Tsunamis from Tectonic Sources along Caribbean Plate Boundaries

A sub-group of the WG2 members of the ICG/CARIBE-EWS

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Introduction

The Caribbean region, home to more than 100 million people, has seen for the last 500 years at least 75 documented tsunamis (*von Hillebrandt-Andrade, 2013*). It has been estimated that more than 4,500 people have perished as a result (*Dunbar et al*, 2008; see Figure 2). The Working Group 2 (WG2) of the ICG/CARIBE-EWS in charge of Tsunami Hazard Assessment is a multinational group of experts from and outside the Caribbean region currently focusing on various tsunami aspects. The WG2 has been assigned the task of compiling a list of most credible sources from tectonic origin for the Caribbean basin that could potentially affect Caribbean nations. For this poster, a subgroup within the WG2 has been formed to evaluate published literature on tsunami sources and develop a comprehensive list based solely on credible sources evaluated through geological and geophysical studies, and seismology. This poster presents the sources and their justification as most-probable tsunami sources based on the context of crustal deformation due to Caribbean plate interacting with neighboring plates and deforming microplates within the plate's boundaries. Simulations of these sources is part of a subsequent phase in which effects of these tectonically induced tsunamis are evaluated both in the near and far fields.

Figures 1: Distribution of population for the Caribbean region.

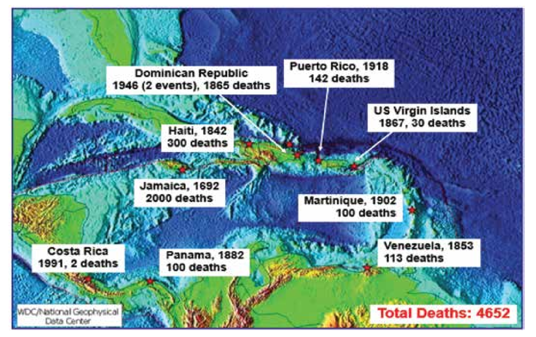


Figure 2: Estimated deaths associated to Caribbean tsunamis.

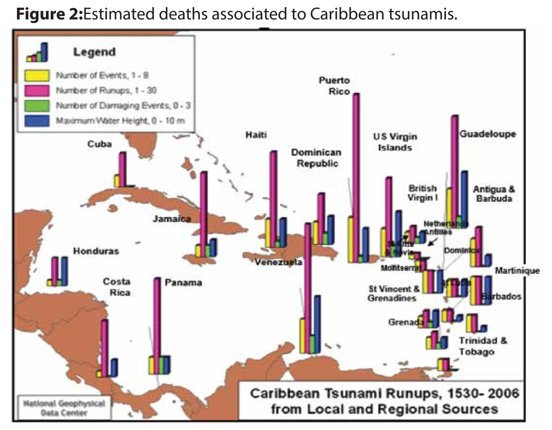


Figure 3: Runups from verified historical and recent tsunamis for the Caribbbean (Dunbar et al., 2008)

Objectives

In the past few years, several publications have attempted to list potential tsunami sources and scenarios for the Caribbean region. These publications come from a wide variety of sources; from government agencies to academic institutions. Although these provide the scientific community with a list of sources and scenarios, it was the interest of the WG2 to evaluate what has been proposed to date. The seismo-tectonics experts of the Caribbean within the WG2 members were tasked to evaluate comprehensively which published sources are credible, worst-cases, and consider other sources that have been omitted from available reports. Although many sources could exist beyond the pure tectonic standpoint, we focus first on dislocative sources, given the highest probability of these events to occur over the other types of sources.

Methods

This study concentrates on Caribbean sources only (no tele-tsunamis). We have divided the boundaries of the Caribbean plate into regional zones with distinctive tectonic features that would result in the generation of tectonic dislocation leading to the formation of basin-wide tsunamis. Each zone was assigned to members of the group specializing in the geology and/or tectonics of the region. Critical information of each zone was obtained through several sources including; seismic catalogs (historical and instrumental), plate motions derived from geological and geodetic data, and marine geological and geophysical studies performed in the past whose data are available in the literature. Once an identified bounding fault has been recognized, the potential is evaluated to estimate rupture area and magnitude. If a fault shows no evidence of seismic rupture in the past, the potential is evaluated based on the estimate of predicted plate motions at the edge of a tectonic feature along a boundary. Then, parameters of the rupture zone are estimated using a pure thrust component that allows a worst case scenario for the source.

Existing Publications

1. "Tsunami Hazard in the Caribbean: Regional exposure derived from credible worst case scenarios" (*Harbitz et al.*, 2012): Quantifies the effects of tsunamis to the Caribbean basin from two seismic sources and three non-seismic tsunamigenic sources.

2. "Global Assessment Risk Reports (GAR) 2009-2015" (Tsunami Modeling and Results Overview 2015 by NGI and Geosciences Australia): Use the study by *Harbitz et al.*,(2012) as a base and include the Puerto Rico Trench, the Lesser Antilles and the Southern Caribbean Deformed Front.

3. "Evaluation of Tsunami Sources with the Potential to Impact the U.S. Atlantic and Gulf Coasts" (*Atlantic and Gulf of Mexico Tsunami Hazard Assessment Group*, 2008): Mostly evaluates the impact of tsunamis to the eastern coast of the US and the Gulf of Mexico from a variety of sources that include western Atlantic submarine landslides as well as teletsunamis originating within the Caribbean and the eastern Atlantic. However, it is one of the most comprehensive studies of sources in the Caribbean given the authors consider sources from northeastern Caribbean, Northern Panama Deformed Belt (NPDB) and Southern Caribbean Deformation Front. While we have adopted the sources from the northeastern Caribbean along the Puerto Rico Trench, and the Southern Caribbean, sources from Hispaniola and eastern Panamá have been modified.

4. The GEM Faulted Earth Subduction Characterisation Project (*Berryman et al*. 2013): produce a global list of source parameters based on the Slab1.0 model (*Hayes et al*., 2012). However, the only source in the Caribbean they consider is the Lesser Antilles trench (only subduction zone currently in the Caribbean). As a result, the report leaves out other well-known potential sources within the Caribbean region. The report states the seismogenic potential of the Lesser Antilles Trench is not well understood because of the low seismicity rate, so this source were given default values.

5. "Earthquake and Tsunami Hazard in Northern Haiti: Historical Events and Potential Sources" (*Intergovernmental Oceanographic Comission*, 2013): The document was the result of a meeting of experts in the subject of both local and global seismology and tectonics seeking to evaluate the tsunami hazard in northern Hispaniola. The meeting was sponsored by the IOC and took place in Haiti on July 10-11, 2013. The experts focused on tsunami threats to northern Hispaniola and recommended three main scenarios. This report adopts their recommendation as a worst-case potential source for the region. Modeling of the suggested sources have been published recently by *Grilli et al*. (2015).

6. LANTEX/CaribeWave Scenarios (2009-2016): Given the objective of testing communications and build preparedness, these excercises are primarily based on scenarios that not necessarily represent realistic ruptures.

7. Northern Lesser Antilles studies: *Feuillet et al.*, 2011; *Roger et al.*, 2013; *Hayes et al.*, 2014: The pair of strongest events in the 19th century (1839 and 1843) dominate the potential for great earthquakes in the Lesser Antilles. Recent publications have revisited these events in order to assess the tsunami hazard to the islands of northern Lesser Antilles.

Future Work

The next phase of this study is to model the sources and evaluate near and far field effects within the Caribbean basin. This is part of a long-standing project of the ICG/CARIBE-EWS. A sub-group of the WG2 specializing in tsunami modeling was formed as an initiative for the CaribeWave15 tsunami excercise scenario this year. This group, composed of scientists and researchers from Colombia, Costa Rica, Panamá and Puerto Rico, have evaluated the effects of the Northern Panamá Deformed Belt scenario in order to provide decision support to emergency managers. The group seeks to help member states do their own modeling based on their best available bathymetry data or alternatively, provide tsunami outcomes if resources are not available.

Northeastern Caribbean

North America (NA) plate subducts beneath the Caribbean (CA) plate in a highly oblique fashion resulting in two distinctive tectonic outcomes along this region. Caribbean plate motion along the northern boundary goes from simple left-lateral strike-slip to transpression at the location of Hispaniola and Puerto Rico - Virgin Islands (PRVI). At least three microplates have been identified in the region; Gonave, Hispaniola and PRVI, of which the most significant tsunami sources are related to the Northern Hispaniola Deformed Belt (NHDB) and the Puerto Rico Trench (PRT). Geodetic studies indicate the CA plate moves to the WNW at a rate of 20 mm/yr (*DeMets et al.*, 2007; 2010). While strain partitioning has been observed in Hispaniola (*Manaker et al.*, 2008), strain to the east is mostly accommodated in strike-slip motion close to the trench (ten Brink and Lin, 2004). The Bahamas bank, on the NA plate is colliding with the Hispaniola platelet resulting in thrusting at the NHDB and strike-slip motion at the Septentrional Fault.

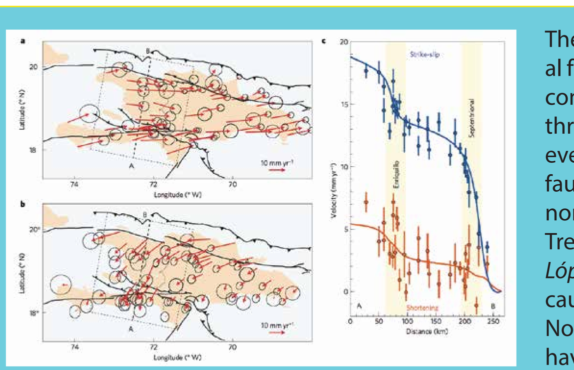
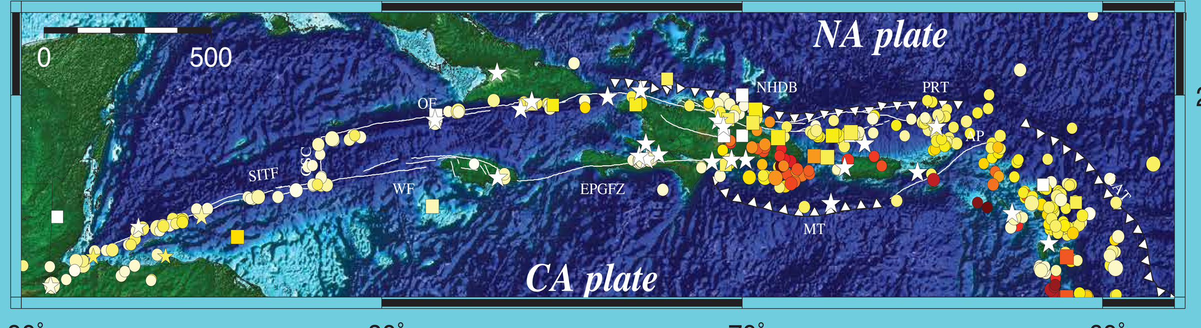


Figure 7 (above): Figure 1 from *Calais et al.* (2010) showing velocity field in both NA (top) and CA (below) indicating strain partitioning across Hispaniola from N-S (right).

The most significant sources in this region come from the Northern Hispaniola Deformed Belt, the Septentrional fault north of Hispaniola and the Puerto Rico Trench. The parameters for the source from northern Hispaniola come from the IOC Expert's meeting on Earthquakes and Tsunami Hazard in Northern Haiti. From this meeting, three scenarios were developed: (1) Mw 8.0 on the Septentrional Fault strike-slip system that is similar to the event of May 7, 1842. (2) Repeat of the Mw 8.1 Dominican Republic August 4, 1946 event on the offshore thrust fault system north of Haiti. (3) An earthquake rupturing rupturing a portion of the offshore thrust fault system north of Haiti that is larger than the portion that ruptured in 1946. To the east of these sources is the Puerto Rico Trench that extends east to the Lesser Antilles Trench. Studies by *ten Brink and Lin* (2004), and *ten Brink and López-Venegas* (2012) have indicated that the trench itself has a low probability of rupturing in a large event because most of the motion is accommodated along the Bunce strike-slip fault system that lies close to the PRT. Nonetheless, NRC, *Harbitz et al.* (2012) and the GAR2015 studies assign Mw 8-9 tsunamigenic events, which we have adopted as a potential source for this region.

Figure 6: Seismicity of the Northern Caribbean Plate Boundary Zone. Circles are M>5 events from the NEIC (1960-2014) and squares are events from the Centennial Catalog (1900-1960). Stars are historical events from the Global Historical Earthquake Catalog from GEM.



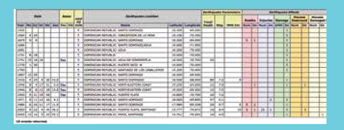


Table 2 : Most significant events in Hispaniola and related tsunamis. From the NCEI global database.

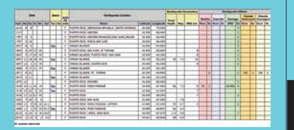


Table 3: Most significant events for PRVI and related tsunamis. From the NCEI global database.

Figure 8: The two main sources of tsunamis for the Northeastern Caribbean. Parameters are shown on Table 1 below (inset of main figure)

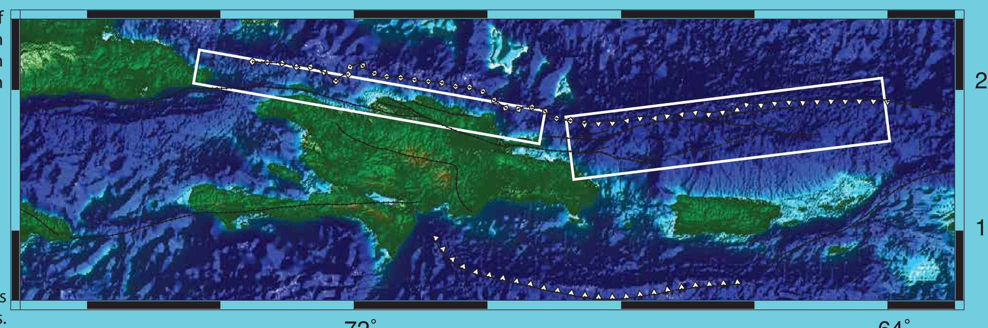


Figure 4: Caribbean Seismicity (M>3) from 1960-2014 obtained from the NEIC catalog define the boundaries of the plate of both wide and narrow deformation. This is indicative that the Caribbean plate is mostly rigid in its interior and the vast majority of its deformation is accommodated along its boundaries.

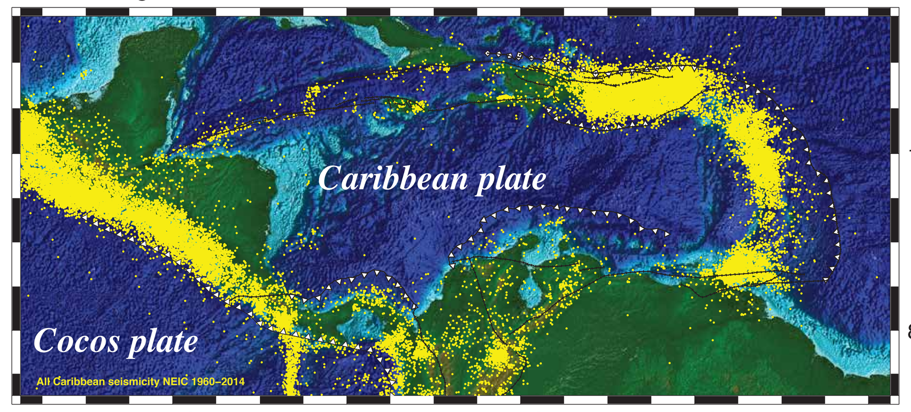
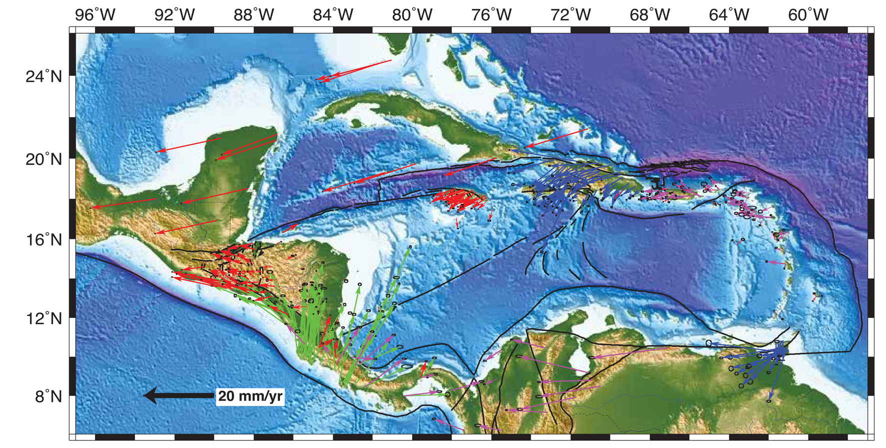


Figure 5: Compilation of Caribbean geodetic velocities from various sources (*DeMets, pers. comm.*). Vectors represent observed data while wider vectors represent predicted velocities at locations of interest from best-fit poles of rotation. These predictions are useful in estimating the relative plate motion that would contribute to tsunamis from rupture zones. (Figure provided by G. Mattioli, pers.comm.).



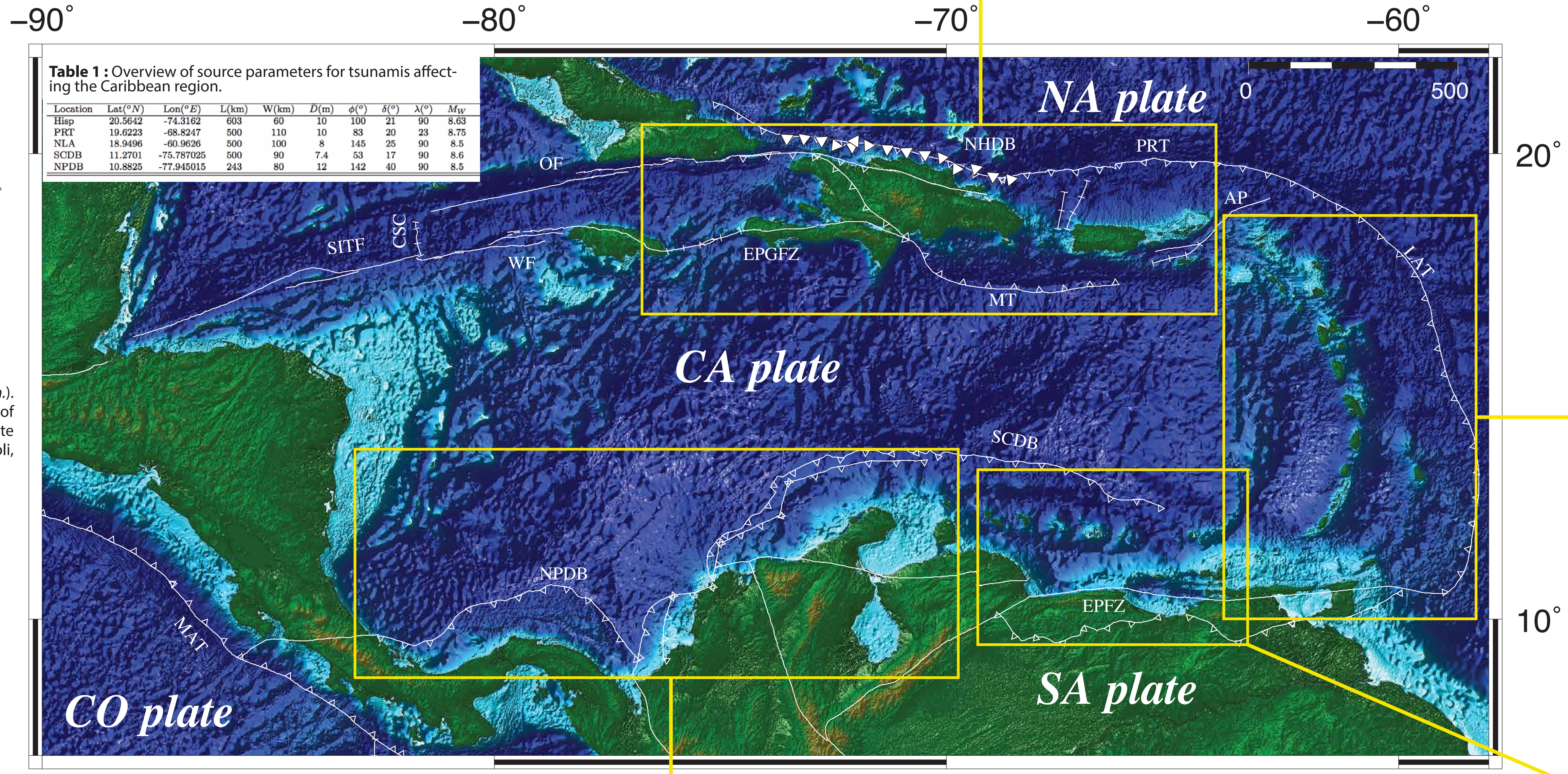


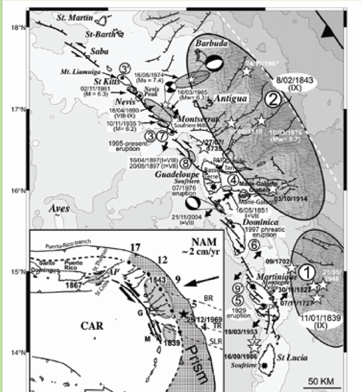
Table 1 : Overview of source parameters for tsunamis affecting the Caribbean region.

Location	Lat(°N)	Lon(°E)	L(km)	W(km)	D(m)	$\phi(°)$	$\delta(°)$	$\lambda(°)$	M_W
Hisp	20.5642	-74.3162	603	60	10	100	21	90	8.63
PRT	19.6223	-68.8247	500	110	10	83	20	23	8.75
NLA	18.9496	-60.9626	500	100	8	145	25	90	8.5
SCDB	11.2701	-75.787025	500	90	7.4	53	17	90	8.6
NPDB	10.8825	-77.945015	243	80	12	142	40	90	8.5

Lesser Antilles

The tsunamigenic capacity of the Lesser Antilles Trench has recently been receiving attention due to a new series of studies that have reevaluated what it appears is the most damaging earthquake in the eastern Caribbean. The Mw 8.4 event on February 8, 1843 may have had a rupture of 300 km along the northern portion of the trench (*Feuillet et al.*, 2011; *Roger et al.*, 2013). This event along with other historical events in the arc are considered potential sources of damaging near-field events to the Lesser Antilles islands as well as far-field effects to Atlantic Ocean islands and western Africa coastlines. A recent study by *Hayes et al.* (2014) indicate the LAT is currently capable of generating a Mw 8.2 event.

Figure 11: Figure 1 of *Feuillet et al.* (2011) indicating the estimated area and location of the Mw 8.3 rupture. The region is characterized by an oblique subduction that has resulted in arc-parallel strain partitioning in both trench-perpendicular normal faults and arc-parallel strike-slip faults along the inner arc.



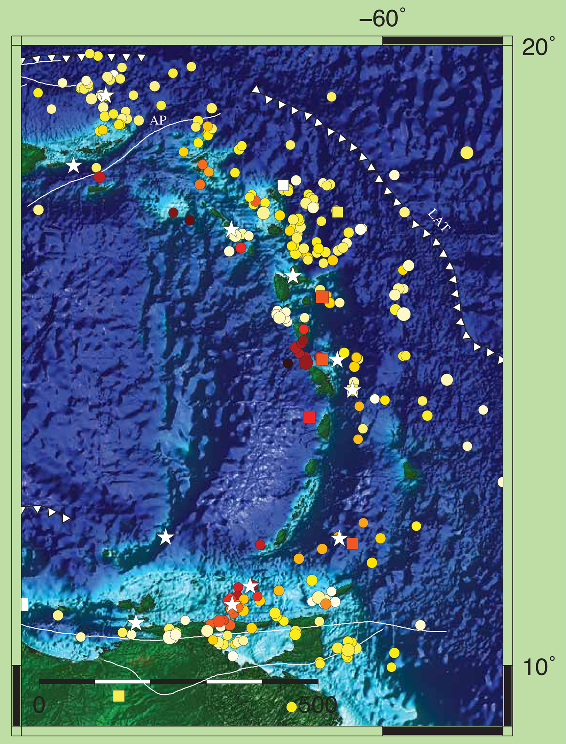
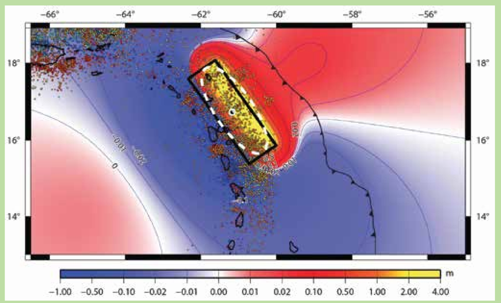
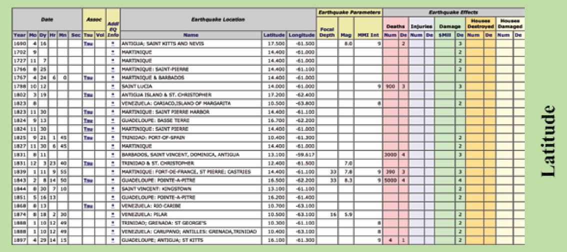


Figure 9 (Above): Seismicity of the Lesser Antilles Arc. Circles are M>5 events from the NEIC (1960-2014) and squares are events from the Centennial Catalog (1900-1960). Stars are historical events from the Global Historical Earthquake Catalog from GEM.

Figure 12: Figure from *Roger et al.* (2013) showing the initial co-seismic deformation of the 1843 event.





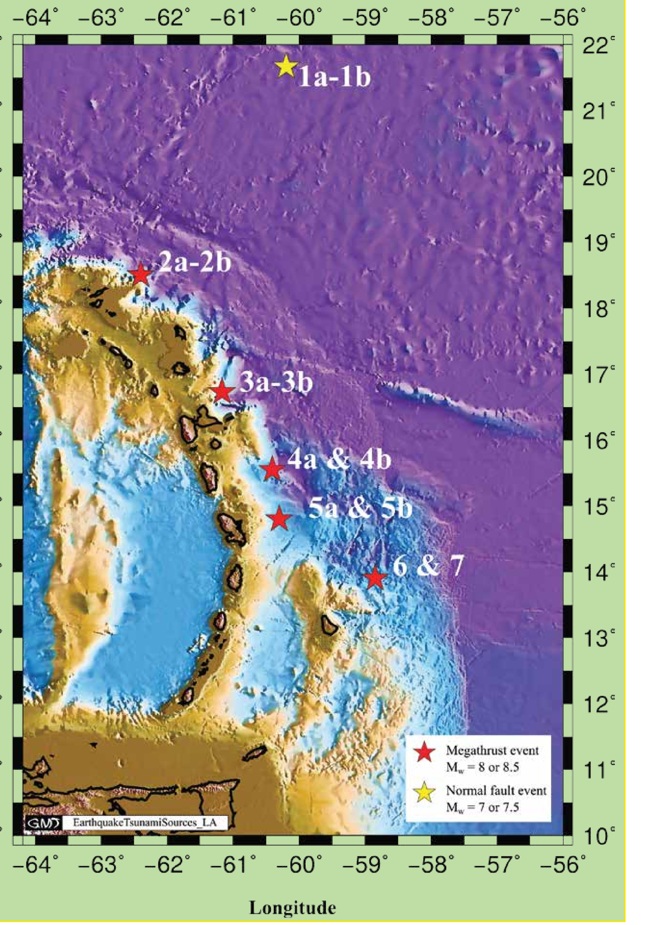
Year	Mo	Dy	Hr	Mn	Tsu	Name	Latitude	Longitude	Focal Depth	Mag	MMI Int	Deaths Num	Deaths De	Damage De
1690	4	16			Tsu	ANTIGUA; SAINT KITTS AND NEVIS	17.500	-61.500		8.0	9		2	3
1702	9					MARTINIQUE	14.400	-61.000						2
1727	11	7				MARTINIQUE	14.400	-61.000						2
1766	8	25				MARTINIQUE: SAINT-PIERRE	14.400	-61.100						2
1767	4	24	6	0	Tsu	MARTINIQUE & BARBADOS	14.400	-61.000						
1788	10	12				SAINT LUCIA	14.000	-61.000			9	900	3	3
1802	3	19			Tsu	ANTIGUA ISLAND & ST. CHRISTOPHER	17.200	-62.400						
1823	8					VENEZUELA: CARIACO,ISLAND OF MARGARITA	10.500	-63.800			8			2
1823	11	30			Tsu	MARTINIQUE: SAINT PIERRE HARBOR	14.400	-61.100						
1824	9	13			Tsu	GUADELOUPE: BASSE TERRE	16.700	-62.200						
1824	11	30			Tsu	MARTINIQUE: SAINT PIERRE	14.400	-61.000						
1825	9	21	1	45	Tsu	TRINIDAD: PORT-OF-SPAIN	10.400	-61.300						2
1827	11	30	6	45		MARTINIQUE	14.400	-61.000						2
1831	8	11				BARBADOS, SAINT VINCENT, DOMINICA, ANTIGUA	13.100	-59.617				3000	4	3
1831	12	3	23	40	Tsu	TRINIDAD & ST. CHRISTOPHER	12.400	-61.500		7.0				
1839	1	11	9	55		MARTINIQUE: FORT-DE-FRANCE, ST PIERRE; CASTRIES	14.400	-61.100	33	7.8	9	390	3	3
1843	2	8	14	50	Tsu	GUADELOUPE: POINTE-A-PITRE	16.500	-62.200	33	8.3	9	5000	4	4
1844	8	30	7	10		SAINT VINCENT: KINGSTOWN	13.100	-61.100						2
1851	5	16	13			GUADELOUPE: POINTE-A-PITRE	16.200	-61.400						2
1868	8	13			Tsu	VENEZUELA: RIO CARIBE	10.700	-63.100						2
1874	8	18	2	30		VENEZUELA: PILAR	10.500	-63.100	16	5.9				2
1888	1	10	12	49		TRINIDAD; GRENADA: ST GEORGE'S	10.300	-61.100			8			2
1888	1	10	12	49		VENEZUELA: CARUPANO; ANTILLES: GRENADA,TRINIDAD	10.400	-63.100			8			2
1897	4	29	14	15		GUADELOUPE; ANTIGUA; ST KITTS	16.100	-61.300			9	4	1	2

Table 4: Most significant events for the Lesser Antilles region and related tsunamis. From the NCEI global database.

Source	strike	dip	rake	depth (km)	L (km)	W (km)	Mw	LAT(N)	LON (E)
1a	256	80	270	10	40		7	21.62	-60.2
1b		80	270	10	100		7.5	21.62	-60.2
2a	340	80	90	31	270		8	18.5	-62.4
2b	340	80	90	35	700		8.5	18.5	-62.4
3a	330	60		35	270		8	16.73	-61.17
3b	145	25	90	40	300	100	8.5	16.73	-61.17
4a				35	270		8	15.545	-60.406
4b					700		8.5	15.545	-60.406
5a	318	55		40	270		8	14.8	-60.3
5b	318	55		40	700		8.5	14.8	-60.3
6	330	81			330		8	14.7	-58.93
7	325	70			270		8	14.7	-58.93

Table 5: Source parameters for events shown in Figure 10. Majority of events are based on significant events in the region.

Figure 10: Scenarios of the Lessear Antilles Arc based on historical and instrumental seismic events. Refer to Table 5 for partial parameter information.



Southwestern Caribbean

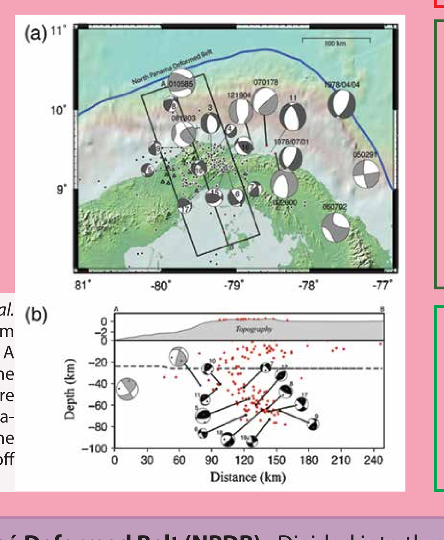
This area comprises Costa Rica, the Panamá Isthmus and Colombia's northern coast. The region has two characteristic tectonic settings governed by two inmature/failed subduction zones where the Caribbean plate underthrust the Panamá microplate and Colombia to form the Northern Panamá Deformed Belt (NPDB) and the Southern Caribbean Deformed Front (SCDF). While several significant earthquakes and related tsunamis have occurred in the NPDB, the likelihood of SCDF to generate significant tsunamis is currently unknown. *Parsons & Geist* (2008) assign moderate probabilities to the coasts of Costa Rica and Panamá, and the NRC report estimates the area is capable of Mw 8.3-8.5 tsunamigenic events.

zone	strike	dip	rake	depth (km)	slip (m)	L (km)	W (km)	Mw	Mo	# of considered historic events	# of solutions	# of considered hypothetic scenarios	historic max Mw	historic tsunamis in the region
NPDB-W	115	27	75	14	3	76	52	7.63	4.51E+20	1	7	1	7.7	4 (1798, 1822, 1916, 1991)
NPDB-E	50	25	90	22	3	220	55	8.04	1.27E+21	0	0	1	7.9	1 (1882)
SCDF	259	26	-90		2			7.50	2.00E+20	0	0	1	6.5	1 (1825)

Table 7: Source parameters for events at the NPDB and the SCDF (refer to Figure 19).

Table 8 : Most significant events in the Panamá - Costa Rica region and related tsunamis. From the NCEI global database.

Figure 17: Figure 3 from *Camacho et al.* (2010) showing focal mechanisms from significant earthquakes in the NPDB. A concentration of events occur in the Central portion of the NPDB where earthquake relocations and determinations of faulting mechanism suggest the location of a defined Wadati-Benioff zone beneath the Panamá arc.



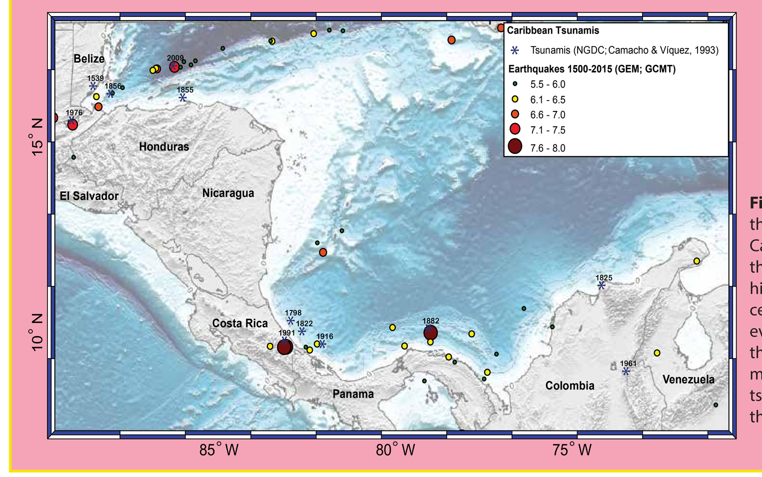


Figure 18: Map of the Southwestern Caribbean showing the location of historical, and centennial catalog events, along with the location of most significant tsunamis affecting the region.

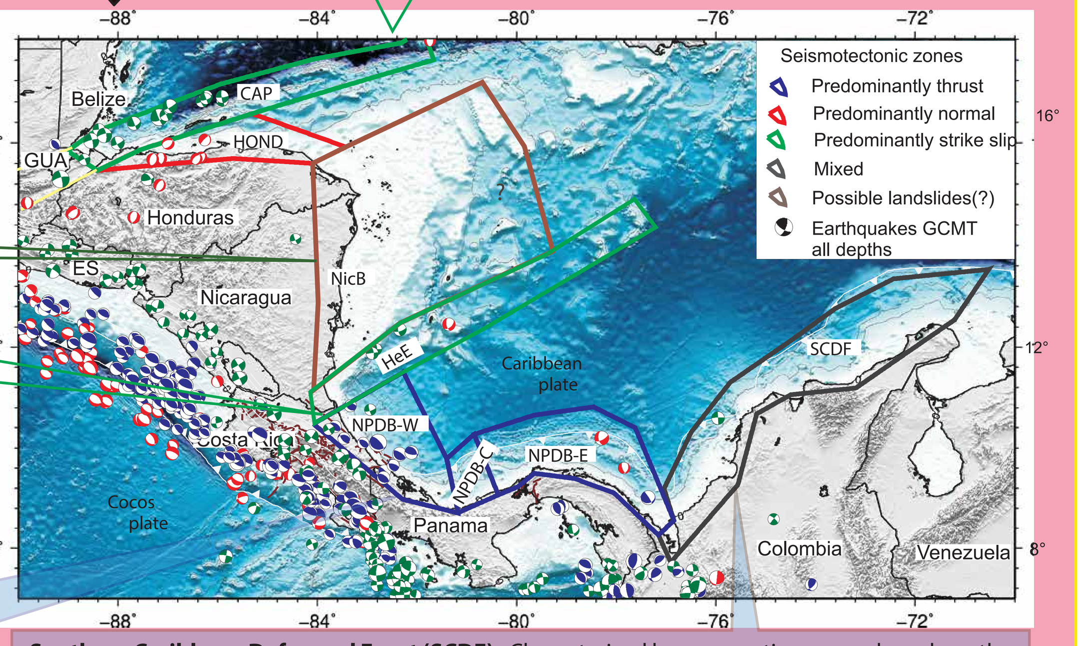
Figure 19: Tsunami sources of the Southeastern Caribbean

Honduras Depression: Fault segments associated to a graben striking N-S along central Honduras, where the largest earthquake (M~6-6.5) was observed in 1851. Potential of normal faults or submarine landslides generating smaller tsunamis in the near field both to Honduran coast and Cayman, Swan and nearby islands.

Motagua/Polochic-Swan: Predominantly left-lateral Strike-slip system extending from the Pacific, crossing through Guatemala and into the Caribbean through the Swan deformation zone. Evidence of tsunamis from this system are events from 1539, 1976 (Mw 7.5) and in 2009 (Mw 7.3). Although this system is mostly horizontal motion, some tsunamis have been generated suggesting some vertical deformation is possible.

Nicaragua Bank: Shallow geomorphic structure extending from Nicaragua to Jamaica. Although not an important seismic and tsunamigenic source, we especulate this region to be a significant source of submarine landslides worth considering for future studies of tsunamis affecting western Caribbean.

Hess Escarpment: Seismicity suggests transtension with predominant normal faults. Although little information exist about its tsunamigenic potential, and the feature is characterized by low seismicity, a Mw 6.9 event has been the largest recorded. It has been suggested to be related to the Beata ridge.

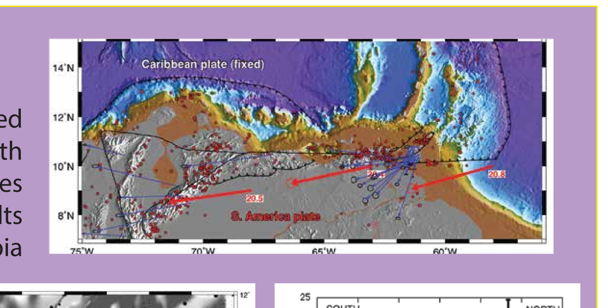


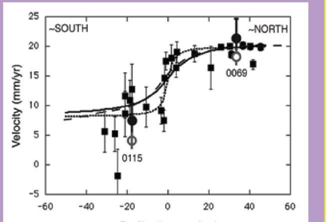
Northern Panamá Deformed Belt (NPDB): Divided into three potential segments due to the distinctive seismicity pattern, the NPDB is where the convergence of ~ 7 mm/yr (*Trenkamp et al., 2002*) of motion between the Caribbean plate and the Panamá microplate take place. The **Western** segment is further divided by *Camacho & Víquez* (1993) into two other sub-segments: Costa Rica, and Panamá. A great variety of events have occurred in this region (largest has been a Mw 7.7 that occurred in 1991) and thus has been considered by *Benito et al.* (2012) as having the highest seismic hazard of the Caribbean side of Central America. The **Central** segment is characterized by having the lowest seismic hazard of the three. The **Eastern** segment is the only part of the belt that shows evidence of a Wadati-Benioff zone since *Adamek et al.* (1988) suggests Caribbean plate subducts at 50° beneath the Panamá microplate. The Eastern segment is where the largest, most significant event has occurred (Mw 7.9 in 1882).

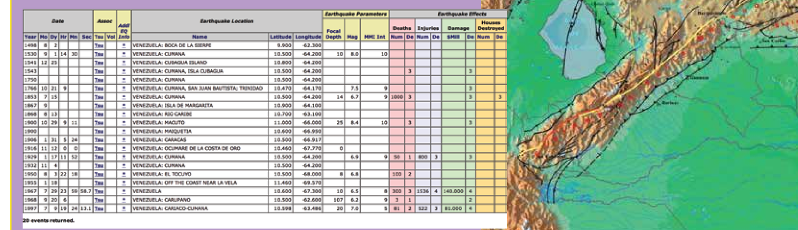
Southern Caribbean Deformed Front (SCDF): Characterized by an accretionary wedge where the Caribbean plate under-thrusts the South America in a transpressive regime with evidence of obduction. Predicted relative motion among the two plates indicate high obliqueness in the apparent convergence, but the lack of seismicity might indicate most of the motion is being effectively accomodated by forearc strike-slip motion. NCEI database has only one questionable tsunami. Recent GPS studies (see poster T11E-2941) suggest a large Mw 8.3 event can be generated at this location.

Northern Venezuela

The southeastern corner of the Caribbean is characterized by a complex transition from subduction of the South America plate at the southern end of the Lesser Antilles Trench, to predominantly right-lateral strike-slip faults through northern Venezuela and northeastern Colombia (refer to the map below right). *O'Loughlin and Lander* (2013) indicate tsunamis have affected the northern coast of Venezuela, however it is unclear if these events are associated to the eastern terminus of the SCDF that is more predominant in northern Colombia. A recent GPS study by *Weber et al.* (2009) demonstrate that most of the motion (12 mm/yr) between the two plates in Trinidad is accommodated along the right-lateral strike-slip Central Range fault (see Figures to the right from their paper).







Year	Mo	Dy	Hr	Mn	Sec	Tsu	Name	Latitude	Longitude	Focal Depth	Mag	MMI Int	Deaths Num	Deaths De	Injuries Num	Injuries De	Damage $Mill	Damage De	Houses Destroyed Num
1498	8	2				Tsu	VENEZUELA: BOCA DE LA SIERPE	9.900	-62.300										
1530	9	1	14	30		Tsu	VENEZUELA: CUMANA	10.500	-64.200	10	8.0	10							
1541	12	25				Tsu	VENEZUELA: CUBAGUA ISLAND	10.800	-64.200										
1543						Tsu	VENEZUELA: CUMANA, ISLA CUBAGUA	10.500	-64.200					3				3	
1750						Tsu	VENEZUELA: CUMANA	10.500	-64.200										
1766	10	21	9			Tsu	VENEZUELA: CUMANA, SAN JUAN BAUTISTA; TRINIDAD	10.470	-64.170		7.5	9						3	
1853	7	15				Tsu	VENEZUELA: CUMANA	10.500	-64.200	14	6.7	9	1000	3				3	3
1867	9					Tsu	VENEZUELA: ISLA DE MARGARITA	10.900	-64.100										
1868	8	13				Tsu	VENEZUELA: RIO CARIBE	10.700	-63.100										
1900	10	29	9	11		Tsu	VENEZUELA: MACUTO	11.000	-66.000	25	8.4	10		3				3	
1900						Tsu	VENEZUELA: MAIQUETIA	10.600	-66.950										
1906	1	31	5	24		Tsu	VENEZUELA: CARACAS	10.500	-66.917										
1916	11	12	0	0		Tsu	VENEZUELA: OCUMARE DE LA COSTA DE ORO	10.460	-67.770	0									
1929	1	17	11	52		Tsu	VENEZUELA: CUMANA	10.500	-64.200		6.9	9	50	1	800	3		3	
1932	11	4				Tsu	VENEZUELA: CUMANA	10.500	-64.200										
1950	8	3	22	18		Tsu	VENEZUELA: EL TOCUYO	10.500	-68.000	8	6.8		100	2					
1955	1	18				Tsu	VENEZUELA: OFF THE COAST NEAR LA VELA	11.460	-69.570										
1967	7	29	23	59	58.7	Tsu	VENEZUELA	10.600	-67.300	10	6.5	8	300	3	1536	4	140.000	4	
1968	9	20	6			Tsu	VENEZUELA: CARUPANO	10.500	-62.600	107	6.2	9	3	1				2	
1997	7	9	19	24	13.1	Tsu	VENEZUELA: CARIACO-CUMANA	10.598	-63.486	20	7.0	5	81	2	522	3	81.000	4	

20 events returned.

Table 6: Most significant events for Northern Venezuela and related tsunamis. From the NCEI global database.