ESTIMATING THE THREAT OF TSUNAMIGENIC EARTHQUAKES AND EARTHQUAKE INDUCED-LANDSLIDE TSUNAMI IN THE CARIBBEAN

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Deformation along the margin of the Caribbean Plate is the principal cause of the tsunami threat in the Caribbean. That margin parallels the northern coast of South America, the Lesser Antilles, and extends along the Greater Antilles from Puerto Rico through Jamaica. The eastern boundary of the Caribbean plate near the Lesser Antilles is the locus of subduction of Atlantic seafloor. At least three distinct, shallow tectonic regimes parallel the margin. They are: an outer tectonic belt where the North America Plate bends to enter the subduction zone, the main interface or zone of contact between the plates, and an inner zone of intraplate activity in the overriding Caribbean Plate. The level of seismic activity and tsunami potential in each of these zones is influenced by the presence of aseismic ridges on the downgoing plate. Ridges may increase the probability of tsunami or slow earthquakes, by reactivating thrust faults in the accretionary prism. The northeastern corner of the Caribbean Plate margin has a smooth transition from the relatively simple subduction zone in the Northern Lesser Antilles into a region of oblique convergence. It is a complex margin dominated by microplate tectonics from near Puerto Rico through Hispaniola. Here too the same three tectonic zones can be defined, but the third zone, "intraplate activity in the Caribbean Plate", is more clearly delineated as microplate deformation in a wide plate boundary zone. Strike-slip tectonics dominates the region from Haiti westward to the northern coast of Honduras. Local bends in the transcurrent fault systems lead to vertical tectonics in the form of push-ups and pull-aparts. Some convergence is absorbed along the southernmost margin of Cuba. Either the tsunamigenic events in this region had source mechanisms with significant vertical components, or they triggered submarine landslides that generated the tsunami. Other potential sources lie along the northern coast of South America ands off the east coast of Central America. Manipulation of gridded bathymetric data to produce maps of seafloor slope, slope direction, and roughness as defined by the curvature of contours, can aid the identification of potential slides/slumps, or reveal portions of subduction zones more likely to produce tsunami earthquakes. A survey of the Caribbean Basin reveals several regions of high slope. Many of these are found where great earthquakes have or are likely to occur, possibly triggering submarine landslides. Regions such as the southern Lesser Antilles have steeper seafloor slopes in the backarc region than in the accretionary prism of the subduction zone. It has been suggested that subduction of rough seafloor highs such as seamounts and fracture zones leads to dewatering and stiffening of the accretionary prism and, as the high enters the deeper portions of the subduction zone, activation of thrust faults within the accretionary prism i.e. above the main decollement. If this were the case, it would enhance the possibility of tsunami or slow earthquakes. The subduction of rough bathymetric highs and its corresponding increasing roughness of the accretionary prism would then be another parameter to determine the likelihood of tsunami earthquakes. Using these criteria, several regions of the NE Caribbean stand out as more likely source for tsunami earthquakes.

1. Introduction

The Caribbean region is well known for its numerous natural hazard such as Hurricanes, Volcanoes, Earthquakes, and Tsunami. Understanding the nature and scope of each of these threats is essential if one is to attempt to mitigate the negative affects of those hazards. This paper will attempt to layout the general framework of the tsunami hazard in the Caribbean Basin. As tsunami have various general generating mechanisms, the threat will be examined in those terms. I will explore tsunami caused by earthquakes, and submarine landslides/slumps or a combination of the two, but only in passing way mention tsunami as generated by volcanic eruptions. Most of the tsunami threat lies along the heavily populated island chains of the Greater and Lesser Antilles or the coasts of Central and South America rimming the Caribbean Basin. This means that in most cases those most affected by a tsunami will have the least warning of a potential or actual tsunami.

Large shallow earthquakes are principal cause of the tsunami threat in the Caribbean. Five Hundred years of damaging earthquakes form a long, nearly continuous belt of seismic activity surrounding the Caribbean Basin (Figures 1, 2, 3.). Most of those quakes occurred in submarine areas and their source mechanisms included a significant component of vertical motion, two necessary conditions for earthquake-induced tsunami. As will be discussed later, the aforementioned region of enhanced tectonic activity is nearly coincident with the provinces most liable for submarine landslides, at least from a seafloor slope point of view.

For the purposes of the analysis presented herein, I will assume that earthquake-induced tsunami are most efficiently generated by thrust, reverse, or normal faulting earthquakes of magnitude, $M \geq 6.5$, and that they either cause significant deformation of the seafloor or rupture the seafloor. Deformation or rupture caused by strike-slip events are considered unlikely to cause tsunami because of the lack of significant vertical motion in their source mechanisms; events $M \leq 6.5$ may cause tsunami, but would pose no significant threat to populated areas. I will also assume that the primary feature causing tsunami generated by landslides is the slope of seafloor. While other factors such as nature of the material on the seafloor (volcanic, sedimentary, etc.) and bedding and dip also influence tsunami potential, consideration of those factors is beyond the scope of this work. The reader is referred to the tsunami catalog of O'Loughlin and Lander (2003) as a source for Caribbean tsunami, and the IPGH/MIDAS catalog as well as to historic catalogs as a source for large earthquakes (Shepherd and Lynch, 1992; Tomblin and Robson, 1977; Utrera 1927; McCann, 2004) and to Mann et al., (1995) for tectonics.

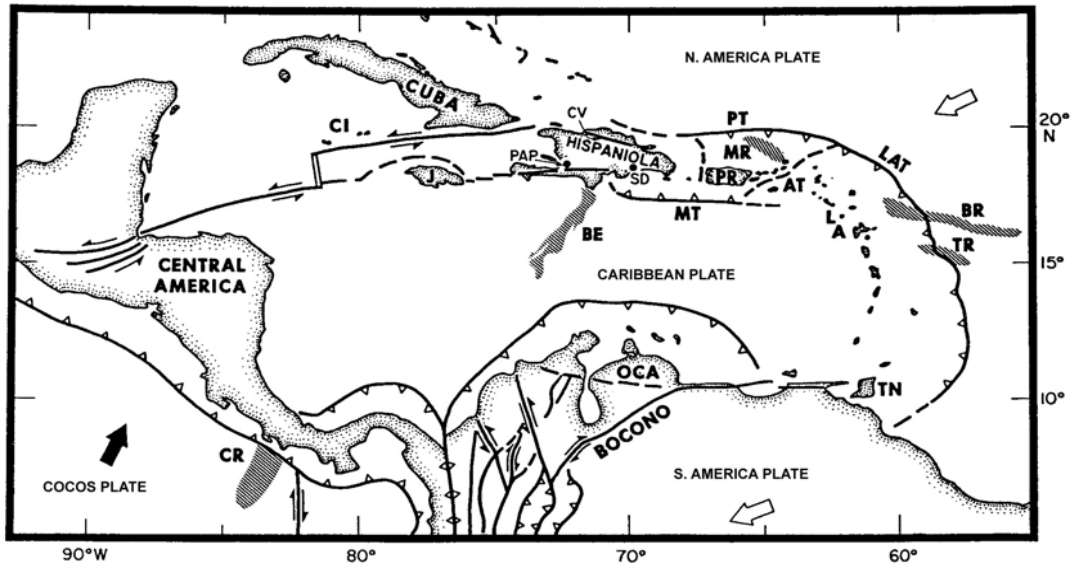

Figure 1. Generalized neotectonic features of the Caribbean region (after Mann and Burke, 1984). Northwestern, western, and eastern margins are comparatively simple; along the other margins, microplates form a buffer zone between the large plates. Convergent margins are characterized by normal faulting in the region near and seaward of the trench axis, thrust events in the zone of interplate contact. Strike-slip event and interspersed reverse and normal events are common along the NW portion of the plate margin. Motion between microplates, are identified in the NE region are complex but predominately extensional in nature. See text for details. Features identified by abbreviations on this map are: the Cayman islands (CI), Port-au-Prince (PAP), Santo Domingo (SD), Cibao valley (CV), Puerto Rico trench (PT), Main ridge (MR), Puerto Rico (PR), Muertos trough (MT), Beata ridge (BE), Anegada trough (AT), Lesser Antilles trench (LAT), Lesser Antilles (LA), Barracuda ridge (BR), Tiburon rise JR), Trinidad (TN), and the Cocos ridge (CR). The white arrows indicate convergence directions of plates relative to the Caribbean according to Jansma et al. (2000).

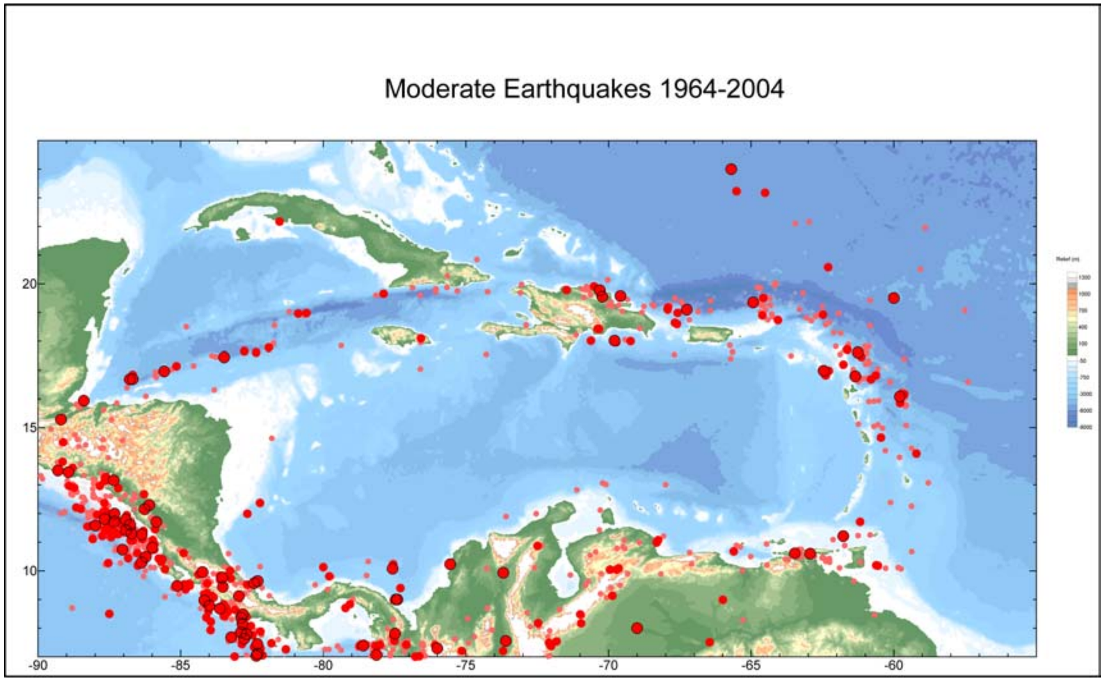

Figure 2. Moderate and smaller events (4.5≥M>6.5) for the period 1964- 2004. Only events with depths of 50 or less are shown. Events were taken from the IPGH and MIDAS/NEIC catalogs. Spatial distribution of these and stronger/historic events, along with other tectonic considerations are used to estimate earthquake tsunami sources for the Caribbean Basin.

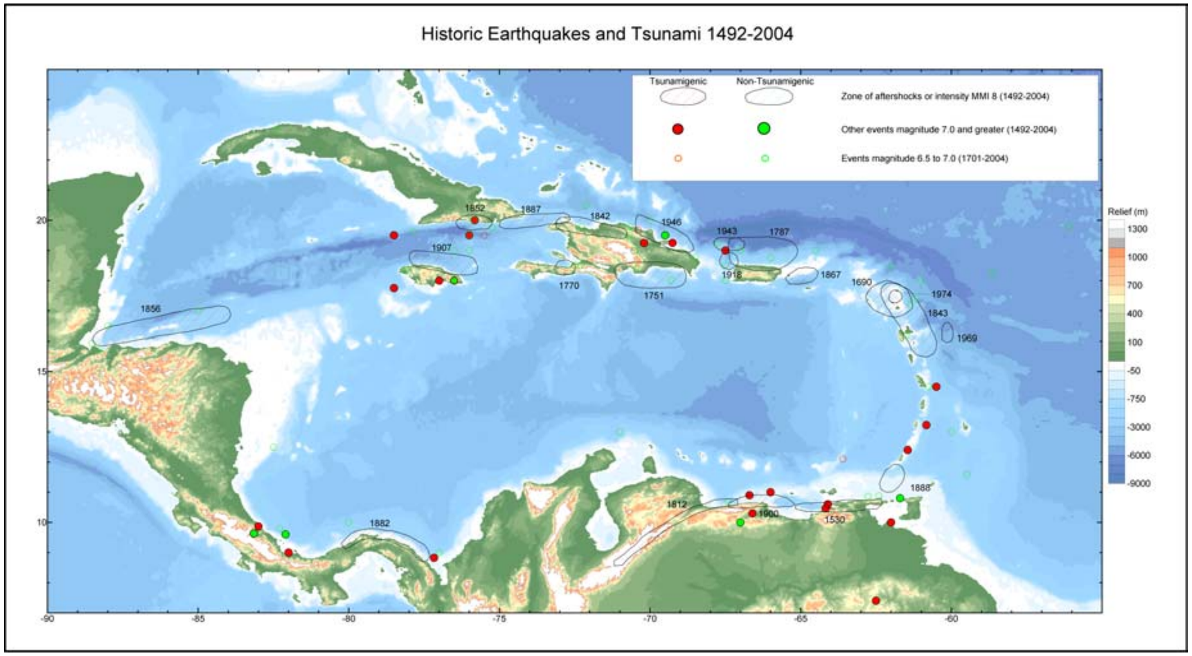

Figure 3. Historic, large (M≥7.0), and strong (7.0≥M≥6.5) recent earthquakes of shallow focus in the Caribbean Basin for the period 1492-2004. Ruptures zones were estimated using region of Modified Mercalli Intensity of VIII and higher, or from 30 days aftershocks. Events along the Pacific margin of Central America and the interior of South America are not shown. Large earthquakes of the last few centuries cover much of the margin of the Caribbean Plate. Major exceptions are the southern Lesser Antilles and the region west of Jamaica. Historic reporting in the latter region is probably incomplete. Two distinct bands of earthquakes are found from Hispaniola through Cuba and Jamaica. Tsunamigenic events are red others are green.

As noted above, the Caribbean has two primary conditions for tsunami generation, a long belt of strong and large earthquakes of shallow focus, and steep slopes that generally flank the islands of the Greater and Lesser Antilles chains. Unfortunately, both conditions are nearly spatially coincident, with a few notable exceptions, and lie near the populated islands and coasts of the region. I will delve into the basis for both sources of the tsunami threat noting the tectonic and geomorphic framework, and historic events as well.

2. Tectonic Framework of Caribbean region

2.1. *Caribbean Plate*

The Caribbean Plate (CA) is one of a dozen rigid parts of the earth's surface. It is bounded to the east, north and south by the North America (NA) and South America plates (SA), and to the west by the Cocos plate and extends from the east near the Lesser Antilles, to the north near Puerto Rio, Hispaniola, and Jamaica of the Greater Antilles, and to the west along the pacific margin of Central America, and to the south along the northern margin of South America (figure 1.). If we consider the Caribbean Plate as stationary, then the NA and SA move slowly to the west at about 20 mm/yr (Mann et al., 2002, Dixon et al., 1997). The NA and SA plates subduct beneath the eastern margin of the CA plate descending into the upper mantle and forming a chain of active volcanoes along the Lesser Antilles. The trace of the subduction zone, the Lesser Antilles Trench, is only well defined along the north part of the subduction zone. In the south it is obscured by a large wedge of sediments that the Caribbean plate encountered off the northern margin of South America. Along the northern margin of the CA plate, motion is transpressional, with oblique subduction along the margin near Puerto Rico, collisional subduction near Hispaniola, and dominated by strike-slip tectonics from near Jamaica, westward to Central America. Several microplates distribute in a complex fashion slip between the NA and Ca plates along this section of the plate margin (Byrne, et al., 1985; Mann et al, 1995). The western margin of the Caribbean Plate lies in the Pacific basin, and so is out of the scope of this work. However, along the western margin of the Caribbean Sea, there are clear active "intraplate" tectonics, both extensional and compressional, and will be discussed in more detail later. The southern margin of the Caribbean plate lies along and complex convergent margin off Venezuela and strike-slip faults onland.

2.2. *Eastern Subduction Zone*

Nearly east-west convergence of the NA and SA plates against the Caribbean plate occurs along the 1000 km long eastern margin of the Caribbean plate. Somewhere to the east of this convergent margin lies the enigmatic boundary between the NA and SA plates. Motion along that boundary is very slow, only a few mm/yr (Muller et al., 1999) but likely to produce occasional earthquakes with significant vertical components of motion. Relatively old Atlantic Ocean seafloor, containing several 1-2 km high aseismic ridges, slides nearly aseismically beneath the overriding CA plate. However, not all of the interplate motions occur aseismically. Great earthquakes in 1843, and probably 1690 ruptured the main interface between the converging plates. Each of these event produced significant tsunami. The downgoing plate bends and, because of its age, is capable of producing large ($M \geq 7$) plate bending (intraplate) earthquakes seaward as well as just landward of the trench axis. The 1969 (Ms 7.2) earthquake is probably a good example of such an event. Active fractures causing NNW-SSE extension (Feuillet et al., 2001) cut the overriding plate from about the Latitude of Guadeloupe and northward along the arc. Event such as that in 1974 and 1986 are good examples of quakes occurring on these intraplate fractures. The 1974 earthquake, while large enough to have caused a significant tsunami, did not. In a detailed study of that event, McCann et al., (1984) determined that the rupture plane, while cutting through most of the crust, did not reach the seafloor.

The southern portion of the eastern convergent margin is notably different for three reasons, first the island arc does not exhibit the intraplate fractures as in the north, second, there is an extremely wide accretionary prism, and third at least in the last 500 years large interplate thrust earthquakes have been relatively sparse. This region may not have the same potential for tsunami as in the north.

2.3. *Oblique Subduction and transition to strike-slip regime*

The northernmost portion of the eastern subduction zone smoothly changes strike from north to west near the end of the Lesser Antilles and the beginning of the Greater Antilles. The trench axis, forearc, and the islands all participate in this change. Also, the trench axis and forearc both deepen and there is a significant break in the island chain where the Anegada Passage intersects the island chain. Although some convergence occurs along the westerly trending portion of the plate edge, most motion is highly oblique, occurring on a thrust plane dipping gently to the south. In this region, in contrast to the distributed arc deformation in the Lesser Antilles, relatively rigid microplates clearly buffer the motion between the major plates, forming numerous interconnected systems of faults, most of which are submarine. Most faulting between the microplates is high angle normal faulting, thus likely to produce tsunami if the events are sufficiently large and rupture of the seafloor occurs. A major earthquake in 1787 probably ruptured the plate interface north of Puerto Rico. A more recent rupture on that interface occurred in 1943. Neither was associated with tsunami. Large tsunamigenic earthquakes ruptured faults along the microplate margins in 1867, and 1918.

Near Hispaniola, the tectonic environment becomes more complicated and a significant portion of interplate and microplate motion occurs onland. Nevertheless, to the north the western extension of the Puerto Rico Trench, here filled by the shallow Bahama Bank, and the Muertos Trough to the south have both been sources of major thrust earthquakes. Ones in 1946 in the north, and 1751 in the south, produced significant tsunami. As mentioned before, Hispaniola is the transition from oblique subduction in the east, through collisional tectonics, to a strike-slip regime with limited thrust belts in the west. Although there is a transition of tectonic style, there is still a record of tsunamigenic earthquakes, or at least tsunami accompanying earthquakes. Events in 1692 off Kingston Jamaica and 1812 are good examples. Significant thrust belts lie off the south coast of Cuba, and perhaps off the north coast of Jamaica. Most plate motion occurs along well-developed strike-slip faults systems and a few intervening transtensional or compressional segments, and except for those cutting the island of Jamaica, all are submarine.

2.4. *Strike-Slip Faults, Transtensional and other Regimes*

Extending west from Jamaica and Cuba are two sub-parallel strike-slip fault systems that merge at the Cayman spreading center. West from there is a single fault system that runs north of the North coast of Honduras, and continues onland in Guatemala. Although no vertical deformation has yet been observed on the seafloor in this region, a major earthquake in 1856 was accompanied by a damaging tsunami.

Holcombe et al., (1990) noted a wide transtensional regime off the east coast off Central America. It extends from Jamaica south to panama along the Nicaragua Rise. This region could produce significant earthquakes of shallow focus, and thus represent a significant tsunami risk for the region. A large earthquake in 1941 is a good example of the earthquake threat. That extensional zone nearly abuts a thrust belt along the east coast of Costa Rica and Panama. In the last several hundred years that region has been the source of large earthquake and tsunami. Events such as 1882 and 1991 are good examples of the threat this region poses.

A wide, arcuate accretionary prism along the northern margin of South America, while not very seismically active in the last 500 years, probably poses an earthquake and tsunami threat. The crust in the vicinity of the Beata Ridge, believed to be experiencing slow compression (Mauffret and Leroy, 1999) and that along the old transform fault along the eastern margin of the Yucatan peninsula, and then easterly along the northern margin of Cuba following the Cuba- Bahama Bank suture, probably pose a tsunami threat, albeit poorly defined.

3. Tsunami Hazard Based on Potential Seismic Sources

The Caribbean Basin's tsunami threat from seismic sources can be classified based on the tectonic mechanism generating the earthquake source. In Figure 4, the various predominate styles of deformation are noted, and the likely tsunami threat associated with each earthquake source noted. The tsunami threat is consider high, medium or low, based on likely angle of faulting, slip direction (varying from vertical to horizontal), simplicity of margin and history of moderate and large earthquakes, and tsunami.

The eastern subduction zone extending from Trinidad northward along the Lesser Antilles and then westward along Puerto Rico and Hispaniola is composed of three parallel belts of earthquake sources. Seaward at, and just landward of the trench axis from Guadeloupe and to the north and west lies a region of plate bending where normal faulting earthquakes predominate. While these plate-bending events might be less frequent than earthquakes on the plate interface, the nature of their motion, high angle normal faulting, makes them efficient producers of tsunami. Events as large as magnitude 8 could occur in this seismic belt.

Immediately landward of that belt lies the main plate interface along which large interplate thrusting occurs. This main plate boundary is characterized by along strike variations in interplate coupling, and probably a corresponding change in tsunami threat. Roughly the southern half of the convergent margin of the Lesser Antilles lies landward of an extremely wide accretionary prism, a feature at coincides with that segment of the margin producing few large interplate earthquake in the last several hundred years. If this pattern persists into the future reflecting a real change in interplate coupling, then both large earthquakes and tsunami would be fewer in number than in the northern region. The third inner zone is a belt of high angle crustal faults within the arc massif

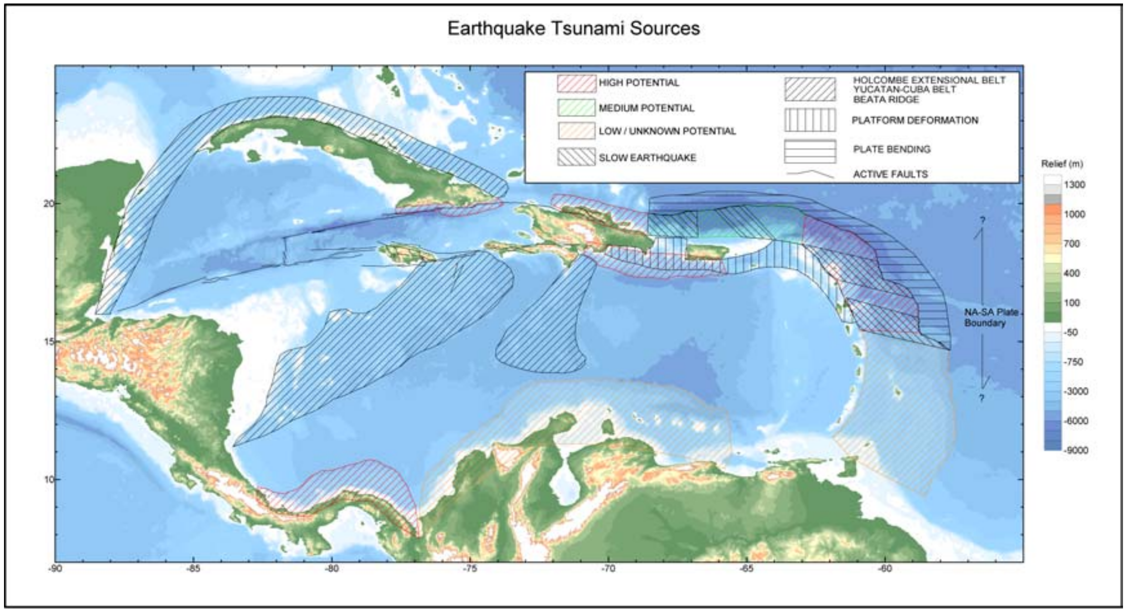

Figure 4. Earthquake Tsunami Sources for the Caribbean Basin. Convergent margins are subdivided into high medium and low potential for interplate earthquake to generate a tsunami based on historic record, obliquity of convergence, and width of accretionary prism. Seaward of the NE portion of the subduction zone intraplate earthquake associated with the bending of the downgoing plate are probable. Segments of subduction zones near the trailing edges of rough seafloor are noted as possible locations for slow or tsunami earthquakes. Active faults in other portions of the main plate boundary zone, some of which could generate tsunamigenic earthquakes, are also shown. Regions with low rates of deformation but still potentially sources for tsunamigenic earthquakes are shown, these include the transtensional belt identified by Holcombe, deformation near the Beata Ridge identified by Mauffret and Leroy, and the old transform/convergent margin near the Yucatan peninsula and Cuba.

(Feuillet et al., 2002). Such faults, while generally short, could produce large earthquakes capable of damaging tsunami.

Great, tsunamigenic earthquakes characterize the hazard of the northeast corner of the Caribbean plate. The presence of aseismic ridges probably plays a role in influencing the occurrence, and limiting the extent of rupture, during these large events. A short segment of the margin near Puerto Rico and the Virgin Islands, and perhaps the northernmost portion of the Lesser Antilles is characterized by a higher level of aseismic slip. Nevertheless, a great earthquake in 1787 probably ruptured the plate interface north of Puerto Rico. As plate motion along this segment of the convergent zone is nearly parallel to the trench axis, little vertical deformation accompanies these large interplate events. No tsunami was observed with the great earthquake in 1787.

The margin north of Hispaniola, while still being classified as convergent in nature has many aspects of a collisional zones, as the buoyant Bahama Bank fills the trench here. Seismic coupling is estimated to be much stronger here, large earthquakes more frequent, and accompanied by tsunami.

Short segments of thrusting are found in association of predominately strike-slip regimes south of Cuba, possibly along the northern coast of Jamaica, and along very short segment of the transform faults that lay between Jamaica and Central America. Another zone of thrusting is found off the Coast of Panama and Costa Rica and south of Hispaniola and Puerto Rico. Each of these regions might produce reverse or thrust faulting earthquakes, possibly producing tsunami. However, the complex nature of the features near Cuba and Jamaica, and their restricted extent, limits the probable size of maximum earthquake (and tsunami). The better developed thrust belts near Hispaniola, and in the SW corner of the Caribbean basin have demonstrated historically, and probably still have the potential for more extensive earthquake ruptures and tsunami. The margin south of Puerto Rico is characterized by strain partitioning into thrusting normal to the margin and strike-slip faulting (with a normal component?) along the investigator fault within the overriding margin (La Forge and McCann, 2004). A similar tectonic environment was found along the margin south of Cuba (Calais et al., 1992). Analogous complexities probably exist in each of the aforementioned thrust belts suggesting an intricate mix of tsunamigenic sources.

Zones of transtension, with normal faulting dominating the local style of deformation are found in the Anegada Passage, the Mona Passage, east and west of Puerto Rico respectively (McCann, 1998, McCann et al., 1994). Other transtensional zones are found in the Morant basin, Yallas Basin, the Cayman Ridge, east, southeast and northwest of Jamaica, and a wide zone extending southwest of Jamaica (Mann et al., 1995; Burke, 1967; Holcombe et al., 1990).

The high angle nature of faulting characterizing these regions makes them prime sources for tsunamigenic earthquakes, although the rates of motion of the causative faults is generally relatively low.

4. Slow Earthquakes, Subduction of Rough Seafloor, and their Relation Tsunami Hazard

There is a special class of earthquakes that should be noted here because they have a special bearing on tsunami hazard. Most major or great earthquakes rupturing the plate interface at a subduction zones are tsunamigenic. The accompanying tsunami is primarily generated by elastic rebound of the accretionary prism, i.e. its attendant vertical and horizontal displacement of the leading edge of the overriding plate, coupled with coseismic deformation along the primary thrust fault or a secondary fault within the stiffer parts of the accretionary prism. In some cases, however, earthquake rupture proceeds more slowly than normal, and is believed to occur within the softer sediments of the accretionary prism. Seismologists call this a "slow" or "tsunami" earthquake (Kanamori, 1972), because of their ability to efficiently generate large tsunami. Bilek and Lay (2002) have noted the generally common nature of small and moderate sized slow earthquakes, suggesting that the conditions for this phenomenon may be widespread in the world's accretionary prisms. If this is true, then these devastating slow or tsunami earthquakes could occur in virtually any subduction zone. While this might be the case, the spatial distribution of large tsunami earthquakes suggest that the subduction of seafloor relief, which demonstrably influences the stability, dynamics and development of accretionary prisms, interplate coupling as well as the occurrences of large earthquakes, may enhance the likelihood of slow earthquakes along certain portions of the world's subduction zones. While a detailed demonstration of the data relating slow earthquakes and subduction of seafloor roughness is beyond the scope of this note, a brief summary outlining the salient points is given and more complete discussion of this issue is reserved for elsewhere (McCann, in prep.).

Under "normal' circumstances, accretionary prism is thought be to in a state of quasi-equilibrium. That equilibrium is related to the mechanical properties of the prism, and the slope of the top and bottom of the prism. That is, the seaward slope of the prism toe is stable just as long as the mechanical conditions of the material in the prism do not change and the slope of the subducting seafloor is also unchanged (Davis, 1983). Subduction of seafloor relief obviously changes this equilibrium state. Positive seafloor relief such as a seamount or a scarp increases the basal slope of the oceanic crust supporting the prism causing the prism to deform, thereby adjusting to a new equilibrium. Dominguez et al. (2000) studied the influence of subducting seamounts and other relief and they found, that as the relief passes deeper into the subduction zone it causes a shadow zone to develop in its wake. That is, the main interface for displacement between the overriding and downgoing material is deflected up along the leading edge of the relief, but does not follow down its trailing edge to return to the interface of the downgoing crust and overriding sediments, but rather cuts through the material of the accretionary prism. This permits the lower portion of the accretionary prism to be carried down into the subduction zone along the trailing edge of the subducting relief. It also means that interplate rupture in this shadow zone occurs within the softer accretionary prism, not at its base. Seismic rupture in softer material is slower than normal due to the low rigidity of the material being broken, i.e. slow earthquakes.

Obviously these observations presume the presence of an accretionary prism, with slow or no erosion, and possible net accretion. These observations also suppose that the relief is limited in extent both vertically and horizontally. If the relief is too high, then it will more likely "collide" with the prism causing substantial deformation, compaction and other radical changes to the condition of the prism; and if the feature is not limited horizontally, it will impinge on the prism never to have a trailing edge. This case would occur if the feature is quasi linear, such as an aseismic ridge, and whose strike is parallel to the local convergence direction.

The observations of Dominguez (2000) provide a mechanism by which subduction of seafloor relief of limited extent may cause a profound, yet transient change, in the character of the plate interface. One sufficiently important to change the character of interplate earthquakes occurring near the trailing edge of the subducting relief from normal rupture velocities to slow or tsunami type. I suggest that this profound change in the subduction process make it more likely that certain margins will suffer tsunami earthquakes. Therefore, regions along the Eastern subduction zone that lay at the trailing edge of a submarine feature of limited relief on the downgoing seafloor have been noted as likely sites for tsunami earthquakes (Figure 4).

5. Steep Seafloor, Submarine Slides, and Tsunami Hazard

Tsunamigenic earthquakes are not the only source of tsunami. Some tsunami appear to also be associated with submarine slumps or slides (Watts and Grilli, 2002). However, submarine slides/slumps are primarily triggered by earthquake shaking, and thus in some cases the cause of the tsunami will be uncertain, being possibly generated by an earthquake source, or a submarine slide/slump. The evidence for a submarine slide/slump associated with historic earthquakes is usually found by a reported break in a submarine cable. More ancient slide/slump events are found on images of debris on the seafloor. The record of tsunami in the Caribbean is interesting in that many of them have occurred in regions where tectonic movements are understood to be primarily horizontal in nature (strike-slip source mechanisms). This suggests that submarine slides or slumps, albeit triggered by earthquake shaking, are common in the region. From here on I will assume that earthquake triggered mass movements of the seafloor are slides. I have no evidence to support this assumption, but for the scope of this present work will relate seafloor topography to the hazard of earthquake triggered submarine slides, saving slumps for another time.

It is generally thought that submarine slides occur in regions of unstable seafloor, i.e. region of relatively high seafloor slopes. Perhaps tilted bedding in submarine outcrops also plays a role in this process. In this section I will discuss the spatial distribution of seafloor relief in the Caribbean Basin region and suggest the role that various submarine features may play in the regional tsunami threat. I will presume that the potential for a submarine slide can be simply mapped, at least to the first order, by seafloor slope as tsunami generation is influenced by water depth at generation, and by depth of seafloor where the steep slope is found (Watts and Grilli, 2002). Slopes of seafloor were calculated using the ETOPO-2 database (NGDC, 2001) and then a "reference" tsunami amplitude was calculated using the formulation of (Watts and Grilli, 2002) for submarine slides:

$$A=0.224\ T\ (b/d)^{1.25}[(\sin(\theta)^{1.29}-0.75(\sin(\theta)^{2.29}+0.17(\sin(\theta)^{3.29}] \quad (1)$$

where A is the tsunami amplitude in meters, T is the maximum slide thickness in meters, b is the initial slide length in meters, d is the mean slide depth in meters, and θ is the mean incline angle in degrees, (assumed to be seafloor slope). I arbitrarily assume the slide has thickness of 20 meters, length of 1000 meters. At a mean depth (d) of 100 meters, and an incline (θ) of 6°, the tsunami height would be about 4 meters. Figure 5 presents these "reference tsunami amplitudes" for the Caribbean Basin. A similar map could be produced for slides of other dimensions or for slumps.

While the map is self-explanatory, some salient points deserve to be noted. 1- High reference tsunami amplitudes are found near every island, 2- Large amplitudes are found along strike-slip margin in west, and may explain the origin of several of the tsunami in this region; 3- Steep slopes found northeast of the Northern Lesser Antilles, but west of the margin of Southern Lesser

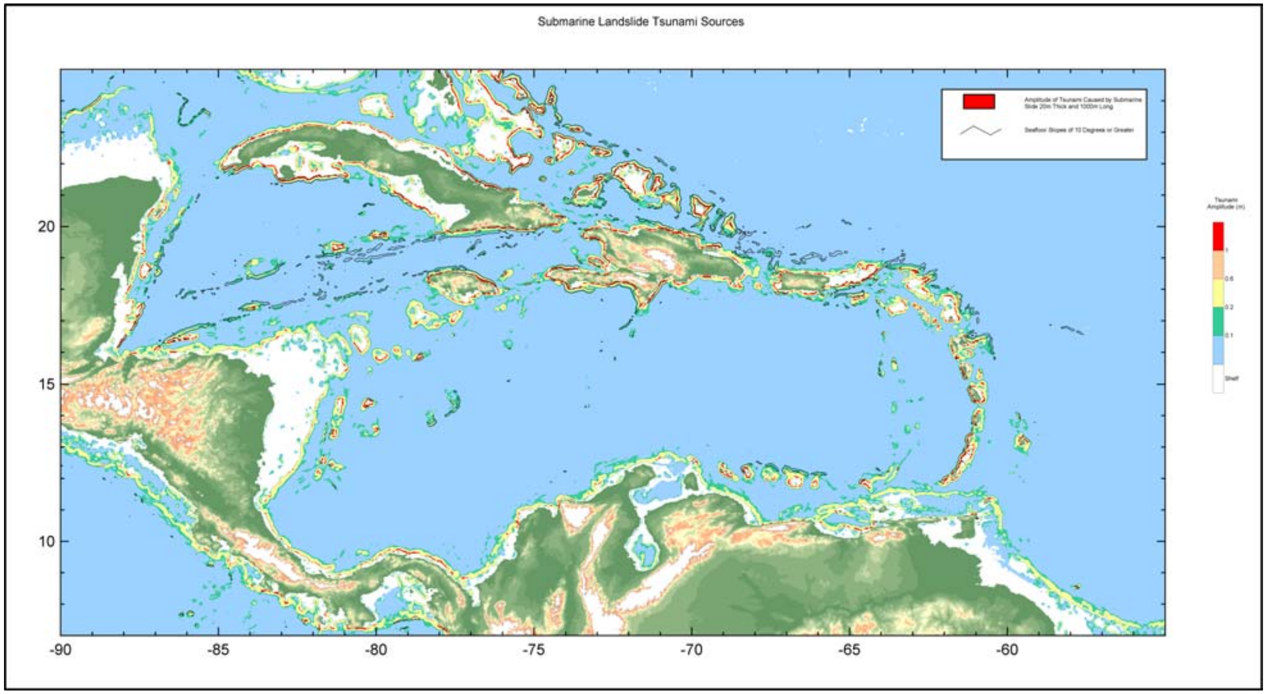

Figure 5. Landslide tsunami sources in the Caribbean Basin. Regions are color coded by the amplitude of tsunami generated by a 20-meter thick 1 km long submarine landslide. Slides are most tsunamigenic in shallower water, so steeper region near island platforms are typically regions of high tsunami potential. Regions with slopes of 10º or greater are also shown. I consider these regions, in combination with regions color-coded in red, to be particularly dangerous.

Antilles; 4- Numerous other regions near strong seismic sources (of all types) have high amplitudes, and could, therefore, be sources for earthquake-induced submarine slides and tsunami 5- The low slide hazard along the *Pacific* coast of Nicaragua and El Salvador, suggests that shelf/slope submarine landslides may be more of a fundamental problem in the Caribbean basin than around the Pacific Ocean.

6. Conclusions

The Caribbean Basin suffers from the presence of several tsunami sources. They include numerous earthquake sources exhibited by zones of major faulting surrounding and within the basin, slide/slump sources as exhibited by steep slopes in relatively shallow water near many of the islands. Using the historic record of earthquakes and the tectonic framework of the basin numerous earthquakes sources have been identified and classified.

The primary source of shallow, potentially tsunamigenic earthquakes is the eastern subduction zone extending from Trinidad north then west through Hispaniola. It is composed of three bands of earthquakes sources, and outer belt representing a zone of plate bending earthquakes, the main plate interface, source of numerous great earthquakes ($M > 7\ ¾$), and finally a band of high angle active faults on the island platform from Guadeloupe to the north and west along the island arc. The main plate interface subdivided into three categories of high, medium and low/indeterminate tsunami potential reflecting the historic earthquake/tsunami record, direction of plate convergence and width of the accretionary prism. A separate supplementary category, the potential for slow or tsunami earthquakes, is added to those regions along the eastern subduction zone recently affected by the subduction of significant seafloor relief.

Other convergent margins are found north of South America (indeterminate potential), south of Cuba and along the Caribbean margin of southern Central America (both high potential). Several systems of active faults (primarily strike-slip) extending west of Jamaica to the east margin of Central America also represent a significant earthquake threat. Events in this region may trigger submarine landslides, and, therefore, be accompanied by tsunami. Several zones of active faulting, but with lower rates of deformation, also represent a non-negligible tsunami threat, these include the Holcombe transtensional zone, the Yucatan-Cuba Belt and the Beata Ridge.

Regions of potential tsunami induced by submarine landslides were identified by manipulating ETOPO2 seafloor bathymetry and seafloor slope to develop a map of relative tsunami amplitude for a submarine slide measuring 20 m by 1 km. Regions with seafloor slope of 10° or more were superimposed on the tsunami amplitude map to indicate regions of particularly high potential. The Caribbean, because of the presence of several limited island platforms, seems particularly prone to the tsunami-slide hazard. Similar maps using different slide dimensions could provide a more clear insight to the total slide-tsunami threat and a similar family of maps could provide similar information about slump related tsunami.

Much work needs to be done before we have a good idea of the tsunami threat in the Caribbean. Clearly, the density of nearby sources is high, perhaps higher than in many other parts of the world. Mitigation efforts would benefit from development of:

- An updated, cross-referenced earthquake/tsunami catalog developed by closing the obvious gaps in the IPGH historic catalog, and using improved earthquake locations such as are found in the Engdahl, Centennial and other catalogs (Engdahl. 1998),
- A catalog with the location and character of slides and slumps in the Caribbean region found by executing a search of the seafloor using existing single and multichannel seismic reflection data.
- A digital atlas/database of available and useful geologic and geophysical data for the study of tsunami in the Caribbean Basin (7º to 25º N, 55º -90º W), including but not limited to parameters such as earthquakes and tsunami and location of existing slumps/slides as mentioned above, focal mechanisms, bathymetry, gravity, magnetics, sediment thickness, seismic velocity of sediments, active faults, regional stress, rates of vertical and horizontal deformation, expected ground accelerations from earthquakes, seafloor geology, and bibliography of important tsunami manuscripts.

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Table 1. Caribbean Basin Earthquakes, 1492-2004, of Magnitude 7.0 or larger, depths 0 to 50 km, as found in IPGH, MIDAS, NEIC or supplementary historic catalogs.

Agency	IPGH	Year	Month	Day	OT	Long.	Lat.	Depth	Mw	MMI	Zone	T
SISRA	2	1530	9	1	14:30:00	-64.10	10.70	10	8	10	M4	yes
SAL	8	1564	4	20		-70.20	19.25	33	7	9		no
SISRA	26	1641	6	11	12:45:00	-66.70	10.90			9		no
SAL	44	1678	2	11	9:00:00	-75.82	20.00	10	7	8		no
SISRA	45	1684	5	5	0:30:00	-64.17	10.47			7		no
SAL	49	1690	4	5		-62.00	17.00	33	7.5	8	K	yes
SAL	50	1692	6	7		-76.50	18.00	10	7.5	10		yes
SAL	109	1751	10	18		-70.00	18.50	33	8		M3	yes
SAL	110	1751	11	21		-72.00	18.50	33	7.5		M3	yes
SAL	125	1766	6	11	0:30:00	-76.00	19.50	10	7	9		no
NOAA		1766	10	21	9:00:00	-62.50	7.40		7.5	9		no
SAL	134	1770	6	3	19:50:00	-72.50	18.50	10	7.5	10	K	yes
NOAA		1787	5	2	15:55:00	-66.00	19.00	33	8		MF	yes
SISRA	188	1794	9	10		-64.17	10.47			7		no
SISRA	193	1797	12	14	23:30:00	-64.10	10.60			9		no
NOAA		1812	3	26	21:07:00	-67.00	10.00		9.6	10		yes
ROJ	256	1822	5	7	6:30:00	-83.15	9.63	20	7.5	9		yes
SISRA	263	1825	9	21		-61.70	10.80			8		yes
SAL	275	1826	9	18	9:08:00	-76.00	19.50	33	7	8		no
MONT	276	1827	4	3		-83.00	9.87		7.5	7		no
SISRA	367	1831	12	3	23:40:00	-61.45	12.40			7		no
SISRA	400	1837	9	10	18:30:00	-66.60	10.30			7		no
SISRA	409	1839	4	12		-64.17	10.47			7		no
SAL	439	1842	5	7	22:30:00	-72.50	19.80	33	8	9	K	yes
SAL	440	1843	2	8		-62.00	17.00	33	8	10	K	yes
SISRA	446	1844	8	30	7:10:00	-60.83	13.23			8		no
SAL	478	1852	8	20	13:36:00	-75.80	20.00	10	7.5	9	CH	yes
SAL	479	1852	11	26		-76.00	20.00	10	7	8	CH	yes
		1856	8	9	22:47:00	-86.50	17.00		8.3		FE	yes
SAL	566	1867	11	18	20:00:00	-65.00	18.50	33	7.5	8	RE	yes
VIQU	680	1882	9	7	8:18:00	-79.00	10.00		7.5	9	ME	yes
SAL	734	1887	9	23		-74.00	20.00	33	7.75	9	M3	yes
SISRA	735	1888	1	10	13:00:00	-62.20	11.30		7	8	K	no
GUT	768	1899	6	14		-77.00	18.00	0	7.8			no

SISRA	777	1900	10	29	9:11:00	-66.00	11.00	25	7.59		M4	yes
AMB	819	1904	12	20	5:42:00	-82.00	9.00	35	7.44	6		no
MACRO	832	1906	2	16	17:25:00	-60.50	14.50	50	7	8		no
MACRO	849	1907	1	14	8:00:00	-76.00	18.00	10	7		H	yes
TOJ	977	1916	4	26	2:21:14	-82.10	9.60	25	7.3	9		yes
A-N	991	1917	2	20	19:29:00	-78.50	19.50		7.09	6		no
GUTE	1006	1917	7	27	1:01:18	-67.50	19.00	50	7			no
GUTE	1056	1918	10	11	14:14:30	-67.50	18.50		7.3	8	M2	yes
GUTE	2172	1941	4	7	23:29:17	-78.50	17.75		7			no
SISRA	2263	1942	5	2		-66.00	11.00			7		no
GUTE	2410	1943	7	29	3:02:16	-67.50	19.25		7.5		K	no
SISRA	2460	1944	2	6	3:50:30	-62.00	10.00			7		no
GUTE	2684	1946	8	4	17:51:05	-69.00	19.25		7.8		K	yes
GUTE	2698	1946	8	8	13:28:28	-69.50	19.50		7.4			yes
GUTE	2850	1948	4	21	20:22:02	-69.25	19.25	40	7.09			no
ISC	12995	1969	12	25	21:32:27	-59.64	15.79	1	7		M4	yes
ISC	17469	1974	10	8	9:50:58	-61.99	17.37	41	7.3		M	no
RSN	52787	1991	4	22	21:56:49	-83.15	9.63	23	7.59	10		yes
OSS-SA	54064	1991	9	24	4:56:31	-77.17	8.82	3	7.69	0		no

Table Notes: Agency, denotes and IPGH agency code for the source of the earthquake information, IPGH is IPGH sequence number, when absent event, was not in IPGH catalog, Mw is moment magnitude, MMI is Modified Mercalli Intensity, Zone gives source for inferred rupture zone, if absent, no rupture zone is shown in figures, T is whether or a not a tsunami was observed. Table is complete up to August 13, 2004. Key for Zone source information is as follows: CH, Chuy (1980); H, Hall (1907) ; FE, Feldman (1993) ; K, Kelleher et al. (1973) ; M, McCann et al, (1984) ; M2, McCann (1998) ; ME, Mendoza and Nishenko (1989) ; M4, McCann and Pennington (1990) ; M3, McCann (2001) ; MF, McCann, et al., (2004) ; RE, Reid and Taber, (1920) .

Table 2. Caribbean Basin Earthquakes, 1700-2004, of Magnitude 6.5 to 7.0, depths 0 to 50 km, as found in IPGH, MIDAS or NEIC catalogs.

Agency	IPGH	Yr	Mo	Dy	OT	Lon	Lat	Dep	Mw	Agc	Mag	Sc	Agc	MMI	Tsunami
SAL	55	1701	11	9		-72.50	18.50	10	6.6	SAT	6.5	Ms	SAL	7	No
SAL	117	1760	7	11		-75.83	20.00	10	6.6	SAT	6.5	Ms	SAL		No
SAL	161	1784	7	29		-72.28	19.78	33	6.8	SAT	6.8	Ms	SAL	8	No
SAL	225	1812	11	11	10:50:00	-76.50	18.00	20	6.8	SAT	6.8	Ms	SAL	8	Yes
SAL	240	1816	12	22		-60.00	13.00	50	6.6	SAT	6.5	Ms	SAL	6	No
SAL	291	1827	12	21		-60.75	14.50	50	6.6	SAT	6.5	Ms	DOR	6	No
SAL	354	1830	4	14	11:30:00	-72.30	18.50	10	6.6	SAT	6.5	Ms	SAL	7	No
SAL	442	1844	4	16		-66.00	18.75	33	6.6	SAT	6.5	Ms	SAL	7	No
SAL	477	1852	7	7	12:25:00	-76.50	19.00	33	6.6	SAT	6.5	Ms	SAL	5	No
SISRA	486	1853	7	15		-63.60	12.10	14	6.7	SAT	6.7	Ms	FIE	9	Yes
SAL	522	1858	1	28	21:45:00	-76.00	19.00	10	6.6	SAT	6.5	Ms	SAL	6	No
SAL	543	1860	10	23		-67.50	18.50	33	6.6	SAT	6.5	Ms	SAL	7	No
SAL	664	1880	1	23		-82.40	23.00	33	6.6	SAT	6.5	Ms	SAL	8	No
SISRA	679	1882	9	7	7:50:00	-77.00	9.00		6.6	SAT	6.5	Ms	IGE	9	No
SAL	753	1895	5	20	21:44:00	-61.00	18.00	33	6.6	SAT	6.5	Ms	SAL	6	No
SAL	758	1897	4	29	14:15:00	-61.50	16.20	10	6.6	SAT	6.5	Ms	BAL	8	No
SAL	759	1897	12	29	11:32:00	-70.70	19.50	33	6.6	SAT	6.5	Ms	SAL	8	No
MACRO	840	1906	6	22		-76.00	19.50	10	6.6	SAT	6.5	Ms	JBS	7	No
AMB	876	1910	1	1	11:02:00	-85.00	17.00	10	7.0	SAT	7.0	Ms	AMB		No
VIQU	891	1910	12	22	3:24:00	-82.30	9.80		6.6	SAT	6.5	Ms	C&V	5	No
GUTE	900	1911	10	6	10:16:12	-70.50	19.00	0	6.9	SAT	6.9	Ms	ABE		No
AMB	910	1912	6	12	12:44:42	-88.00	16.50	35	6.8	SAT	6.8	Ms	AMB		No
GUTE	956	1915	10	11	19:33:12	-67.00	19.00	0	6.8	SAT	6.8	Ms	PAS		No
GUTE	990	1916	11	30	13:18:00	-70.00	20.00		6.8	SAT	6.8	Ms	PAS		No
GUTE	1120	1920	2	10	22:07:15	-67.50	18.00		6.6	SAT	6.5	Ms	PAS		No
GUTE	1294	1925	9	29	17:33:50	-62.00	18.50		6.6	SAT	6.5	Ms	PAS		No
ROR	1306	1926	2	1	1:17:47	-62.40	10.88	5	6.6	SAT	6.5	Ms	PAS	5	No
AMB	1311	1926	3	17	11:53:36	-82.50	12.50	35	6.8	SAT	6.8	Ms	AMB		No
GUTE	1354	1927	8	2	0:51:46	-64.50	19.00		6.6	SAT	6.5	Ms	PAS		No
ROR	1414	1928	9	27	0:44:09	-59.49	11.58	30	6.6	SAT	6.5	Ms	PAS	7	No
ROR	1428	1929	1	17	11:45:42	-63.98	10.35		6.9	SAT	6.9	Ms	PAS	9	Yes
GUTE	1559	1932	2	3	6:15:55	-75.50	19.50		6.8	SAT	6.8	Ms	PAS	8	yes
GUTE	2413	1943	7	30	1:02:30	-67.75	19.25		6.6	SAT	6.5	Ms	PAS		no
SISRA	2441	1943	12	21	13:46:21	-71.00	13.00		6.6	SAT	6.5	Ms	R-I	7	no

SISRA	2443	1943	12	22	12:53:00	-71.00	13.00		6.6	SAT	6.5	Ms	R-I	7	no
SISRA	2444	1943	12	23	15:56:05	-71.00	13.00		6.6	SAT	6.5	Ms	R-I	7	no
GUTE	2750	1946	10	4	14:45:26	-68.50	18.75	50	6.5	SAT	6.4	Ms	ABE		no
GUTE	2796	1947	8	7	0:40:20	-75.25	19.75	50	6.8	SAT	6.8	Ms	PAS		no
SAE	3521	1953	5	31	19:58:35	-70.40	19.68		6.9	SAT	6.9	Ms	SAE	5	yes
SAE	4220	1957	3	2	0:27:33	-78.11	18.35		6.6	SAT	6.5	Ms	SAE	8	no
CGS	4308	1957	8	15	8:32:56	-80.00	10.00		6.7	SAT	6.7	Ms	ROT		no
ROR	4335	1957	10	4	5:26:03	-62.77	10.86	6	6.7	SAT	6.7	Ms	ROR	9	no
SAE	5655	1962	1	8	1:00:23	-70.46	18.40	33	6.5	SAT	6.4	Ms	SAE		no
SAE	5733	1962	4	20	5:47:51	-72.13	20.50		6.8	SAT	6.8	Ms	SAE		no
ISC	7153	1964	10	23	1:56:05	-56.11	19.80	43	6.8	SAT	6.2	mb	ISC		no
SISRA	10226	1967	7	30	0:00:03	-67.40	10.68	26	6.6	SAT	6.6	Ms	MOS	8	no
ISC	10634	1967	12	24	20:03:13	-61.19	17.42	42	6.7	SAT	6.1	mb	ISC		no
1	26226	1980	8	9	5:45:07	-88.52	15.93	9	6.5	CMT	6.5	Mw	CMT		no
ISC	34819	1984	6	24	11:17:11	-69.30	18.02	20	6.7	CMT	6.7	Mw	CMT		no
SBAC	44604	1988	4	22	4:03:32	-61.37	17.22	32	6.5	CMT	6.5	Mw	CMT		no
GSM	55214	1992	5	25	16:55:04	-77.87	19.61	23	6.9	SAT	6.9	Ms	GS	C	no
MIDAS	4676	1999	7	11	14:14:15	-88.261	15.702	10	6.6	/Ms	6.1	mb	USGS		no
PDE		2003	5	14	6:03:35	-58.63	18.27	41	6.7	GS					no
PDE		2003	9	22	4:45:36	-70.67	19.78	10	6.6	GS/Ms					no

Table Notes: Agency, and Agc denotes IPGH agency code for the source of the respective information, IPGH is IPGH/MIDAS sequence number, when absent event was not in IPGH or MIDAS catalog, Yr, Mo, Dy, Ot, is year month day and origin time (UT) of earthquake, Lon, Lat, Dep are Longitude, Latitude and Depth estimates for hypocenter, Mw is moment magnitude, Mag and Sc is other magnitude and its scale, MMI is Modified Mercalli Intensity, Tsunami is whether or a not a tsunami was observed. Table is complete up to August 13, 2004.