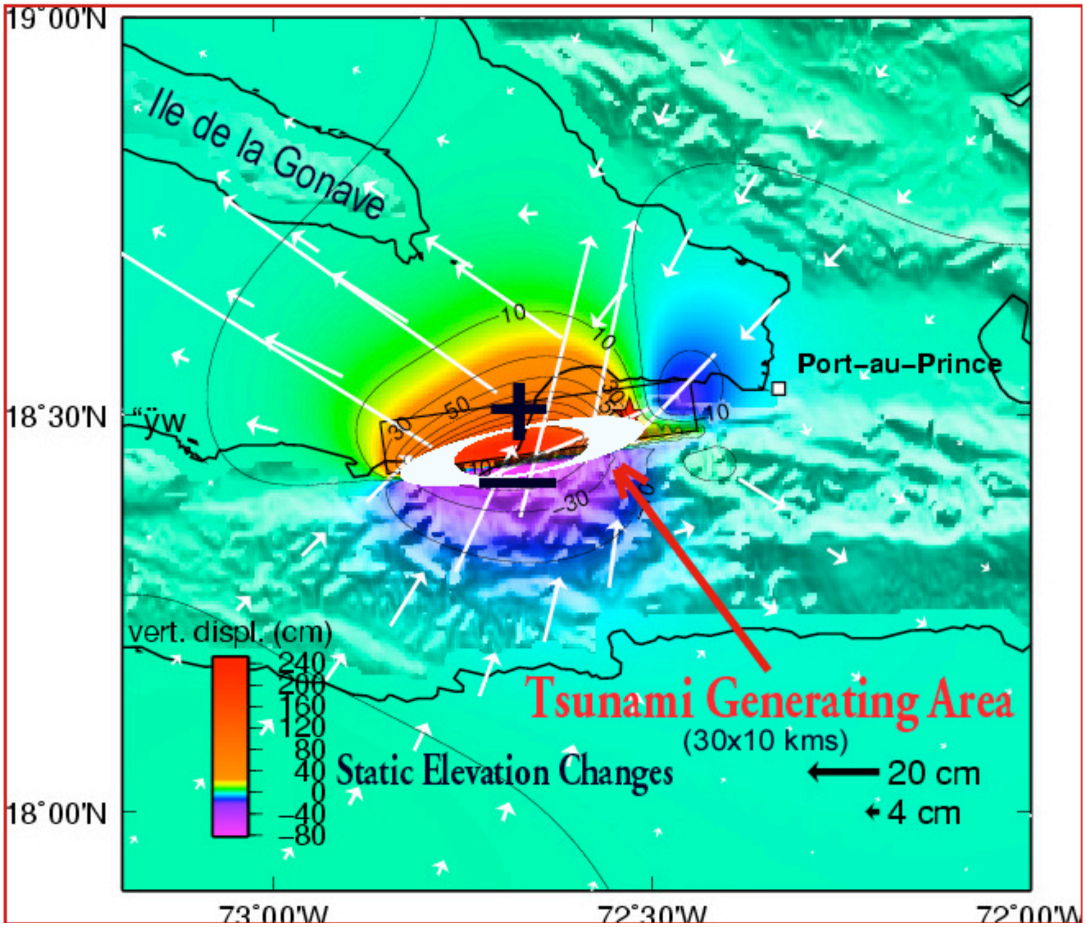

Figure 11. Tsunami Generating Area as inferred from Distribution of Static Elevation Changes and visual field observations (Modified web map of reported static elevation changes with superimposed tsunami generation area estimated at 300sq. Kms.)

Additional field investigations found that sizeable tsunami waves with periods of about 5 minutes and as high as three meters struck along a 100-kilometer stretch of the shoreline on the southern coast of Haiti, all the way into the neighboring Dominican Republic. This led to the conclusion that the tsunami generation in this region was caused by multiple coastal and underwater landslides or perhaps from a larger offshore region. A major landslide is evident on satellite imagery (Fig. 12) at the Bay of Jacmel, on the southern coast of Haiti where a field survey documented strong wave activity. Tsunami wave action washed boats and boulders ashore and knocked down walls at the town of Jacmel (Fritz, 2010). There is also evidence that strong seismic waves from past earthquakes triggered numerous landslides along the southern coast (Bilham, 2010).

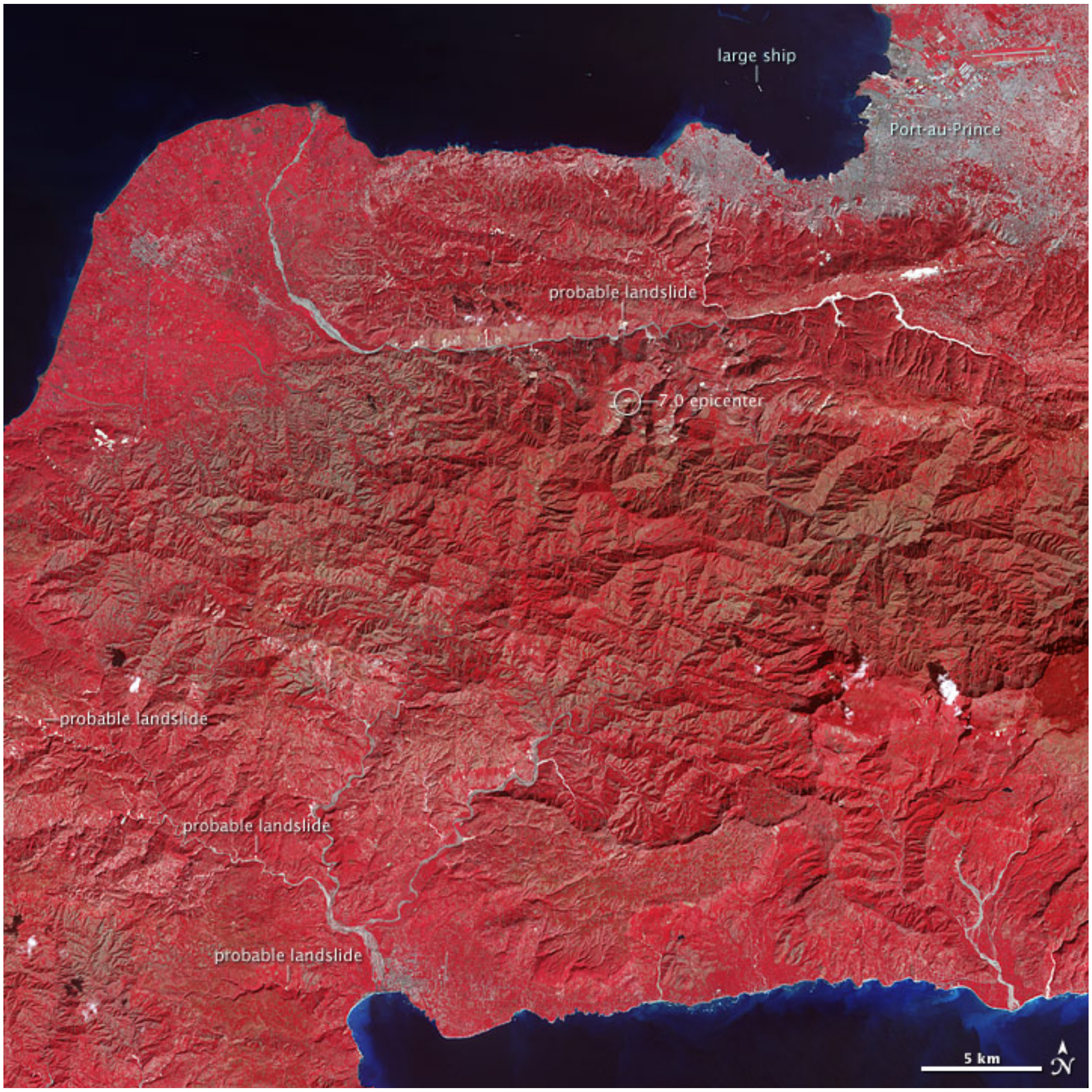

Figure 12. Satellite image (false color) of Haiti's southern peninsula taken on 21 January 2010 with ASTER instrumentation (resolution 15 m) from NASA's Earth Satellite shows (in lighter color) landslides generated by the strong ground motions of the 12 January 2010 earthquake and the location of the ones that generated a local tsunami at the Bay of Jacmel, and elsewhere on the southern coast (Modified NASA graphic haiti_ast_2010021_lrg-1.jpg)

4. HISTORICAL EARTHQUAKES AND TSUNAMIS ALONG THE NORTHERN CARIBBEAN MARGIN

Assessment of the tsunami risk along the Northern Caribbean margin requires review of past events, of their source mechanisms and of their specific impacts. There is a long record of earthquakes throughout the Caribbean region since the arrival of Christopher Columbus in 1492. Some of the larger quakes generated destructive local tsunamis. However not all of the tsunamis were sufficiently documented and could be confirmed.

The historic record shows that at least six of the more significant tsunamis were generated along the Northern Caribbean margin. Also, that a total of twenty-three tsunami-like events occurred along the Lesser Antilles region on the Eastern Caribbean margin. Sixteen of those in the Lesser Antilles were identified as having seismic origin, four of volcanic origin and three of unknown source (Zahibo et al., 2003).

Jamaica has a long history of earthquakes and was severely struck by two destructive earthquakes in 1692 and 1907. As previously stated, most of the larger destructive earthquakes in Haiti and the Dominican Republic have occurred along the EPGFZ in the southern part of Hispaniola and along the SFZ in the northern part of the island.

Figure 13 below shows the focal mechanisms of earthquakes that have occurred along the eastern segment of the Northern Caribbean Margin (Ali et al., 2008). As described subsequently, some of these quakes generated destructive tsunamis.

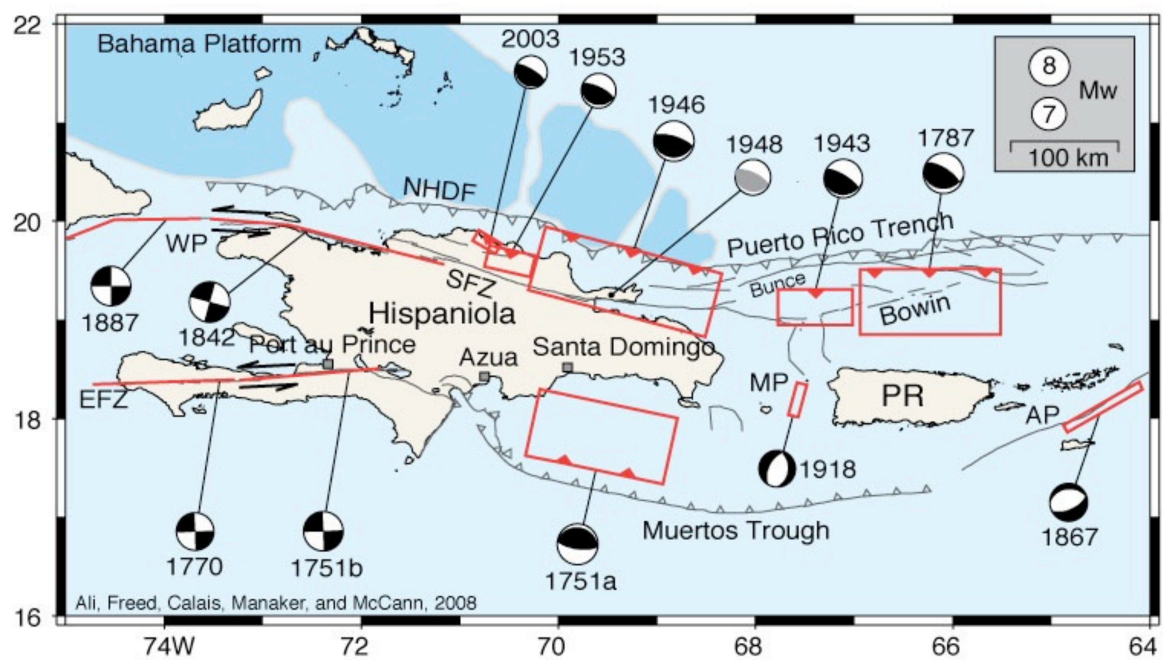

Figure 13. Focal mechanisms and surface projections of estimated rupture planes/geometries for large (M>7.0) historic and a recent M6.5 earthquakes in the Gonave microplate boundaries region since 1751. (Acronyms - NHDF: North Hispaniola Deformation Front; NHF: North Hispaniola Fault; WP: Windward Passage; EFZ: Enriquillo Fault Zone; SFZ: Septentrional Fault Zone; MP: Mona Passage; PR: Puerto Rico) (From Ali et al., 2008).

Along the EPGFZ on Hispaniola, large, destructive earthquakes occurred in 1701, 1751, 1770, 1842, 1860 and 1887 (Dixon et al., 1998; Mann, 2005). Along the SFZ, large destructive earthquakes occurred at Cape Haitien in 1842 and at Pointe-a-Pitre in 1843 (Tomblin, 1981). The following is a listing of the most destructive earthquakes and tsunamis in the northern Caribbean region that impacted Hispaniola and some of the other Greater Antilles Islands up to 1946.

1554 - The first recorded earthquake occurred in 1554 when Haiti was still the Spanish colony of Española. This earthquake destroyed Concepción de la Vega and Santiago de los Caballeros.

1692 June 7 - An earthquake (Epicenter 17.80 N - 76.70 W) that destroyed Port Royal, Jamaica, caused a tsunami that inundated the south coast of the island. About 2,000 people died.

1701 November 9 – The earthquake was one of the most destructive and believed to have occurred between Ile de la Gonave and Haiti's southern peninsula. Port-au-Prince had not yet established. There was severe damage and subsidence around Léogâne. Reportedly, the coastal road from Léogâne to Petit Goâve sank into the sea (Taber, 1922). A tsunami was generated but there are no details of its height of extent of destruction.

1751 October 18 – A major shallow quake with an estimated magnitude up to M8 and epicenter at 18.50 N -70.70 W, destroyed Port-au-Prince and adjacent region of southern Haiti (Taber, 1922).

1751 November 21, 22 - Two more severe quakes occurred on the segment of Enriquillo Fault Zone between Petionville and Tiburon and destroyed the newly established town of Port-au-Prince. There was extensive ground cracking and liquefaction on the Cul-de-Sac plain, which caused the collapse of many buildings.

1770 June 3 – A major, shallow quake occurred at 7:15 pm. Its epicenter was estimated to have been at 18.30 N -72.20 W along the segment of Enriquillo Fault Zone extending from Petionville to Tiburon. There was a subsequent shock. Reportedly the ground motions lasted for about four minutes. Strong ground motions felt as far as in Cap-Haïtien, about 160 kilometers (99 mi) away. Reports that even chimneys in Jamaica collapsed. There were landslides in the mountains, and rivers were dammed. The quakes caused ground cracking and liquefaction, which resulted in extensive destruction from Croix de Bouquets in the east through the plain of the Cul-de-Sac, to Port-au-Prince, as well as along the north coast of the Tiburon Peninsula as far as Miragoâne to the west (Taber, 1922). All buildings between Lake Miragoâne and Petit-Goâve, to the west of Port-au-Prince were leveled. At Grand Goâve the foot of the mountain of La Saline was partly submerged. The village of Croix des Bouquets sank below sea level.

Also, the earthquake generated a tsunami in the Gulf of Gonâve that inundated the coastline inland by as much as 7.2 kilometers (4.5 mi) in the Cul-de-Sac depression (O'Loughlin & Lander, 2003). However this extensive inundation may have been partially due to the effects of subsidence and ground liquefaction. - as in the Gulf of Izmit, in Turkey when the 1999 struck. The death toll from the tsunami is not known.

The death toll of the earthquake was surprisingly low. The reason may have been a rumbling sound that preceded the earthquake, which served as a warning for people to evacuate structures that subsequently collapsed. Only 200 people died in Port-au-Prince from the collapse of buildings, including 79 of 80 people in the hospital. Fifty more people died in Léogâne. However, following the earthquake, 15,000 more people died from famine and diseases.

1781 October 22 - A 10-foot high sea wave swept away houses and killed 10 people on the south coast of Jamaica after an earthquake (epicenter 18.20 N -78.10 W) that occurred during a hurricane.

1783 - A strong quake caused partial collapse of a principal church in Santigo.

1842 May 7 - A disastrous quake (M7.7) near Cap Haitien (epicenter 18.50 N -72.50 W) killed half the population of the town of ten thousand. There were two distinct shocks - the second lasting longer. The earthquake did serious damage to Henri Christophe's palace at Sans Souci image and to the Citadelle La Ferrière near Milot. Milot was Haïti's former capital under the self-proclaimed King Henri Christophe, who ascended to power in 1807, three years after Haïti had gained independence from France.

The earthquake generated a tsunami with an approximate run-up of 4 or 5 meters (13 to 16 feet), which struck the nearby city of Port de Paix (O'Loughlin & Lander, 2003). The tsunami was preceded by a 60-meter (about 197 ft) withdrawal of the sea. The tsunami struck along the northern coasts of the Dominican Republic, Haiti and the Virgin Islands. Several hundred fatalities were recorded at the time, but it is not clear how many were tsunami-related.

1843 February 8 - An earthquake (M8.3) at Pointe-a-Pitre (epicenter 16.50 N - 62.20 W). No information available on a tsunami

1867 November 18 – A 7.5 earthquake along the north scarp of the Anegada Trough, followed by another strong quake ten minutes later (epicenter 18.40 N - 64.30 W about 15 to 20 km southwest of St. Thomas), generated a tsunami that struck the U.S. Virgin Islands. Only 17 lives were lost. A maximum tsunami height of 10m was reported for two coastal locations (Deshaies and Sainte-Rose) in Guadeloupe (Zahibo et al 2003). The US Navy ship *Monongahela* was cast ashore at St. Croix by the tsunami (refloated six months later).

1907 - Major earthquakes occurred in Jamaica. No information available on a tsunami.

1918 October 11 - A 7.5 magnitude earthquake in the Mona Passage, between Puerto Rico and Hispaniola (Epicenter 18.50N - 67.50 W), produced a tsunami waves that struck the western coast of Puerto Rico with run-up of up to 6 meters. There were 116 fatalities, 40 of them directly from the tsunami. Two-inch waves were recorded at Atlantic City, N.J. A second strong tsunamigenic earthquake in the same epicentral origin occurred on 25 October 1918.

1946 August 4 – A magnitude M8.1 earthquake off the northeast coast of the Dominican Republic (epicenter 19.30 N - 69.00 W) triggered a tsunami that killed about 1,800 and partially impacted Haiti. 20,000 people rendered homeless (O'Loughlin & Lander, 2003). The wave was also recorded as far as Daytona Beach in Florida and Atlantic City in New Jersey. A second large earthquake (M7.9) occurred on August 8, 1846.

A more recent tsunami list for the Caribbean published in 2002 shows that in the last 35 years prior to 2002, four local tsunamis occurred along the Eastern

Caribbean margin. Subsequently, however, there have been additional local tsunamis in the Lesser Antilles generated by volcanic flank collapses and pyroclastic flows – specifically from recent eruptions of the Soufriere Hills volcano on Montserrat.

1969 December 25 - An earthquake with magnitude M7.6 in the Lesser Antilles (epicenter 15.79 N - 59.64 W) generated a local tsunami. Maximum tsunami height in the Barbados was 46 cm.

1985 March 16 – A moderate earthquake with magnitude 6.3 in Guadeloupe, generated a local tsunami of several centimeters in height which was recorded at Basse Terre, on Guadeloupe.

1997 July 9 - An earthquake of magnitude 6.8 off the coast of Venezuela generated a small local tsunami on Tobago.

1997 December 26 - A volcanic eruption of the Soufriere Hills volcano in Montserrat generated a wave with a height of 3 m at Old Road Bay (Hooper and Mattioli, 2001).

5. ASSESSMENT OF TSUNAMIGENIC POTENTIAL ALONG THE NORTHERN CARIBBEAN MARGIN

A total of 88 tsunamis - most of them moderate - have been reported in the earthquake-prone, volcano-ringed Caribbean area since 1489. Several of these were generated by volcanic eruptions, collateral volcanic flank failures, debris avalanches and landslides (Pararas-Carayannis, 2006). Based on the historic record, there is a high probability that a destructive tsunami will be generated again in the Northern Caribbean region that will affect coastal areas of the Virgin Islands, Puerto Rico, the Dominican Republic and Haiti. Tsunami waves with a height of up to 10-12 meters could strike coastal areas. The effects of past tsunamis generated along the eastern segment of the Northern Caribbean margin have extended up to 1,320 miles. Thus, there is a high probability that future events may have some far-field impact. Additionally, there is a possibility that an outer ridge earthquake on the Northern Caribbean margin (Fig. 14) but further away from the zone of subduction, could trigger a significant tsunami.

Because of the oblique subduction, there is a great deal of crustal deformation, not only along the southern side of the tectonic boundaries, but also along the outer ridge of the North American plate to the north.

5.1 Potential Tsunamigenic Earthquakes along the Eastern Segment of the Northern Caribbean Margin.

The strain that has been accumulating along the eastern segment of the Northern Caribbean margin was not fully released by the 1867 Anegada Trough or the 1918 Mona Pass events. In addition to past earthquakes, many small underwater landslides and cracks, 20 miles or more long, exists on the sea floor off the coast of Puerto Rico, near where the 1918 tsunami originated. Cracking indicates that these areas are close to failure. Besides the 1918 event occurred in Mona Pass, along the eastern inter-plate convergent boundary of the Gonâve microplate and not exactly on the northern edge of the Caribbean margin. As previously mentioned, three main types of plate boundaries characterize the northeastern Caribbean region: convergent, compressional and collisional. There is also an abrupt change in the obliquity of tectonic convergence. Thus, there is a high probability that a major or even a great tsunamigenic earthquake ranging in magnitude from 7 to 8 - or even greater - could occur somewhere along the northeastern segment of the Northern Caribbean margin. Also a repeat of the May 7, 1842 quake (M7.7) near Cap Haitien on Hispaniola could generate a destructive tsunami.

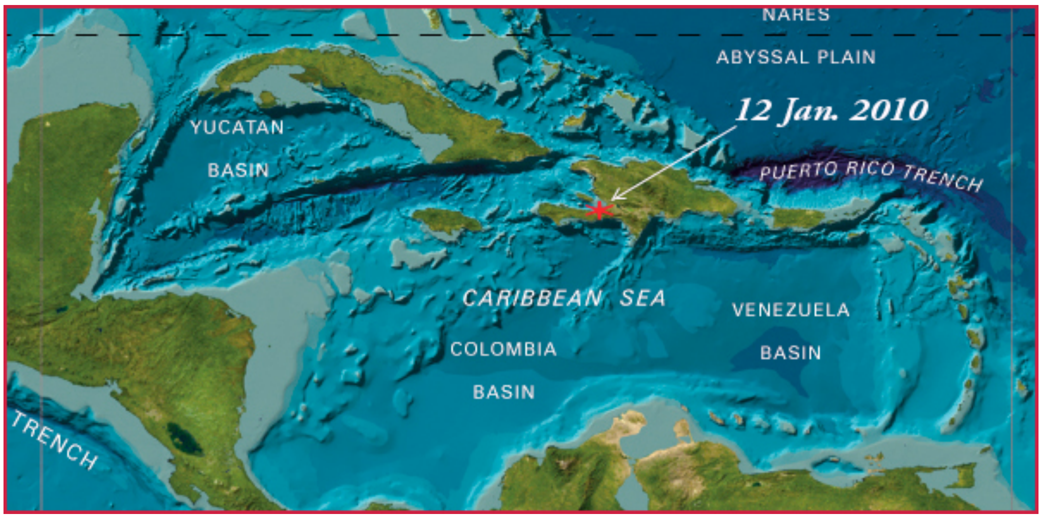

Figure 14. The Northern Caribbean Margin.

5.1.1 Potential Tsunami Impact in the Virgin Islands, Puerto Rico and Hispaniola.

As indicated, the northeastern region of the Northern Caribbean margin is tectonically complex. A great amount of stress has been building up along the segment closer to the Virgin Islands and Puerto Rico caused by about 20 to 30 millimeters of westward movement of the North American plate. Based on localized crustal movements, as well as the oblique convergence between the North American and Caribbean plates, it would be expected that stress is distributed, not only between the inter phases of subduction but also along the major strike-slip faults within the overriding Gonave microplate and the adjacent segment of the Antilles Arc where subduction is more oblique. The next tsunami generated in this northeastern region of the Northern Caribbean margin can be expected to be very destructive since a great deal of development has taken place.

Virgin Islands and Puerto Rico

Continuous underthrusting by the North American plate has also increased the possibility of a major earthquake to occur along the Puerto Rico Trench as well as the likelihood of an outer ridge event to the north of the tectonic boundary - where there is a lot of tectonic deformation and tilting of large fractured, limestone slabs. A major or even a great earthquake along this northeastern boundary has the potential of generating a destructive tsunami in the Virgin Islands and Puerto Rico and could also have significant far-field impact in Florida, the Bahamas and elsewhere. Large-scale landslides could also be triggered and there is evidence that such events have occurred in the past (Fig. 15) that perhaps generated tsunamis.

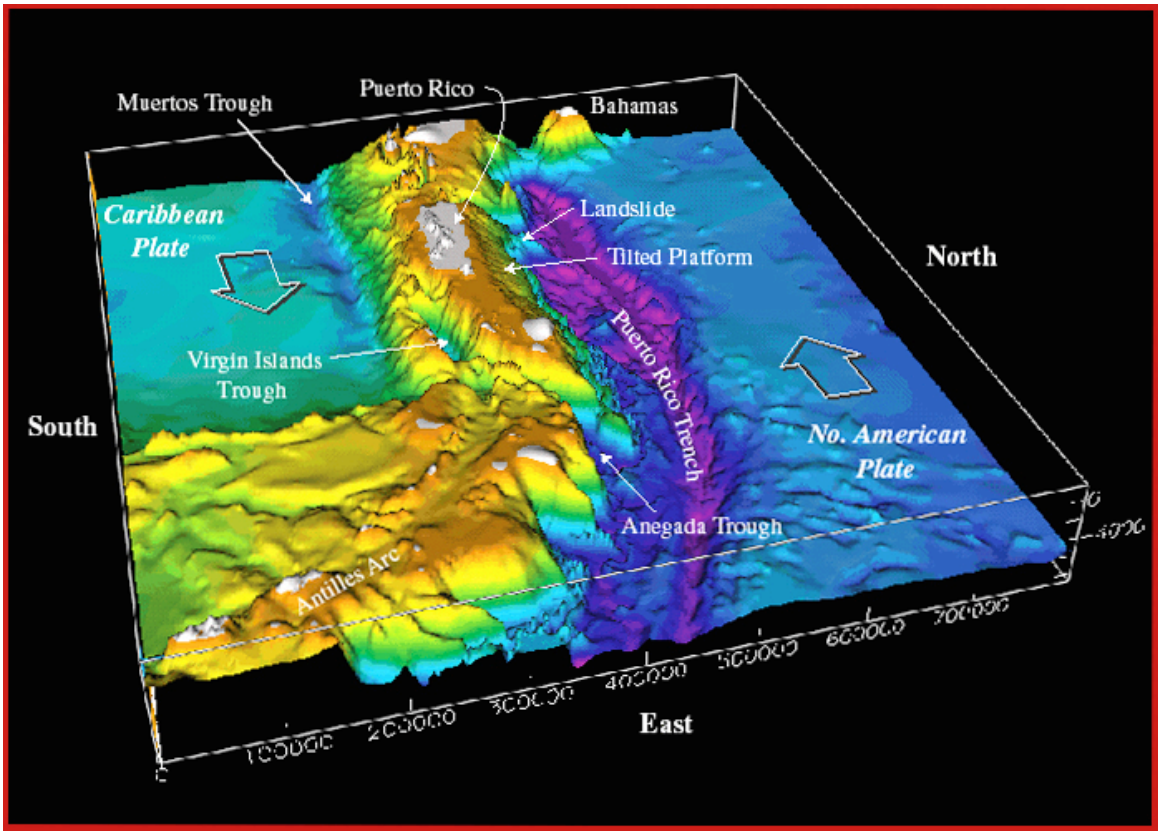

Figure 15. Morphology and bathymetry of the Northeastern segment of the Northern Caribbean Margin (Woods Hole Oceanographic Institute and NGDC graphic)

Additionally, tectonic irregularities in both the Anegada Trough and the Mona Pass regions could also result in major earthquakes. Thus, there is great potential for tsunami generation along the bend of the Antilles Arc closer to the Anegada Trough where the 1867 earthquake occurred (Fig. 15). Such an event is long overdue. This time, the tsunami that will be generated will have a more severe impact in the Virgin Islands because of population growth and development along coastal areas. It could also have far-field impacts in Florida, Bahamas and as far north as the eastern U.S. coast.

Also, as previously indicated, the Mona Pass marks the boundary of the western boundary of the Puerto Rico microplate east of Hispaniola (Figs. 13, and 15). Major earthquakes along this microplate boundary have the potential to generate local tsunamis, particularly in the region closer to Puerto Rico. Another major earthquake similar to the two which occurred in 1918 (M7.5, Epicenter 18.50N - 67.50 W) can be expected to occur in the future. Such earthquake will generate destructive tsunamis that will strike mainly the western coast of Puerto Rico and to a lesser extent the eastern coast of Hispaniola and perhaps the Virgin Islands. Waves with run-up of up to 6 meters can be expected on the western coasts of Puerto Rico, with lesser heights elsewhere in the region.

Hispaniola (Haiti and Dominican Republic)

As previously indicated, the 12 January 2010 earthquake in Haiti did not release totally the strain that has build up along this segment of the Enriquillo-Plaintain Garden fault (EPGFZ) on Hispaniola. Figure 16 (JAXA image, Univ. of Miami, 2010) depicts the 2010 earthquake's rupture and the potential future rupture to the east that may result from stress transference.

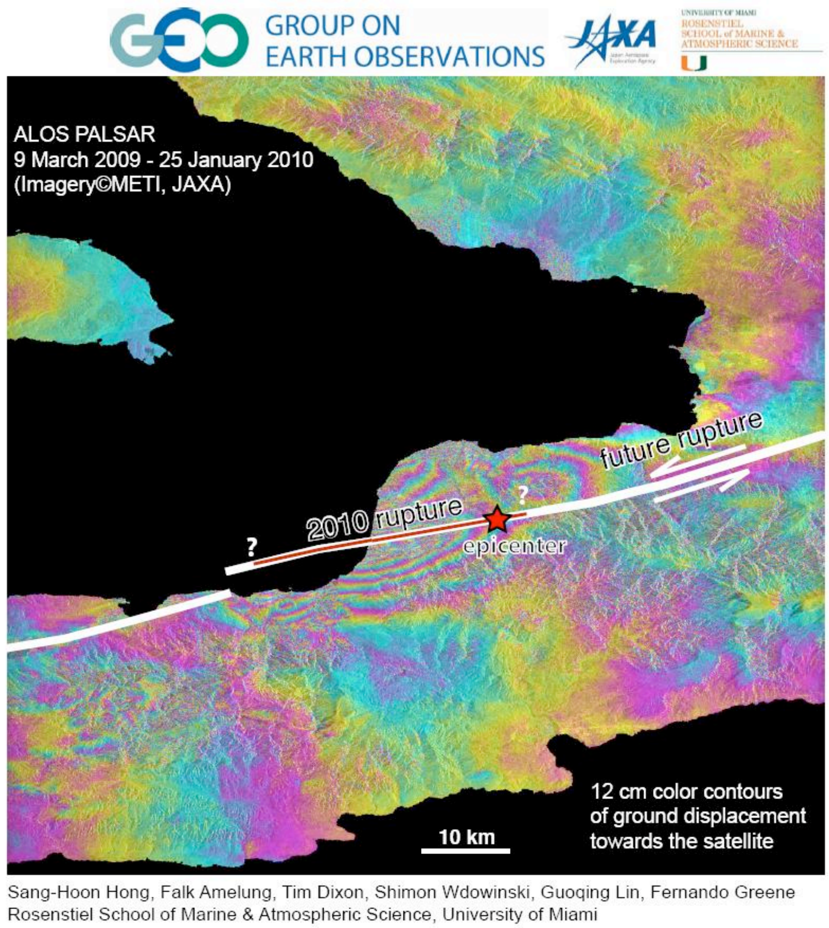

Figure 16. JAXA image illustrating the segment to the east of the 2010 earthquake on the EPGFZ that is likely to have a destructive earthquake in the future.

Coulomb stress is evident to the segments east, west and south of the stricken area. The adjacent segments of the subsurface rupture on the EPGFZ are now near breaking point because of stress transferred to them (Bilham, 2010). Such progression of Coulomb stress occurs along similar strike slip faults, as for example the Northern Anatolian fault in Turkey (Pararas-Carayannis, 1999). Thus a major earthquake similar to the 2010 event is likely to occur again – more likely along the eastern segment where the stress is greater (Ali et al. 2008).

Such an earthquake could result in further transtension (extension and shear) and pull-apart displacement on the fault or its offsets, as in the Mirogoane Lakes in the Gulf of Gonâve. The earthquake epicenter will be closer to Port au Prince, so it could be very destructive, given the population density and poor construction of buildings. Also, crustal extention and shear along offsets will result in strong ground motions that would trigger again landslides that could generate local tsunamis in the Gulf of Gonâve and along the southern coasts of Haiti and the Dominican Republic.

Additional study of Coulomb stress changes in the areas affected by the February 12, 2010 earthquake in Haiti, based on coseismic slip distribution (Fig. 17), is also indicative of stress to the south of the stricken area. An earthquake further south could result in landslides that could generate local tsunamis at the Bay of Jacmel and elsewhere along the southern coast of Hispaniola.

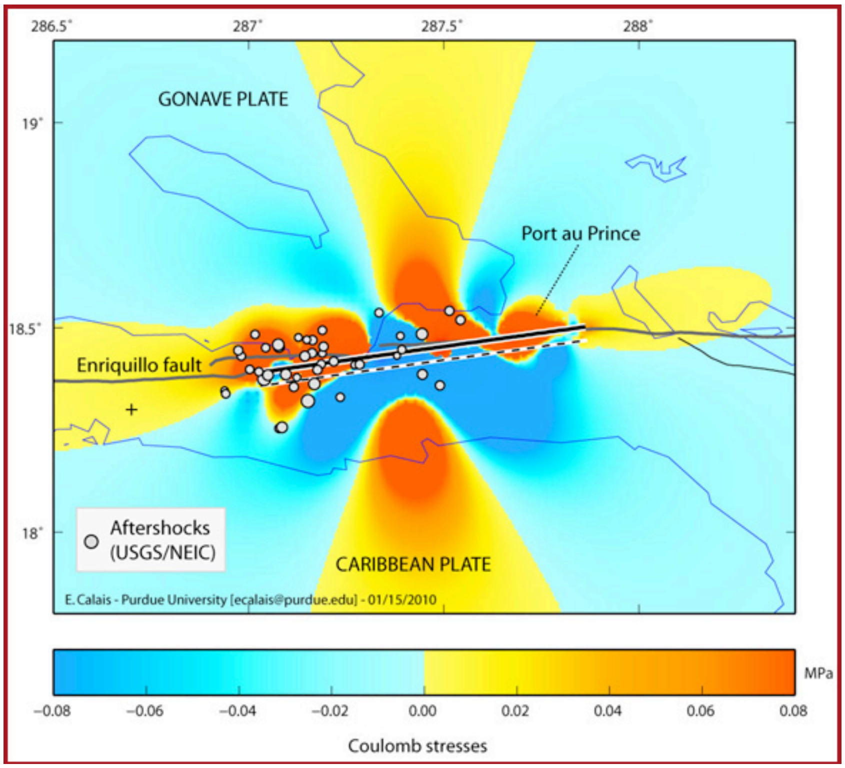

Figure 17. Changes in Coulomb failure stresses caused by the February 12, 2010 Haiti Earthquake, with red indicating regions that have been brought closer to rupture. Calculations assume friction of 0.2 on receiver faults with strike = 90°, dip = 90°, and rake = 0° (i.e., assuming pure left-lateral strike-slip). (Modified from: http://web.ics.purdue.edu/~ecalais/haiti/ based on coseismic slip distribution from G. Hayes (USGS/NEIC)

Along the southern margin of the Gonâve microplate, earthquakes near the subduction region characterized by the Muertos Trench (Figs. 13 &15) have the potential to generate local tsunamis that can impact mainly Hispaniola and Puerto Rico, with lesser effects on the Virgin Islands. Another earthquake similar to the1751 on the Muertos Trench (Fig. 13) is very possible. Also, further west off the southern peninsula of Haiti, there are short subduction zones where earthquakes could generate destructive local tsunamis along the coasts of southern Hispaniola.

Additionally, major or even great earthquakes can occur off the northeast coast of the Dominican Republic along the North Hispaniola Deformation Front (NHDF), or along the North Hispaniola Fault (NHF) or along the Puerto Rico subduction margin (Fig. 13). Earthquakes along the NHDF, or along the NHF, have the potential to generate very destructive tsunamis similar to those of August 4, 1946, that will impact greatly the northern coasts of the Dominican Republic and Haiti but may also have significant far-field impact elsewhere. Based on the historical record and rates of crustal movements, large tsunamigenic earthquakes on the NHDF can be expected on the average every 100 years, but may occur at more frequent intervals. Thus tsunamigenic earthquake on the northeast coast of the Dominican Republic is highly probable.

Finally, and as previously mentioned, earthquakes along the Puerto Rico subduction margin can also generate tsunamis, which can affect the northern coasts of Hispaniola. Also, another earthquake along the Mona Pass similar to the 1918 is very likely to occur again that will affect mainly the eastern coast Hispaniola.

5.2 Potential Tsunamigenic Earthquakes Along the Western Segment of the Northern Caribbean Margin.

5.2.1 Potential Tsunami Impact in Jamaica, Cuba and the Cayman Islands.

Jamaica

The historic record indicates that only two confirmed tsunamis have occurred in Jamaica over the past 300 years from local earthquakes. Accordingly, a destructive earthquake in 1692 that killed 2,000 people at Port Royal resulted in ground subsidence and the generation of a local tsunami in the harbor which reached a maximum height of 1.8 meters (6 feet). Another earthquake along the north coast of Jamaica in 1907 generated a tsunami with waves ranging from 1.8 - 2.4 meters between Portland and St. Ann and was accompanied by 70-90 meter withdrawal of the sea. Waves of 2.5 meters from the same event were observed in Kingston Harbor.

Cuba

Of a total of six purported tsunamis in Cuba (in 1766, 1775, 1852, 1831, 1932 and 1939) only the 1755 event in Santiago De Cuba appears to be an actual tsunami event. All others in Santa Clara, Las Villas and Santiago de Cuba represent questionable tsunamis

Cayman Islands

The western boundary of the Northern Caribbean margin extends for about 1500 km from the Sierra Maestra Mountains of Cuba to the Misteriosa Bank near Belize and the Gulf of Honduras. Movement of the North American tectonic plate along the Caribbean boundary at a velocity of about 20 mm/year has formed the Cayman Ridge and Trough, also known as the Cayman Trench or Bartlett Deep. West of Jamaica and south of Grand Cayman Island group lies a pull-apart basin, a divergent feature known as the Cayman Spreading Center, which represents the broader western boundary of the Gonâve microplate, consisting of two parallel branches separated by approximately 125 km. This west boundary zone of the Northern Caribbean margin is characterized by a relatively simple set of transform faults. The historic record does not document tsunamis of any significance generated by earthquakes in this western segment of the northern margin – mainly because seismic events in the region are of lesser magnitude and involve primarily lateral moments along regional faults. Thus, there is little danger of significant tsunami generation in this western region, or of the Cayman Islands being struck by a significant tsunami. The most recent significant earthquake near the Grand Cayman Island occurred on 14 December 2004 and measured 6.7. Its epicenter was about 30 kms south of George Town and its focal depth was 10 kms. It was reported to be the strongest earthquake to hit Grand Cayman since 1900 and was also felt in Cancun, Mexico and Kingston, Jamaica. No tsunami was generated.

5.3 Recurrence Frequency of Tsunamigenic Earthquakes Along the Northern Caribbean Margin

The overall tsunami recurrence period in the Caribbean has been estimated to average about 19 ± 22 years between deadly events (Proenza & Maul, 2010) - which include tsunamis from volcanic sources such as those caused by debris avalanches and pyroclastic flows of the Soufriere Hills Volcano in Montserrat (Hooper and Mattioli, 2001; Pararas-Carayannis, 2006). A rough evaluation of the cumulative frequency of tsunamis was done for Barbados and Antigua (Zahibo et al, 2003).

Along the Northern Caribbean margin boundary, the historic record of the past 500 years indicates that at least ten destructive tsunamis were generated by earthquakes. Thus, the recurrence frequency for the Northern Caribbean margin averages to one significant tsunami every 50 years. Of the ten known tsunamis in the region, those, which occurred in 1692, 1781, 1842, 1867, and 1918 and in 1946, resulted in deaths and destruction. The most significant of the six were the two tsunamis of 1946. Since 1946, sixty-four (64) years have passed without another significant tsunami in the region. Thus, based on statistical probability alone, another destructive tsunami is long overdue to occur somewhere along the Northern Caribbean margin.

5.4 Potential Tsunami Generation from an Outer Rise Earthquake near the Eastern Segment of the Northern Caribbean Margin

There is geological evidence that large tsunamis were generated in prehistoric times (before 1400 AD) along the northern margin of Puerto Rico that were much larger than any of those known from 500 years of historical records. There is evidence that a major earthquake along the Northern Caribbean plate boundary occurred about 800 years ago. This may have been an outer ridge event. Thus, a repeat of such an event is possible – and perhaps overdue - given the estimated rate of about 20 to 30 millimeters that the Caribbean plate is moving in relation to the North American plate.

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