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A BRIEF HISTORY OF TSUNAMIS IN THE CARIBBEAN SEA

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ABSTRACT

The area of the Caribbean Sea is geologically active. Earthquakes and volcanoes are common occurrences. These geologic events can generate powerful tsunamis some of which are more devastating than the earthquake or volcanic eruption itself. This document lists brief descriptions of 91 reported waves that might have been tsunamis within the Caribbean region. Of these, 27 are judged by the authors to be true, verified tsunamis and an additional nine are considered to be very likely true tsunamis. The additional 53 events either are not described with sufficient detail in the literature to verify their tsunami nature or are judged to be reports of other phenomena such as sea quakes or hurricane storm surges which may have been reported as tsunamis. Included in these 91 reports are teletsunamis, tectonic tsunamis, landslide tsunamis, and volcanic tsunamis that have caused major damage and deaths. Nevertheless, in recent history these events have been relatively rare. In the interim since the last major tsunami event in the Caribbean Sea the coastal regions have greatly increased in population. Coastal development has also increased. Today tourism is a major industry that exposes thousands of non-residents to the disastrous effects of a tsunami. These factors make the islands in this region much more vulnerable today than they were when the last major tsunami occurred in this area. This paper gives an overview of the tsunami history in the area. This history illustrates what can be expected in the future from this geologic hazard and provides information that will be useful for mitigation purposes.

INTRODUCTION

The region of the Caribbean Sea is beset by many natural hazards; among the most destructive of these are earthquakes, hurricanes and tsunamis. Each of these dangers can be mitigated with action based on appropriate knowledge.

While tsunamis are a relatively minor natural hazard in the Caribbean, the potential they have to disrupt public and private lives and destroy property in the area can be mitigated if appropriate preparations based on the available history of this hazard in the region are undertaken. Most hazard histories for the Caribbean have emphasized hurricane or earthquake hazard and effects with relatively little emphasis on the danger that tsunamis pose in this region. The purpose of this work is to provide a short history of Caribbean tsunamis that can be used by local and regional hazard mitigators in designing plans for reducing the disastrous effects of the many natural hazards that are found in this area. More extensive works such as O'Loughlin and Lander (in preparation) are useful for more detailed studies of this hazard in the Caribbean.

This catalog of historical Caribbean tsunamis contains brief descriptions of the effects of 91 reported waves that might have been tsunamis within the Caribbean region. Of these, 27 are judged by the authors to be true, verified tsunamis and an additional nine are considered to be very likely true tsunamis. The additional 53 events either are not described with sufficient detail in the literature to verify their tsunami nature or are judged to be reports of other phenomena such as sea quakes or hurricane storm surges which may have been reported as tsunamis.

Tsunamis in the Caribbean have affected 22 countries and administrative areas including Central America and northern South America. The record for the last hundred years lists 33 possible tsunamis or one about every three years. This includes seventeen of the 34 likely or verified tsunamis in the catalog - or half of these events. The last destructive tsunami in the Caribbean occurred in August, 1946, more than 55 years ago. Destructive tsunamis have typically occurred with inter-event times that average about 21 years between destructive events. Since major tsunamis in the region are apparently overdue, it is hoped that this listing will aid local hazard planners in executing plans to protect local populations from this threat before the next destructive tsunami occurs in the region.

Tsunamis can arise from at least four different sources, all of which have produced observed tsunamis in the Caribbean during recorded history. These tsunami sources include tsunamis from remote sources (teletsunamis); tsunamis generated by mass movements such as debris and landslides (landslide tsunamis); tsunamis generated by volcanic processes (volcanic tsunamis); and finally tsunamis that are produced by the sudden movement of plates and crustal blocks (tectonic tsunamis).

The geography and bathymetry of the Caribbean region are shown in Figure 1. Nearly all areas within the Caribbean region have experienced a tsunami in historical times. Figure 1 includes the main geographical boundaries and place names that have been associated with tsunami occurrence in this catalog. In some cases the location of ancient towns or areas has been interpreted by the authors from descriptions in the literature.

BACKGROUND INFORMATION

The Caribbean region, bounded by Honduras, Nicaragua, Costa Rica, Panama, Colombia, Venezuela, the Lesser Antilles, Puerto Rico, Hispaniola, and Jamaica, defines a plate of Earth's surface that moves semi-independently of the surrounding plates. The Caribbean plate, flanked by the North American and South American plates, moves eastward, or possibly slightly north of eastward. As the Caribbean plate moves, the American plates are driven under it on its eastern side, a process known as subduction. A vertical offset of the ocean floor can occur in this area. The crust of the Atlantic plates begins to melt as it descends into the hot rocks of the mantle. The molten material, or magma, thus created rises to form volcanoes that become the Lesser Antilles island arc. Along the northern and southern boundaries the Caribbean plate is sliding past the American plates along broken and irregular boundaries that contribute to the complexity of the movement. Finally, on the west, the Cocos plate is being driven northeastward, and is being subducted beneath the Caribbean plate. This movement causes the plate to strain against the surrounding plates, and thus, its boundaries are disclosed by a band of earthquakes that extends around the plate's periphery.

While the eastern boundary with its typical island arc structure of oceanic trough and volcanic islands would be expected to be the source of tsunamigenic earthquakes, the two major tsunamis affecting Puerto Rico and the Virgin Islands originated on structures transverse to the arc. The 1867 Virgin Islands earthquake and tsunami most probably originated on the Anegada Trough and the 1918 Puerto Rico event occurred along the northeast boundary in the region between Hispaniola and Puerto Rico. Stresses along this northern plate boundary have caused uplift in many of the islands and subsidence in some other areas. Upraised limestone strata (layers) on a fault block create the spectacular cliffs of Mona Island between Puerto Rico and Hispaniola. Upraised limestone strata are also found on Puerto Rico's north coast although they are deeply weathered and eroded.

Intensive study of this region by side-scan sonar has revealed an unusual formation on the northern slope of Puerto Rico. A large amphitheater and a smaller one farther to the east apparently were created by slumping that could have been triggered by earthquakes in this area of high seismicity. If these large areas of rock and sediment slid as a single mass, large and destructive sea-surface waves (tsunamis) would have been generated.

This catalog was compiled from historical descriptions and primary source material wherever possible. However, in many cases secondary descriptions were the only data available relating to tsunami occurrence and were the primary references used in this compilation.

Mitigation of the tsunami hazard in the Caribbean from locally generated tsunamis will be difficult because of the relatively short travel time of waves generated in trench or volcanic areas to nearby inhabited land. In general this is less than 30 minutes to an hour. The local population should be educated to understand that in the event of a strong earthquake or a sudden recession of the sea or strange sounds coming from the sea, the appropriate action is to move to high ground to avoid the possible danger of a coming tsunami.

Both Alaska and Hawaii suffered from a major tsunami and loss of life in the last half of the twentieth century before [a tsunami warning system was established to save lives and property] it was determined that a tsunami warning system would help to save lives and property. However, because tsunamis are relatively rare, they are often overlooked in hazard mitigation planning. The current efforts to develop a tsunami warning system within the Caribbean include the need to understand the historical tsunami hazard in each area. We hope that this catalog will be a first step in that process.

DISCUSSION

TYPES OF TSUNAMIS

A. Teletsunamis. Teletsunamis are tsunamis originating more than 1000 km from the affected area. They are the major tsunami type affecting Hawaii and the west coast of the United States. Since they originate at a considerable distance there is time for tsunami warning systems to detect the existence of a tsunami and to warn the population at risk. Only two historical teletsunamis are known to have affected the Caribbean - both occurred off the coast of Portugal. The first was a major tsunami from the 1755 Lisbon, Portugal, event that took seven to eight hours to reach the Caribbean as a destructive teletsunami. A second teletsunami was generated by an aftershock in 1761. This wave, while observed in the Caribbean, did little damage. Another teletsunami from this region off western Europe is possible at any time.

B. Landslide Tsunamis. Tsunamis generated by landslides are usually but not always triggered by earthquakes. They can have devastating effects locally, but the effects are limited to a small area. As the source of a landslide is normally near shore, the warning time is usually short (only a few minutes). Education of the public to seek high ground immediately if they feel an earthquake or notice a withdrawal of the sea is probably the only effective mitigation measure. Landslides are common throughout the Caribbean Sea, and are a major cause of tsunamis in this region.

C. Volcanic Tsunamis. Volcanoes can create tsunamis in a number of ways including explosions, caldera collapse, and landsliding. Volcanic tsunamis have been observed in the Caribbean from eruptions of Mt. Soufriere and Nevis. Volcanoes in the Canary Islands may also be capable of creating teletsunamis which can reach the Caribbean with destructive results. The December, 2001 eruption of Kick-'em-Jenny emphasized Shepherd's (1997) hypothesis that a major tsunami could occur in association with a strong eruption has raised public and academic interest in the tsunami danger in the Caribbean from volcanic eruptions.

D. Tectonic Tsunamis. Tectonic tsunamis are produced when one portion of the sea floor moves vertically with respect to an adjacent portion. This usually occurs in subduction zones where oceanic plates move beneath lighter continental material. The North American tectonic plate is subducting beneath the Caribbean plate on the eastern and northern boundaries of the Caribbean. Several great earthquakes ($M_w >= 8$) have occurred along the northern boundary in historical times (1946 and 1918), along the northeastern section (1867) and in the eastern subduction zone in the Windward and Leeward Islands (e.g. in 1969).

E. Tsunami Effects. Tsunamis cause damage in a number of ways. While large, breaking waves are rare, the force of the waves can destroy buildings, piers, bridges and other structures. Even relatively small waves can cause strong currents that in San Francisco and Los Angeles have caused millions of dollars in damage, principally by breaking free fishing boats and yachts which collide with each other and with harbor structures. Damage can also be caused by battering by water carried debris such as logs, boats, autos etc. The retreating waves can scour the support for bridges, piers, breakwaters, etc. and cause failures. Chemical spills and fires caused by ruptured storage tanks are also common. Waves can travel long distances up rivers as bores. It is important to include search and rescue operations in emergency plans.

F. Tsunami History. The preparation of a thorough history of tsunami occurrences and effects is important in understanding the local nature of the hazard and designing the most effective plan for mitigation. In Jamaica, for instance, the history shows that most tsunamis are related to landslides. Education regarding protective steps in this country would include warnings to seek higher ground in case of an earthquake. In Puerto Rico and the Virgin Islands, however, a greater danger comes from tectonic tsunamis. People in these areas should be warned to watch for a recession of the sea after an earthquake and to seek higher ground should a strongly felt earthquake occur. In the eastern Caribbean, on the other hand, most tsunamis originate from volcanic activity. Since volcanoes erupt over a period of days to weeks, local populations should have sufficient warning from local officials to make appropriate decisions. But it is only through a study of the past causes and effects of local tsunamis that such decisions can be made with intelligence.

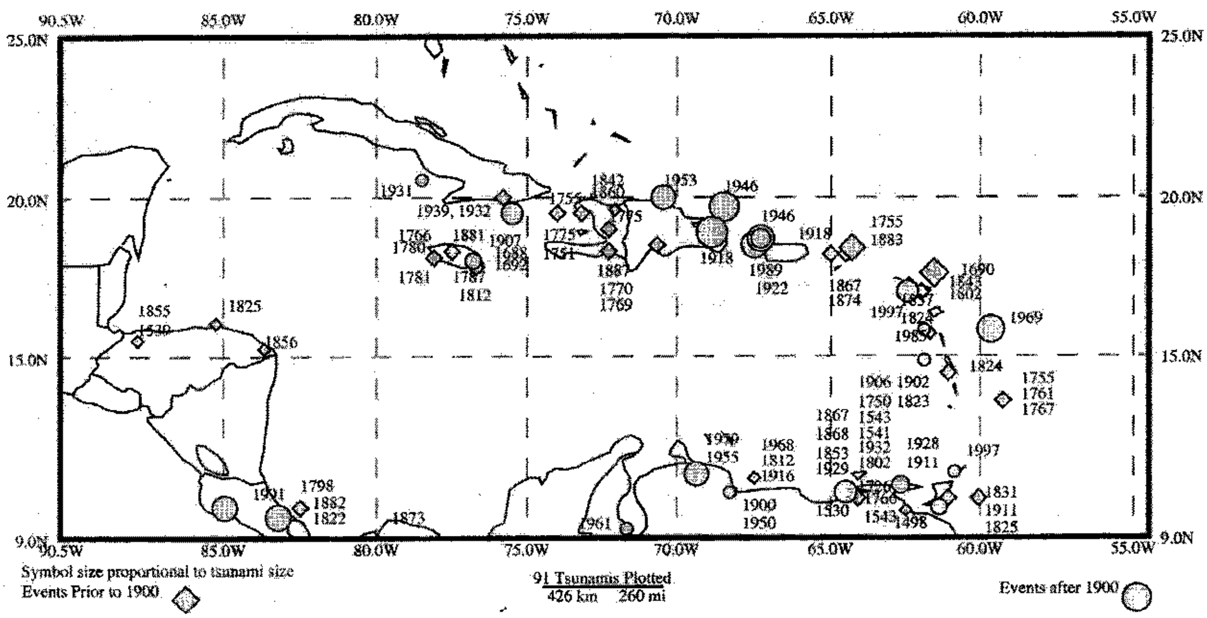


FIGURE 2: TSUNAMIS OF THE CARIBBEAN SEA (1492 - 2000)

Figure 2 shows the localities and years during which tsunamis have affected the various coastlines of the Caribbean. This information can be useful in regard to when the next earthquake might be expected in a specific locale. Throughout this catalog, descriptions of earthquake effects have been avoided in order to emphasize the tsunami danger, however, it must be acknowledged that most tsunamis occur in association with earthquakes and often effects and damages from the two events are difficult to consider separately. Localities shown for tsunamis in Figure 2 are often the sites of the tsunami-generating earthquake, and not the locations of the regions where the tsunami was observed.

This catalog contains two separate listings of data. The first is a brief description of possible tsunami effects as noted in the literature for each of the 91 reported instances of tsunamis in the Caribbean area. Details have deliberately been avoided in favor of a short, readable description. For further reading, there is an extensive listing of references with each description of an observed tsunami. The second data listing includes information regarding Caribbean tsunamis in tabular format. The first of these tables (Table 2) lists those tsunamis that the authors have judged to be verified or very likely to have occurred. Table 3 lists tsunamis that have been reported, but in the opinion of the authors are not verifiable from the reports at hand. The validity rating at the end of each entry is based on the following considerations:

Table 1. Criteria for assigning validity to tsunami reports

VALIDITY RATING	CRITERIA FOR ASSIGNMENT
V0	Tsunamis did not occur; the cited literature is considered in error or invalid.
V1	The tsunami is considered unlikely or doubtful. Information is considered unreliable, but the possibility of a tsunami cannot be ruled out.
V2	A tsunami may or may not have occurred; data are insufficient to ascertain occurrence.
V3	The tsunami is considered likely or probable.
V4	A tsunami did occur; information is considered reliable.

In many cases, sources contradict each other. In these cases, reference has been made to the primary source cited by others. There is much subjectivity in assigning validity as the authors must interpret the judged accuracy of others, many of whom wrote in languages unfamiliar to the authors or during times that conditioned their observations and recordings. The authors hope that this catalog will provide helpful in defining the tsunami hazard in the Caribbean.

HISTORICAL EVENTS

1498, August 2 or 3: An earthquake and possible tsunami affecting Pedernales in Boca de la Sierpe, Venezuela was reported. Singer, et al., 1983. **V2**

1530, September 1: Ground cracking occurred on a mountain near the Gulf of Cariaco, Venezuela. Black salt water and asphalt flowed from ground openings. A fort and many houses were destroyed perhaps by the combined effects of the earthquake and tsunami. The sea rose 7.3 m, and subsided near the coast of Paria. It rose 6.0 m near the island of Cubagua, and at Camana. Berninghausen, 1968; Heck, 1947; Mallet, 1853; Milne, 1912; Robson, 1964; Schubert, 1994; Singer, et al., 1983. **V4**

1539, November 24 [23:00 Local Time (LT)]: Sailors in three ships 160 km off Cabo de Higueras in Northern Honduras reported a shaking of the sea and headed for shore. Reportedly the sailors described the shock as crashing against the rocks. An earth movement began at the river mouth, and advanced slowly wiping out massive amounts of land 84 m north to south, and ruining a large house. The shaking reportedly lasted many hours. Earthquake effects were reported in the region of the Gulf of Honduras. Molina reports a seaquake. Feldman, 1993; Molina, 1997. **V2**

1541, December 25: A tsunami was reported at Cubagua Island, along with possible tsunami damage at Nueva Cadiz, Venezuela. Singer says an earthquake is doubtful. Schubert, 1994; Singer, et al., 1983. **V2**

1543: Reports included accounts of waves and a sea that was much higher than the land. This was probably due to subsidence. The city of Cumana, Venezuela, was destroyed, possibly by an earthquake. Berninghausen, 1968; Ceteno-Grau, 1969; Grases, 1971; Heck, 1947; Robson, 1964; Singer, et al., 1983. **V2**

1688, March 1: [Gregorian date] Earthquakes were felt throughout Jamaica, and waves damaged ships in Port Royal. A ship at sea was reportedly damaged by a hurricane. No hurricanes are listed in Millas, since this is not in hurricane season. Berninghausen, 1968; Mallet, 1853; Millas, 1968; Milne, 1912; Perrey, 1847. **V1**

1690, April 16: An earthquake with magnitudes reported variously up to Ms>8 occurred in the Leeward Islands, and generated waves after substantial recession of the sea at many locations. This is the earliest record of a tsunami affecting any U.S. territories. Olsen, citing letters from the Danish West Indian and Guinea Company, reported for Sunday, April 6 (the Julian date) at Charlotte Amalie, St. Thomas: Eyewitnesses reported an earthquake around four pm which lasted one fourth to one-half an hour and caused the sea to recede so that it was possible to walk out 18 meters and pick up the fish. The earthquake was also listed as MMI=IX at Antigua, where there were several deaths. At St. Kitts (St. Christopher) large earth cracks opened. The earthquake caused the collapse of the Jesuit College and all other stone buildings at Nevis, where landslides generated on volcanic Nevis Peak caused the sea to withdraw 201 m from Charleston, before returning in two minutes. Guadeloupe also incurred much damage. Lander and Lockridge, 1989; Mallet, 1853; Olsen, 1988; Robson, 1964, citing Calendar of State Papers 1689-1692 (1901); Oldmixon (1741); Schubert, 1994; Shepherd and Lynch, 1992; and Taylor, 1888. **V4**

1692, June 7 [11:43 LT]: An earthquake at Port Royal, Jamaica, caused a landslide within the harbor, generated a tsunami, and destroyed ninety percent of the buildings in the city. Portions of the city slipped into the water. A 1.8 m wave crossed the bay. Ships overturned. Along the coast of Liganee (possibly Liguanea Plain, site of present-day Kingston) the sea withdrew 274 m, exposing the bottom. The returning water overflowed most of the shore. The sea withdrew 1.6 km at Yallhouse (possibly Yallahs). A large wave was reported at Saint Ann's Bay. Approximately 2,000 were killed in the earthquake and tsunami. Berninghausen, 1968; Heck, 1947; Mallet, 1853; Milne, 1912; Myles, 1985; Perrey, 1847, Rubio, 1982; Sloane, 1809; Taber, 1920. **V4**

1726: A large wave partially destroyed a Spanish fort on the Araya Peninsula. At Salina de Araya, the waves destroyed a salt plant by an inundation of the sea. This event is reportedly one of two large waves reported for Venezuela (the other occurred in 1900) but is not associated with an earthquake. Schubert, 1994; Singer, et al., 1983. **V2**

1750: A tsunami reportedly associated with an earthquake in Venezuela was reported. Schubert, 1994; Singer, et al., 1983. **V1**

1751, September 15: A large earthquake reportedly destroyed Port-au-Prince and caused subsidence off the coast. There is uncertainty as to whether this event is really a separate event or another account of the November 21st event in that year. Seismic activity continued for months and reportedly involved most of the island of Hispaniola. The earthquakes were felt as far away as the Lesser Antilles. The mainshock was estimated as Ms=8.0, with numerous aftershocks. No tsunami was reported. Lyell, 1875; Perry, 1843, Milne, 1912; Shepherd and Lynch, 1992. **V1**

1751, October 18 [19:00 UT]: The city of Azua de Compostela, Hispaniola, was destroyed by an earthquake and the resulting tsunami. Damaging waves were also reported at Santo Domingo and Santa Cruz El Seybo. Berning-hausen, 1968; Heck, 1947; Mallet, 1853; Perrey, 1847; Rubio, 1982; Taber, 1922a 1922b. **V4**

1751, November 21: A violent shock at Port-au-Prince, Haiti, caused a twenty-league (96 km) section of the coast to fall into the sea. No tsunami was reported. Mallet (1853). **V1**

1755, November 01 [9:50 LT]: A teletsunami was generated by a strong earthquake in Lisbon, Portugal. This North Atlantic teletsunami reached Antigua in about 9.3 hours. Later waves with estimated runup heights of 7 m were observed at Saba, Netherlands Antilles. At St. Martin, the runup was 4.5 m. The full height of the tsunami could have been as high as ten meters. Antigua and Dominica each had runups of 3.6 m. At Barbados, the waves were 1.5 - 1.8 m, and were reported to have a very short period of only 5 minutes. The water looked as black as ink (perhaps from a local landslide). Waves were also reported at Samana Bay, Dominica. At Martinique, the water was reported to have withdrawn 1.6 km and returned to inundate the upper floors of houses. Lowlands on most of the other French islands were inundated. At Santiago de Cuba, Cuba, waves damaged buildings near the bay and inundated the town. Affleck, 1809; Heck, 1947; Herridge de Guerrero, 1998; Lander and Lockridge, 1989; Mallet, 1853; Robson, 1964; Rubio, 1982; Scherer, 1912; Schubert, 1994; Southey, 1827; Taber, 1922a, 1922b. **V4**

1755, November 18: The earthquake shock was felt from Chesapeake Bay to the Annapolis river, Nova Scotia. It was felt on Lake George, and a ship at sea 200 miles east of Cape Ann experienced a sea quake. The tsunami which accompanied this earthquake withdrew the water from St. Martins Harbor in the West Indies, leaving vessels aground. (This may be the only tsunami generated by an earthquake on the western shores of the Atlantic off the United States East Coast.) (Dombroski, 1973)

1761, March 31 [12:05 LT]: An earthquake near Lisbon, Portugal, reportedly caused a 1.2 m tsunami at Barbados. Berninghausen, 1968; Davidson, 1936; Mallet, 1854; Schubert, 1994. **V4**

1766, June 12 [4:45 UT]: An earthquake lasting one and a half to seven minutes hit Santiago de Cuba, and Bayamo, Cuba, and was felt strongly on Jamaica. Ships reported to be 7.2 km from the coast of Jamaica rolled so much that their gunwales were immersed in the water. A tsunami would not greatly affect ships in deep water. Either the ships were in shallow water or the effect was due to a seaquake. Grases, 1971; Mallet, 1854. **V2**

1766, October 21 [9:00 UT]: Very violent shocks destroyed Cumana, Venezuela, and caused the island of Orinoco (Venezuela) to sink and disappear. In many places the water surface was disturbed. Mallet, 1854. **V1**

1767, April 24 [6:00 UT]: Robson reported shocks at Martinique, Barbados and British Guiana. According to reports an agitated sea ebbed and flowed in an unusual way at Martinique and Barbados. Berninghausen, 1968; Mallet, 1854; Robson, 1964, **V3**

1769: A tsunami reportedly inundated 15 leagues (72 km) along the coast at Port-au-Prince, Haiti. Schubert 1994. **V2**

1770, June 03 [19:15 LT]: A strong earthquake caused 200 fatalities in Port-au-Prince, Haiti. Waves were noted at Golfe de la Gonave and Arcahaie in Haiti. The sea inundated 7.2 km inland. Berninghausen cites Mallet and gives a similar report dated 1769 (two reports of the same event). Berninghausen, 1968; Heck, 1947; Mallet, 1854; Milne, 1912; Rubio, 1982; Schubert, 1994; Southey, 1827; Taber, 1922a, 1922b. **V4**

1775, February 11: An earthquake at Hispaniola reportedly leveled several storehouses, and great damage was done by a tsunami, but the exact date and location are unknown. Event may be identical with March 1775 and December 18, 1775. Shepherd and Lynch, 1992; Southey, 1827. **V2.**

1775, March: Three strong shocks were felt on Hispaniola. Several storehouses were destroyed, and great damage was done by the sea. May be identical with February 11, 1775, and December 18, 1775. Grases, 1971; Rubio, 1982. **V2.**

1775, December 18: Three earthquakes were reported, and waves reportedly did extensive damage at Hispaniola and Cuba. However, Rubio does not mention any effects in Cuba. Event may be identical with February 11, 1775, and March, 1775. Berninghausen, 1968; Heck, 1947; Rubio, 1982; Southey, 1827; Taber, 1922a, 1922b. **V2**

1780, October 03 [22:00 LT]: An earthquake was reported to have occurred during a hurricane at Savanna La Mar, Jamaica. The sea rose to 3 m at 0.8 km from the beach and swept away a number of houses. Ten people were killed by the wave, and approximately 300 deaths resulted from the storm. All vessels in the bay were dashed to pieces or driven ashore. It is believed to be a spurious tsunami report, with the effects due to the hurricane storm surge. Heck, Milne, and Berninghausen all quote a date of Oct. 2, as reported by Perry. Millas reports Oct. 3 as the date of the storm. Berninghausen also gives Oct. 22 for this event, incorrectly citing Mallet, who gives the date as Oct. 2. Berninghausen, 1968; Heck, 1947; Mallet, 1854; Milne, 1912, Millas, 1968; Perrey, 1847; Shepherd and Lynch, 1992. **V1**

1781, August 01: Grases, citing Henderson's *Jamaica Almanac for 1852*, reported that a series of waves and disastrous earthquakes that nearly ruined the island of Jamaica. No other reports of earthquakes could be found for this day, but a major hurricane is reported. Not reported in Hall. Hall, 1907; Grases, 1971; Henderson, 1852; Millas, 1968. **V2**

1787, October 27 [14:20 LT]: A small local shock was felt at Montego Bay, Jamaica, and the vessels in the harbor were agitated. Mallet reports earthquakes in Jamaica at Kingston and Port Royal on Oct. 1 and 21. This is a low validity report since no wave was reported, and the agitation may have been due to a seaquake. The event was not reported in Hall, 1907. Berninghausen, 1968; Mallet, 1854; Rubio, 1982; Hall, 1907. **V1**

1798, February 22: A local tsunami was reported at Matina, Costa Rica. Eyewitnesses noted unusual sea noises between seven and eight p.m. Molina, 1997. **V2**

1802, March 19: Earthquakes were reported in February and March at Antigua, St. Christopher, and other West Indies Islands, with the largest (Intensity IV) on this date. It was accompanied by great agitation of the sea. There were no tsunami reports so this was probably due to a sea quake. Berninghausen, 1968; Heck, 1947; Mallet, 1855; Robson, 1964. **V2**

1802, May 5: Earthquakes at Cumana, Venezuela, reportedly caused the water of the Orinoco River to rise, and left part of the river bed dry. This could describe wave action near the mouth of the river, or bore action up the river. The rudder of a vessel was broken. Mallet, 1855. **V3**

1812, March 26: A rise of sea level associated with an earthquake reportedly occurred on the Venezuelan coast. Gigantic waves reportedly broke stretches of the sea wall that protected the coast near La Guaira. Singer, et al., 1983. **V2**

1812, November 11 [10:50 UT]: The sea was much agitated following an earthquake. At Annotto Bay, Jamaica, anchorage ground sank causing a ship to lose its anchor and 90 fathoms (~180 m) of cable. This may be the description of the effects of a submarine landslide or of subsidence, or could be the description of a tsunami or the action of a seaquake. Hall, 1907; Mallet, 1855. **V2**

1822, May 7: At Matina, Costa Rica, earthquake shaking lasted almost 24 hours and caused ground cracking. A local tsunami was reported. The rivers and bays experienced flooding (possible description of a tsunami). Molina, 1997. **V2**

1823, November 30 [3:10 LT]: At 2:45 LT a strong earthquake was followed by a tsunami at 3:10 LT that caused damage in Saint-Pierre Harbor. Berninghausen, 1968; Heck, 1947; Mallet, 1955; Perrey, 1847; Robson, 1964. **V4**

1824, September 13: Earthquakes were felt at Basse Terre, Guadeloupe, on September 9th. On the 13th there was a remarkable rise and fall of the tide at Plymouth, Montserrat. There had been a terrible storm and heavy rain from September 7th to the 9th. Mallet, 1855. **V2**.

1824, November 30: A severe shock was reported at St. Pierre, Martinique. Ships were thrown on shore. Heavy rain lasting 10 days followed. Mallet, 1855. **V2**

1825, February: A shock was reported by passengers on a boat near Honduras. A rumbling noise was heard. This is a description of a seaquake. Arce, 1998. **V1**

1825, September 20 [1:45 UT]: A local earthquake and oscillations of the sea were noted in Demerara County, British Guiana. An earthquake (MMI=VIII) was also noted at Trinidad, Tobago, St. Vincent, and Barbados. Berninghausen, 1968; Mallet, 1855; Milne, 1912; Perrey, 1847, **V2**

1831, December 3: At Trinidad and St. Christopher, a violent disturbance at sea was reported, and the shocks were felt on board ship as well as on land. This was a seaquake. An earthquake was also reported at Grenada, Tobago, St. Vincent, and British Guiana. Berninghausen, 1968; Mallet, 1855; Perrey, 1847, Robson, 1964. **V1**

1837, July 26: Several shocks accompanied by a large wave occurred during a Martinique hurricane. The wave source is uncertain. Berninghausen, 1968; Grases, 1971; Mallet, 1855; Perrey, 1847. **V2**

1842, May 7 [17:30 LT]: A strong earthquake caused extreme damage, generated a tsunami, and killed 4,000-5,000 people. At Haiti, the destructive tsunami struck the northern coast. At Mole Saint-Nicolas, and Cap-Haitien, extensive destruction was caused by the earthquake and tsunami. At Port-de-Paix, the sea receded 60 m, and the returning wave covered the city with 5 m of water killing 200-300 of the city's 3,000. At Santo Domingo, 2 m waves were observed. The tsunami was observed at Forte-Liberte and Santiago de los Caballeros. At St. John, U.S. Virgin Islands, the height was 3.1 m. Waves of 2 m caused destruction on the north coast of Hispaniola. Note the large area of this event, but that no tsunami report is available from locations such as Puerto Rico, although there are reports from Haiti and the U.S. Virgin Islands. Berninghausen, 1968; Grases, 1971; Heck, 1947; Mallet, 1855; Milne, 1912; Rubio, 1982; Scherer, 1912; Taber, 1922a, 1922b. **V4**

1843, February 8 [14:50 UT]: A disastrous earthquake (Mw=8.3) occurred at Pointe-a-Pitre, Guadeloupe. It was felt at Antigua, St. Lucia, St. Kitts, Montserrat, Martinique, and other islands. At Antigua, the sea rose 1.2 m and sank again immediately. Robson, 1964. **V4**

1843, February 17: A volcanic eruption near Marie Galante Antigua, of February 17, ejected jets and columns of water, and may have resulted in a minor tsunami. Robson, 1964. **V1**

1852, July 17 [7:25]: At Santiago de Cuba, Cuba, a strong surge in the bay affected the port buildings and loading docks. It may have been the product of an earthquake that also affected the U.S. frigate, *Tropic*, which was about 113 km from Jamaica. Rubio, 1982. **V2**

1853, July 15: A violent earthquake (MMI=X) in Cumana, Venezuela, was followed by a probable tsunami several meters high. Houses were destroyed at Sabana de Salgado, Puerto Sucre. Sabana de Caiguire was also affected. Berninghausen, 1968; Ceneno-Grau, 1969; Milne, 1912; Perrey, 1847; Robson, 1964; Singer, et al., 1983. **V3**

1855, September 25 [10:45 LT]: Feldman reports that the first shock (lasting 15 seconds) of an earthquake sequence in Honduras caused the *Simporonius*, a ship anchored in the bay, to drop suddenly. (a seaquake) The phenomenon, which created a wake, was repeated several times. A total of nine shocks were counted on the 25th. During the next 17 days, recurring shocks were experienced. The city of Trujillo was heavily damaged. Reports indicate heavy rain for three days. This event was probably associated with a hurricane. Feldman, 1993; Molina, 1997. **V1**

1856, August 9: Earthquakes (from August 4 to 14) damaged villages, on the Honduras coast from the banks of the Rio Tinto to Rio Ulna and Omoa, Livingston, Santo Tomas, Belize, Jamaica, and Guatemala City. Tsunami effects included the following: At Omoa, the sea fell and rose 5 m reaching the base of the fortress and adding to the earthquake damage. During violent trembling at the mouth of Rio Patuca, the water receded from the 8 km broad Criba lagoon toward the sea, leaving the bottom dry. The waters returned from every direction, rose in a column then fell and advanced toward the land. The tsunami carried whole trees, branches, and stones. Natives reported that water swept into the interior about 24 km. The tsunami affected several towns, including Cortez, Atlantida, and Trujillo. There were reports of rivers changing directions, probably due to bores. Feldman, 1993, (citing Anthony, 1856:167-171); Molina, 1997. **V4.**

1860, March 8: An earthquake was reported from Port-au-Prince and Anse-a-Veau, Haiti. Waves were reported from Golfe de la Gonave, Cayes, and Acquin. At Anse a Veau the sea withdrew and broke with a crash on the shore upon returning. Berninghausen, 1968; Heck, 1947; Milne, 1912; Taber, 1922a, 1922b. **V4.**

1867, (September or October): Singer reports a tsunami at Margarita Islands, Venezuela, but is doubtful about a link to an earthquake. Given the uncertainty of the date and the likelihood of effects on Venezuela from the Nov. 18th event, this is probably a description of the Nov. 18th event in Venezuela. Singer, et al., 1983. **V1** [See Nov. 18, 1867]

1867, November 18 [18:45 UT]: An earthquake occurred in the Angegada trough between St. Croix and St. Thomas, U.S. Virgin Islands generated a tsunami with waves reaching the shore about 15 minutes later. The waves were observed from Puerto Rico to Grenada, possibly reaching the northern coast of South America. It is reported to have been the most destructive tsunami in the U.S. Virgin Islands. At Deshaies, Guadeloupe, shortly after the earthquake, the sea receded 100 m and returned as an 18.3 m wave about 5 km broad (the largest tsunami ever recorded in the Caribbean), damaging dwellings and carrying all floatable objects away. At Sainte-Rose, the wave height was 10 m. At Basse-Terre, the height was 1.0 m, and the sea retreated far from the coast. At Isles des Saintes, there was a slight swell, and at Fond-du-Cure, houses were inundated to a depth of 1 m. At Pointe-a-Pitre, there was a slight swell.

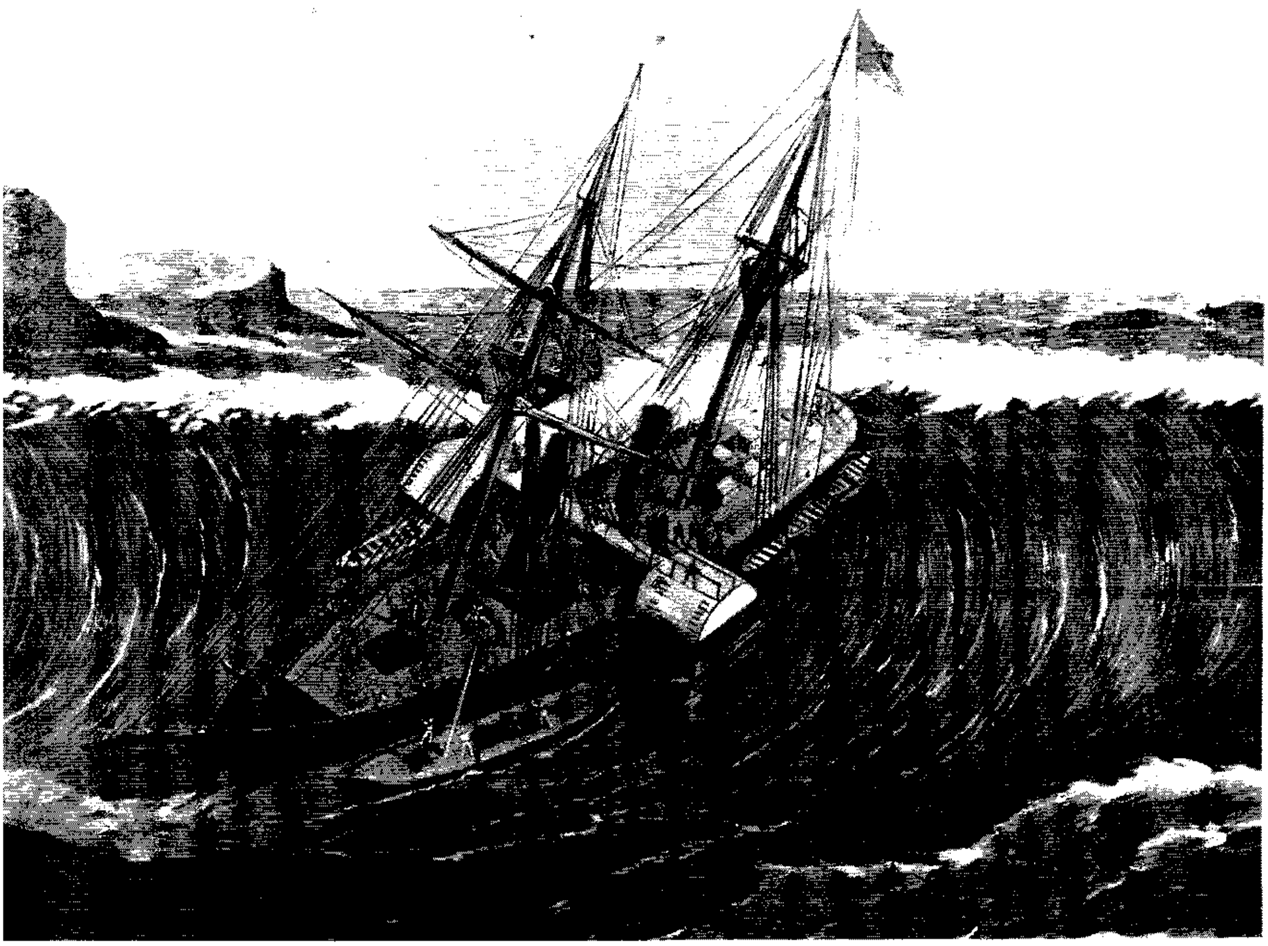


Figure 3 The Royal mail Steamer *La Plata* anchored near the southern point of Water Island about 4 km from Charlotte Amalie engulfed by the tsunami of November 18, 1867. Lithograph Credit: Harpers Weekly

At Charlotte Amale, St. Thomas, the water receded nearly 10 m and returned as waves 4.5 to 6 m high, killing 12 people, swamping small boats in the harbor and damaging the *USS De Soto*. The U.S. cruiser,

USS De Soto, was able to rescue at least three people from the water in the harbor. A lithograph depicting the *La Plata Mail Steamer* floundering in the waves appeared in a *Harper's Weekly*. A coal barge was also depicted. The barge was destroyed along with most of the crew of the *La Plata*. The pier was covered with 2.4 m waves, and the lower part of the city was flooded.
At Altona, houses were washed far inland, and there was damage at Hassel Island. At St. Croix, the waves were 7 to 9 m. At Christensted, waves swept inland 91 m, and at Gallows Bay, 20 houses were damaged.

At Frederiksted, the sea withdrew and returned as a wall of water 7.6 m high, leaving the USS Monomgahela stranded. Five were killed, 3-4 injured, and 20 houses were damaged.

At Puerto Rico the waves were 1 to 6 m, depending on the orientation of the particular coast. At San Juan and Arroyo, water rose 0.9 to 1.5 m, and high waves were observed at the Vieques Islands. At Fajardo, a very small wave was reported, and at Yabucoa the sea retreated and inundated 137 m on its return. At Peter Island, British Virgin Islands, waves 1.2 to 1.5 m were reported, and people fled to Tortola.

At Roadtown, Tortola, 1.5 m waves swept some houses away. At Saba, Netherlands Antilles, damage was reported. At St. Christopher, waves were also observed. At St. Martin and St. Barthelemy, damage was also reported. At St. Johns, Antigua, the waves had a height of 2.4 to 3.0 m. The wave was observed at Martinique, and St. Vincent had unusually high water. The height was 3 m at Grenada, and Gouyave (Charlotte Town) and 1.5 m at St. Georges. Waves were 1.8 m at Bequia, in the Grenadines. A tsunami is also mentioned at Margarita Islands, Venezuela, dated September or October 1867, possibly associated with an earthquake (see above), which may actually refer to this event. Deville, 1867; Lander and Lockridge, 1989; Milne, 1912; Paiewonsky, 1979; Reid and Taber, 1920, Robson, 1964, Schubert, 1994, Singer et al., 1983; Van Housel, 1878; Watlington and Lincoln, 1997. **V4**

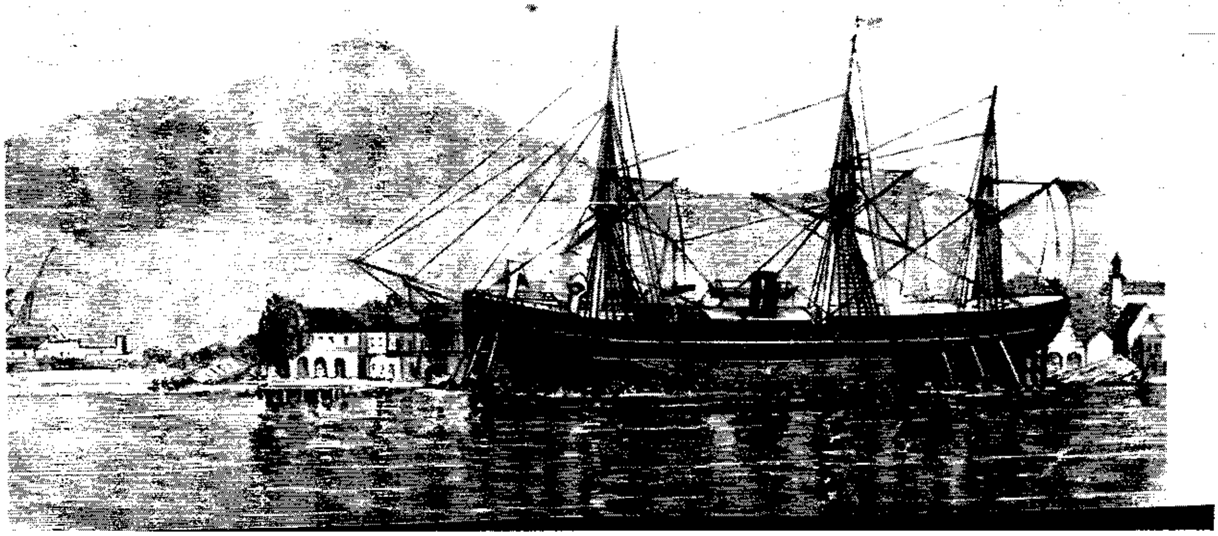


Figure 4. Position of the *Monongahela* following the tsunami of November 18, 1867. Photo Credit: Harpers Weekly.

1868: A tsunami was reported at Cabo Blanco Maiqueta, Venezuela, with a doubtful link to an earthquake. No specific date or details are listed. Singer, et al., 1983. **V1**

1868, August 13: A tsunami reportedly occurred at Juangriego, Margarita Island, and also at Rio Caribe, Venezuela, associated with an earthquake. Shaking effects linked to an earthquake are mentioned at Rio Apure, Rio Arauca, Rio Yaruari, and Rio Orinoco (Ciudad Bolivar in Venezuela). Singer, et al., 1983; Schubert, 1994. **V2**

1873, October 13 [18:05 LT]: At 18:05 LT, an earthquake of intensity V was felt at Panama City, on ships in the harbor, and at Aspinwall, Panama, where the shock was more severe and the people were frightened. Fear of a tsunami added to the concern. Since tsunamis are rare in this area, this may mean that some wave activity was noticed. The report of the earthquake being felt on ships in the harbor could mean that this was a seaquake. Molina, 1997. **V1**

1874, March 11 [4:30 LT]: A submarine shock southeast of St. Thomas, shook the island and ships in the harbor. Simultaneously, the water in the bay appeared turbid as though clouded by sand and mud. A little later strong ripples from the south lasting some time agitated the water surface. These ripples may have been a tsunami, with the earlier effects being from the seismic waves agitating the bottom. At Dominica, the steamer, *Corsica*, reported a series of heavy rollers in the harbor at 5:00 LT, that lasted half an hour, and rendered communication with the shore impossible. Those on the steamer did not feel the earthquake. Reduced effects at Charlotte Amalie may indicate a source on the eastern side of the island. Berninghausen, 1964; Palgrave, 1874. **V2**

1881, August 12: An earthquake was felt on Jamaica, and a wave was reported from the north coast. Six hours after the earthquake, the water rose approximately 46 cm at Kingston Harbor. (This is probably too long after the earthquake for a local tsunami. The event may have been related to a delayed submarine landslide.) There was a hurricane near Cuba on this date. This wave may not have been caused by the earthquake. Berninghausen, 1964; Hall, 1907; Taber, 1920. **V1**

1882, September 07 [7:50 UT]: A Ms = 7.9 earthquake reportedly occurred at 7:50 UT and was observed in Colombia, Panama, Nicaragua, and Ecuador. The cable to the West Indies was broken, which suggests a submarine landslide. A 3 m tsunami affected the San Blas coast of Northern Panama, and washed out most of the islands of the San Blas Archipelago, which were submerged for several minutes. Between 75 and 100 were drowned. Unfortunately the marigram from the French Canal Company at Colon, which had recorded the tsunami, is lost. Camacho, 1994b; Milne, 1912; Molina, 1997. **V4**

1883, August 27 [10:00 LT]: A tsunami was reported on August 27, at St. Thomas. The water receded from the shore three times. Sharp shocks of earthquakes were felt at 10:00 LT, on the following evening, and on August 30. These effects may have been related to the Krakatoa, Indonesia, volcanic eruption on August 26, 1883, that caused 30,000 regional fatalities and produced air waves that caused small water waves widely recorded in the harbors of Hawaii, California, Alaska, South Sandwich Islands, Great Britain, Japan, and Australia. Hurricanes passed north of St. Thomas, on Aug. 18-19 and 24-27. *Monthly Weather Review*, 1883. **V3**

1887, September 23 [12:00 UT]: An earthquake, felt at Port-de-Paix, Haiti, Inagua Island, Bahama Islands, and Jamaica, apparently occurred near the Bartlett trough, a short distance southwest of Mole-Saint-Nicolas. At Jeremie, Haiti, the sea withdrew 20 m and returned with a rush. Waves were observed at Mole-Saint-Nicolas, Anse d'Hainault, Point Tiburon, Haiti, and other ports. Berninghausen, 1968; Heck, 1947; Milne, 1912, Scherer, 1912; Taber, 1922a, 1922b. **V4**

1900, October 29: A possible tsunami was reported at Macuto, Venezuela, associated with an earthquake, and at Puerto Tuy, a wave of 10 m, was also associated with an earthquake. The destructive earthquake reportedly destroyed several towns and caused 25 fatalities. An islet in the mouth of the Neveri River disappeared, but a tsunami is not mentioned at this location. This is reportedly one of two large "sea waves" reported for Venezuela (1726 and 1900). Grases, 1971; Schubert, 1994; Singer, et al., 1983. **V3**

1902, May 8: There was a devastating eruption of Mont Pelee, Martinique, which sent a nuée ardente into St. Pierre, killing about 3,000 inhabitants. It caused fires on the ships in the harbor, and hit and overturned some of them. Ship captains remarked about a material change in the course of currents sweeping along the west and north coasts of Martinique. *The New York Times* gives the following report: "The fall of lava into the sea had pushed all the water out to the open ocean, as if trying to topple the harbor into the Atlantic a league away. There was never a storm that raised waves like those we saw in the waters of St. Pierre...They lay groaning about the decks, as may of them as had not been washed overboard." In a second article the *New York Times* states: "Fort de France yesterday was covered with ashes, stones were falling, and a tidal wave added to the terror of the population, which was flying to the hills." Heilprin, 1903. ." *New York Times*, Wednesday, May 21, 1902; Thursday May 22, 1902. **V2**

1902, May 20: Continuing eruptions of Mont Pelee, Martinique caused disturbances of coastal waters. "At five o'clock in the morning of May 20 a tidal wave parted *Helga*'s hawsers, (anchored at Fort de France) and the steamer went adrift, but we brought to anchor quickly. The heavy fall of volcanic matter compelled the crew to seek shelter, and the tidal waves recurred rapidly, causing great danger...At noon the sea began to recede (at Fort de France) with a heavy ground swell tossing the shipping so severely that vessels broke from their moorings. Then a long, rolling wave spread over the sea front, but it did little damage, and the sea again receded and left a considerable area of the shore permanently uncovered....The sea itself seems troubled. It has invaded Le Precheur, undermining several houses, and adding the ravages of inundation to those of fire." A severe inundation at Basse Pointe, on the northeast coast of this island, at 2 o'clock a.m., swept away twenty houses...A tidal wave has destroyed a portion of the village of Le Carbet. *New York Times*, Wednesday, May 21, 1902, Thursday, May 22, 1902, Friday, May 23, 1902.

1902, May. The *New York Times*, Saturday May 17, 1902. AT the same time as the eruption of Mont Pelee, Soufriere of St. Vincent erupted. This eruption also caused fluctuations of the sea level. "It is estimated that the sea has encroached from ten feet to two miles along the coast near Georgetown, and that a section of the north of the island has dropped into the sea. This is apparently verified by the report of the French cable ship *Pouyer-Quertier* that soundings now show seven fathoms where before the outbreak, there were thirty-six fathoms of water." The *New York Times* May 17, 1902.

1902, August 30 [21:25 LT]: At 1 p.m. LT a great volcanic cloud flowed from NW to SW from the crater of Mont Pelée, Martinique to about half the distance to Fort-de-France. A violent eruption at 9 p.m. in the evening, comparable to the May, 1902 eruption, advanced almost to Fort-de-France with a light fall of ashes and small stones. The sea retreated at 9:25 p.m., followed by a rapid rise of about 1 m, which covered the quays and came to the border of the grassland area. Heilprin, 1903. **V4**

1902, September 3: This quote was found in the *New York Times:* "To add to the miseries of Martinique, a tidal wave has swept the shore towns, rising sixty feet at fort de France. The inhabitants to escape this new danger are fleeing in great numbers to the mountains." *New York Times*, Wednesday September 3, 1902.

1906: A tsunami was reported at Cabo Blanca, Maiquetia Island, Venezuela, with an uncertain link to an earthquake. An earthquake (MMI=VIII) reportedly occurred on February 16, 1906, at 1:25 LT at St.

Lucia. Other islands affected were Martinique, St. Vincent, Dominica, Guadeloupe, Barbados, and Grenada. Lynch and Shepherd, 1995; Robson, 1964; Schubert, 1994; Singer, et al., 1983. **V2**

1906, January 31: A tsunami was reported at Cumana, at Carupano, at Costas Nueva Esparta, at Rio Caribe, and at Isla de Margarita, Venezuela. Also reported were shaking effects of the waters, inland at Rio Apure, Rio Arauca, Rio Catatumbo, Rio Escalante, Rio Zulia, and Cano Colorado, Maturin. Schubert, 1994, Singer, et al., 1983. **V3**

1907, January 14: An earthquake (MMI=IX) ruined most of Kingston, Jamaica, and damaged much of the surrounding area, including a suspension bridge at Port Maria. Buff Bay was destroyed. About 1,000 people perished. A large tsunami pounded the northern coast with waves of 2.5 m, at Hope Bay, Orange Bay, Sheerness Bay, and St. Ann's Bay, Jamaica, where the sea receded and dropped 3.7-6.2 m. At Annotto Bay, the sea receded 73-93 m, dropping 3-3.7 m below mean sea level three minutes after the shock. The returning wave raised the water level 1.8-2.4 m above normal, sweeping into the lower parts of town and destroying dwellings. On higher land it came up 7.6-9.1 m. At Port Maria, the sea receded 25.6 m 3-4 minutes after the shock and returned 1.8-2.4 m above sea level. At Ocho Rios the sea withdrew 69 m and also receded at Bluff Bay. At Port Antonio, the wave moved a small building near the beach. Waves of lesser significance were reported along the southern coast of Jamaica. Seiches of 2.5 m were set up in Kingston Harbor. The short time period after the earthquake and recession of the water suggest a local submarine landslide source. Berninghausen, 1968, Hall, 1907; Heck, 1947; Lynch and Shepherd, 1995; Murty, 1977; Rubio, 1982, Taber, 1920. **V4**

1911, November 3: A volcano-related tsunami produced extraordinary waves at Trinidad, following an explosion of a mud volcano island. Arnald and Macready, 1956; Berninghausen, 1968. **V3**

1916, April 24 [8:02 UT]: An earthquake (Ms=7.5) caused considerable damage at Bocas del Toro and Almirante, Panama, disrupting electric and water service and cutting the submarine cable linking the two areas. Debris and canoes were carried 198 m inland by knee-deep waves. Storage tanks were destroyed. The pier was damaged, houses were shifted from their supports, small buildings tumbled down, and fresh water flowed from cracks in the ground. Waves flooded Bastimento, Panama, and parts of the city were completely covered by the sea.

Witnesses on board a ship reported the event at Bocas del Toro. The earthquake was felt as if they were on land. The boat was lifted by the waves and was swept by strange sea currents. A second earthquake (MMI=IX) was listed as having occurred at 4:26 UT on eastern Hispaniola. Berninghausen, 1968; Feldman, 1984; Heck, 1947; Kirkpatrick, 1920; Molina, 1997; Reed, 1917. **V4**

1916, August: Powerful waves caused "the loss of USS Memphis, an 18,000 tonne [sic] cruiser, which in August 1916 was anchored in Santo Domingo harbour. At 1530 the vessel, which drew 8.2 m was anchored 3 ½ cables SW of Punta Torrecilla in a light NE breeze. By 1700 she was a total wreck having been carried a distance of over 5 cables by waves estimated to have exceeded 15 m in height." *West Indies Pilot*, Volume 1 Art 1.149.

1916, November 12: A tsunami reportedly connected with an earthquake occurred at Ocumare de la Costa, Venezuela. Schubert, 1994; Singer, et al., 1983. **V2**

1918, October 11 [10:14 LT]: A tectonic event that generated an earthquake (M=7.5) in the Mona Passage, west of Puerto Rico, may have been due to subduction near the Brownson deep. A tsunami with runup heights reaching 6 m followed the earthquake (MMI=IX) causing extensive damage along the western and northern coasts of Puerto Rico, especially to those villages established in a flood plain. At Punta Agujereada, the 5.5-6.1 m amplitude tsunami drowned 8 people, uprooted several hundred palm trees, and destroyed several houses. Waves having a travel time of 6 minutes from the tsunami origin to Aguadilla, rose 2.4-3.4 m above mean sea level, drowning 32 people and destroying 300 dwellings. At Rio Culebrinas, 1000 kg blocks of limestone from the wrecked Columbus monument were carried inland to distances of 46-76 m by waves 4.0 m high. At Punta Higuero Lighthouse, waves uprooted coconut palms and stranded fish on the railroad tracks located 5.2 m above sea level, while 800 m SE of the lighthouse the water rose 2.6-2.7 m. Water levels rose 1.5 m, 23 minutes after the earthquake at Mayaguez, entering the lower floors of buildings near the waterfront, overturning a brick wall, destroying several dwellings, and carrying a small house seaward. At Isla Mona, the receding water bared the reef and the returning 3.0-m wave washed away a pier and flooded a cistern. Submarine cables were cut in several places. At Punta Borinquen Lighthouse, 4.5-m waves inundated 100 m into a grove of coconut palms. About an hour after the earthquake the sea dropped 1.5 m and rapidly rose to 90 cm at Bahia de Boqueron. This was followed by several smaller waves. Near the bay entrance 800 m southeast, the water rose 45 cm. At Guanica, 50-cm waves were observed as well as slight water movements at Playa Ponce. The sea rose 75 cm at Cayo Cardona, and at Isla Caja de Muertos, water rose to 1.5 m, covering 15 m of the beach. A 10-cm bore went up the Rio Grande, and water receded and rose 1 m at Rio Grande de Loiza. At Puerto Arecibo, 30-60 cm waves were observed, and at Isabella, the water rose 2.0 m. The waves rose 1.2 m at Krum Bay, St. Thomas, and 45 cm at Charlotte Amalie, St. Thomas. The tsunami was also noted at Tortola. At Santo Domingo, Dominican Republic, the waters of the Rio Ozama fell and rose to 70 cm with a period of 40 minutes. The death toll for this event was 116 people, 40 of those perishing from the tsunami. A recent survey by the University of Puerto Rico, Mayaguez, indicated that tsunami fatality data should also include 100 people previously reported as missing, bringing to 140 the total fatalities from the tsunami. Berninghausen, 1968; Lander and Lockridge, 1989; Lynch and Shepherd, 1995; Mercado and McCann, 1998; Reid and Taber, 1919a; Robson, 1964. **V4**

1918, October 24 [23:43 LT]: Submarine cables were cut again, as on Oct. 11, two weeks earlier, and the steamship Mariana plunged and rolled heavily 11 km southwest of the Mona lighthouse. It is likely that the northwest coast of Puerto Rico experienced at least a small tsunami, since a wave was recorded on the tide gage at Galveston, Texas. This was the most severe aftershock of the October 11th earthquake. Berninghausen, 1968; Heck, 1947; Lander and Lockridge, 1989; Lynch and Shepherd, 1995; Reid and Taber, 1919b. **V4**

1922, May 02 [20:24 UT]: A wave that may have been associated with a small earthquake at Isla de Vieques, Puerto Rico, four hours earlier, was recorded as 0.6 m on the tide gage at Galveston, Texas. Parker observed a train of three waves with a period of 45 minutes, followed eight hours later by a similar train of smaller waves. It does not seem likely that this slight shock lasting two seconds would have produced a recordable tsunami. Berninghausen, 1968; Campbell, 1991; Lander and Lockridge, 1989; Parker, 1922. **V2**

1928, September 13: Singer reported a wave at Carupano, Venezuela, but with an absence of any link to an earthquake. Singer, et al., 1983. **V1**

1929, January 17 [11:52 UT]: The city of Cumana, Venezuela, was destroyed by an earthquake (Ms=6.9) that killed 50 and injured 800 people. It was also felt in Caracas and Barcelona. It was followed by a tsunami that caused great damage at Cumana and was also reported at Minicuare, at El Dique/El Barbudo, and El Salado, and Puerto Sucre. A steamer off-shore was endangered by a large wave. Two five-ton launches were washed ashore and stranded. Many sailboats and dwellings were wrecked by the tsunami. Singer reported that an active fault ruptured with displacement along the length of the fault (4 km) east to west at El Penon, Caiguire, and fault activity shifting southwest to northeast at Luis/Bededero and El Penon, San Antonio, Cumana, as well as settlement and collapse of Pointe Guzman Blanco at Cumana, and other earthquake related phenomena. There were many slides and collapses throughout the area. Berninghausen, 1968; Lynch and Shepherd, 1995; Robson, 1964; Schubert, 1994; Singer et al., 1983; *Seismological Notes*, 1929. **V4**

1931, October 01: At Playa Panchita, Rancho Veloz, Las Villas, Cuba, waves beat on the beaches. The jetty and coastal houses were inundated to a depth of one meter, damaging contents. No earthquake was reported. No hurricanes were in the area at this time. Neumann, et al., 1988; Rubio, 1982. **V1**

1932, February 03 [06:16 UT]: A strong earthquake (MMI=VIII) that affected 80% of the buildings at Santiago de Cuba, Cuba, killed eight people, and injured 300. A person aboard a North American ship reported seeing a wave. Later, after checking marigrams from different points in the Caribbean, it was concluded that the tsunami would have been small. Berninghausen, 1968; Hess, 1932; Lynch and Shepherd, 1995; Rubio, 1982. **V2**

1932, November 04: Singer reported a wave at Cumana, Venezuela, with an uncertain link to an earthquake. Singer, et al., 1983. **V1**

1939, August 15 [3:52 UT]: At Cayo Frances, Cuba, movement of the sea reportedly woke up the sailors on two vessels. The earthquake (Mb=5.6) that caused this movement affected the Las Villas and Santa Clara provinces. Rubio gives the epicenter as localized in the ocean. Lynch and Shepherd, 1995; Rubio, 1982. **V2**

1946, August 04 [17:51 UT]: A magnitude 8.1 earthquake devastated the Dominican Republic, extended into Haiti, and shook many other islands. This was one of the strongest earthquakes ever reported in the Caribbean. The greatest damage and loss of life occurred at Matancitas and nearby coastal towns where a 2.5-m tsunami flattened homes and buildings. Matancitas was totally destroyed by the tsunami and abandoned. The tsunami was formed by a sudden disturbance of the ocean floor about 65 km offshore northeast of Julia Molina. The ocean receded from the Matancitas coast, and people left the shore to collect the stranded fish. At Julia Molina, the tsunami height was 4-5 m. At Cabo Samana, several ebbs and flows were observed, but no damage occurred. The wave was recorded at San Juan, Puerto Rico, 36 minutes after the earthquake, where some damage occurred on the west coast from the earthquake. Waves were also recorded with travel times of 2 hours 7 minutes after the earthquake at Bermuda, 3:59 at Daytona Beach, and 4:49 at Atlantic City, New Jersey. De Guerrero reports that the wave entered almost 1 km inland sweeping away the city of Matancitas and several villages, and killing approximately 1,790 people. Previous estimates placed the death toll near 100. This substantially increased the total number of fatalities in the Caribbean due to tsunamis. Continuing aftershocks bothered the coastal villages for months. Berninghausen, 1968; Bodle and Murphy, 1948; Heck, 1947; Herridge de Guerrero, 1998, Lynch and Bodle, 1948; Lynch and Shepherd, 1995; Murty, 1977. **V4**

1946, August 08 [13:28 UT]: In Puerto Rico the sea withdrew at Aguadilla (24 m), and at Mayaguez (76 m), returning as devastating waves. The earthquake and tsunami caused 75 fatalities and left 20,000 homeless. At San Juan, the tsunami was recorded on a tide gage 35 min. after the earthquake. This was due to second shock (Ms=7.9) nearly as strong as the earthquake of August 4, but located about 100 km northwest. The waves were also recorded with travel times of 2:02 after the earthquake at Bermuda, 4:02 at Daytona Beach, and 4:42 at Atlantic City. Berninghausen, 1968; Bodle and Murphy, 1948; Lander and Lockridge, 1989; Lynch and Shepherd, 1995; Rubio, 1982; Schubert, 1994. **V4**

1950: An earthquake destroyed the tide station at Puerto Armuelles, Panama. The tide gage at Puntarenas, Costa Rica, was shaken and soon afterward recorded a seiche or possible tsunami. Small oscillations that may have resulted from this earthquake were also recorded on the tide gages at San Juan del Sur, Nicaragua, and La Union, El Salvador. Murphy and Ulrick 1952. **V2**

1950, August 3: A wave was reported at Puerto Cabello, Venezuela, with an uncertain link to an earthquake, although there were verified reports of an inland earthquake (6.8) at Laguna La Gonzales, Chabesquen, where a mud slide caused flooding northwest of Chabasquen. The above quake also caused landslides at Caserio Providencia, Chabasquen, emptying the Laguna del Catire and destroying coffee plantations and three dwellings, and damaging dwellings at Los Bucarer. The earthquake also caused landslides at Puente Saguas, Biscucuy; Barrio El Atlantico, Caracas; La Boca, Anzoategui, Curumato, Guarico; La Adjuntas; and La Aguada, El Tocuyo; and at La Laguna and El Penon, Humocaro Bajo; as well as surface ruptures at La Calebrina; Humocaro Bajo; Cementario; Humocaro Alto; San Rafael; Sanare; and Cerros de El Paraiso, Maracaibo. Singer, et al., 1983. **V2**

1953 May 31 [19:58 UT]: A 6 cm wave was recorded on the Puerto Plata, Dominican Republic, tide gauge. It may have been a wave from hurricane Alice that was in the area at this time. Millas, 1968; Murphy and Cloud, 1955. **V2**

1955 January 18: A wave caused four ships to be wrecked, and four waterfront buildings to be damaged in La Vela, Venezuela. An earthquake (Mb=5.5), off the coast of Panama, is listed for this time. Berninghausen, 1968; *Seismological Notes*, 1955. **V2**

1961 June 16: It was reported that a wave caused partial flooding of the towns south Lake Maracaibo in Venezuela. Also mentioned were landslides at Altamira and Calderas, Venezuela. Singer et al., 1983. **V2**

1968, September 20: An earthquake (Ms=6.2) occurred near the coast of Venezuela, and a tsunami was reported. Singer made no mention of the tsunami, but reported landslides at Chaguama de Loero, Rio Caribe, that destroyed one dwelling and damaged three others. Landslides at La Cumbre Mariano Leon, Tunapuy, reportedly injured two people, and a collapse and settlement occurred at Guiria. Hurricane Edna was passing north of Venezuela at this time. Coffman and Cloud; 1970; Singer, et al., 1983; Lynch and Shepherd, 1995. **V2**

1969, December 25 [21:32 UT]: A magnitude 7.6 earthquake was felt on Guadeloupe, Dominica, and Martinique, St. Vincent, Antigua and Barbados. A wave was recorded at Barbados, Antigua, and Dominica, with a maximum amplitude of 46 cm at Barbados. Von Hake and Cloud, 1971; *Preliminary Determination of Epicenters* (PDE), 1969. **V4**

1979 September 13: A wave that may have been associated with a Panamanian earthquake (Mb 5.0) on this date destroyed the pier at Puerto Cumarebo, Venezuela. Schubert, 1994, Singer, et al., 1983. **V2**

1985 March 16: A moderate earthquake (Mw=-6.3) caused damage and injuries to six people at Guadeloupe and minor damage at Montserrat. It was also felt at Antigua, St. Kitts, and Puerto Rico. A several-centimeter tsunami was recorded at Basse-Terre, Guadeloupe. Lynch and Shepherd, 1995; PDE, 1985. **V4**

1989 November 1 [10:25 UT]: An earthquake (Ms=4.4) occurred in the Mona Passage off the north coast of Puerto Rico, generating a small wave that was reported in El Nuevo Dia on the 2nd. The Puerto Rico Civil Defense reported a notable augmentation of the sea level in the area of Cabo Rojo. El Nueva Dia, 1989; PDE, 1989. **V3**

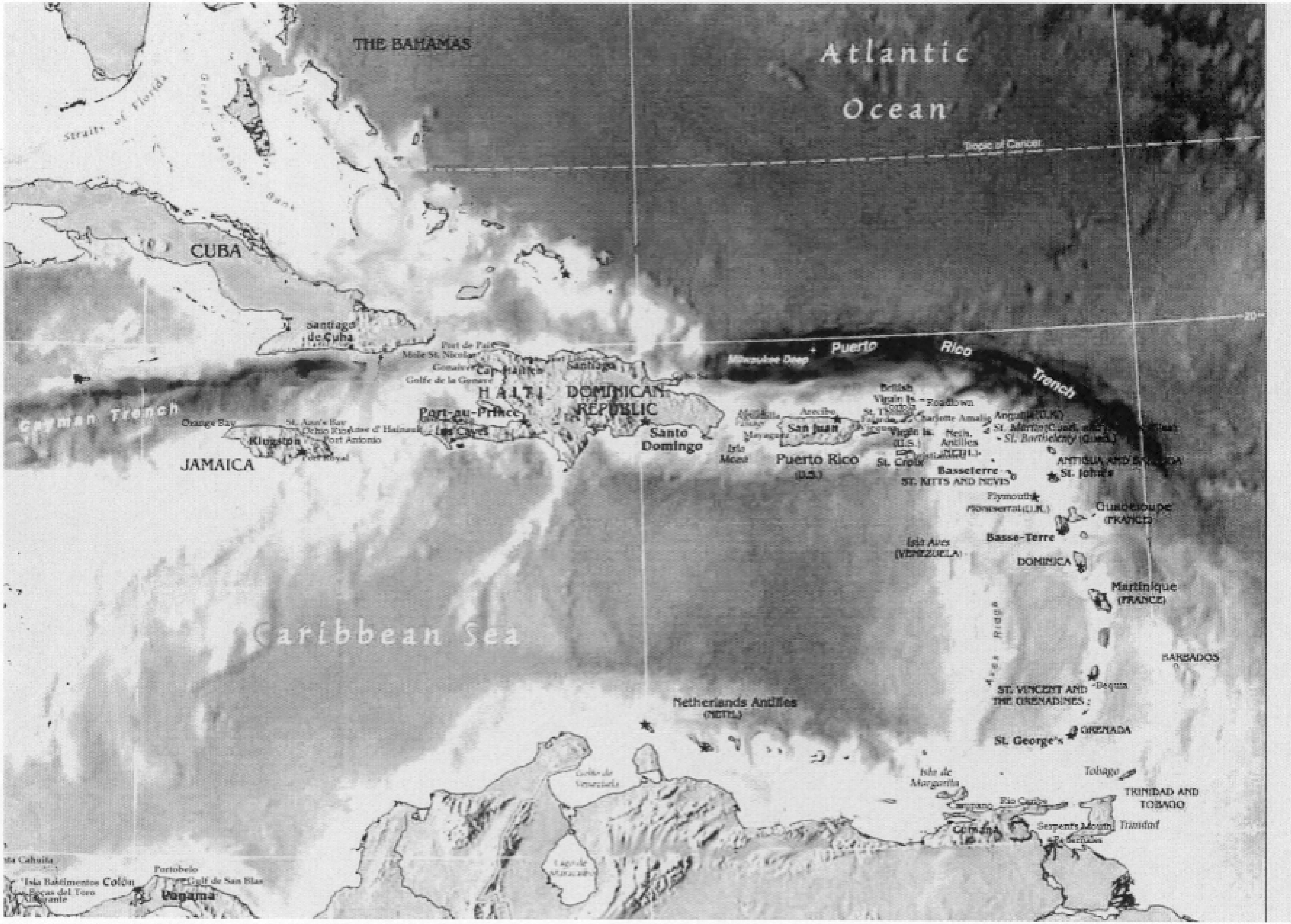
1991 April 22 [21:56 UT]: A Ms = 7.6 created a tsunami that affected the coast of Central America from north of Limon, Costa Rica, to Panama. Less than 10 minutes after the earthquake, the residents at Bocas del Toro, Panama, reported that the Las Delicias sand bank, normally covered by 60-90 cm of water, emerged as the sea receded and remained above water for 5-7 minutes. Then several waves entered the bay with great force, flooding the flat northern part of the town 50-100 m from the coast. At Isla de

Carenero, violent waves destroyed dwellings. At San Cristobal Island, the sea receded several meters for 45 minutes. People went onto the exposed beach to catch trapped fish. Tsunamis were also observed in Panama at Bastimento, Cristobal, 10 cm; Portobelo, 60 cm; and Coco Solo, Colon, 76 cm. A 2-m tsunami inundated 300 m in the Cahuita-PuertoViejo area, Costa Rica, causing some additional damage. The tide gage at Limetree, St. Croix, U.S. Virgin Islands, recorded amplitudes of 7 cm. Camacho, 1994; *PDE*, 1991. **V4**

1997, July 9 {19:24 UT]: A Ms = 6.8 earthquake occurred off the coast of Venezuela, near Isla de Margarita, causing extensive damage and landslides in the Cariaco-Cumana region. At least 76 people perished and 500 were left homeless. James Trim, a participant at the Emergency Planning and Management Workshop for Industrial Disasters, October 1997, in Trinidad, reported that his brother had seen a wave come ashore then recede on the south coast of Tobago, a few minutes after the earthquake. Mercado, 1997. **V3**

1997, December 26 [3:00 LT]: A volcanic debris slide of 60 million cubic meters occurred in the White River Valley, Montserrat, on Dec. 26th (named the Boxing Day Collapse.) On the night of the eruption there were reports of a wave inundating the Old Road Bay area, 10 km from the landslide site. A small tsunami was probably generated by the debris avalanche possibly assisted by the pyroclastic flows as they entered the sea at the mouth of the White River Valley. The tsunami wave was refracted around the coastline of Montserrat, and achieved considerable run-up in Old Road Bay.

The wave was estimated to have been about 1 m higher than the road which lies 2-m above water level, and to have moved inland a maximum distance of 80 m. A variety of objects, including a small wooden boat, a roof to a shelter, and a stone table were displaced several meters inland and a large log was carried even further by the wave. Impact marks up to 1 m were also on the side of palm trees facing the sea. The grass was oriented in such a way as to indicate the retreat of the wave. An observer reported seeing the sea move out and then back in, which is typical of a landslide-generated tsunami. The focusing of the wave at Old Road Bay can be attributed to the peculiarities of wave behavior along a coastline and the abrupt change of coast direction at Old Road Bay. The wave moved inland here, because the coast abruptly changes its direction, and the wave moving parallel to the coast would have met the shore head-on. Also, the shallow offshore bathymetry and onshore topography in the area aided extended wave run-up. Since July 18, 1995, when this stratovolcano in the Soufriere Hills began erupting (the first recorded eruption of this volcano in historic times) there have been several debris slides that reached the ocean, but the authors have not found a report of unusual waves other than this one. Mangeney, et al., 1998; Calder, et al., 1998. **V4**



Map of the Caribbean showing locations of towns that experienced tsunamis.

Verified and Probable Caribbean Tsunamis, 1498-2000

ORIGIN DATA				EFFECTS DATA		
Date	Lat. Long.	Eq. Mag.	Area	Location of Effects	Runup (m)	Deaths
1530 09 01 14:30 UT	10.7N 64.1W	MMI = X	Venezuela	Venezuela: Paria Cumana Cubagun Island Gulf of Cariaco	 7.3 6.0 6.0	
1690 04 16	17.5N 61.5W	Ms 8.0	Leeward Is.	U.S. Virgin Islands: St. Thomas: Charlotte Amalie Nevis: Charleston		
1692 06 07 [11:43 LT]	17.8N 76.7W	Ms 7.7	Jamaica	Jamaica: Port Royal Liganee (Kingston) Saint Ann's Bay	 1.8	 2000*
1751 10 18 [19:00 UT]	18.5N 70.7W	Ms 7.3	Hispaniola	Hispaniola: Azua de Compostela Santo Domingo Santa Cruz El Seybo		
1755 11 01 [9:50 LT]	36.0N 11.0 W	MMI = XI	Lisbon, Portugal	Netherlands Antilles Saba St. Martin Antigua Dominica Barbados Martinique Cuba: Santiago de Cuba	 7.0 4.5 3.6 3.6 1.5-1.8	
1755, 11 18	42.7N 70.3W	VIII	Cape Ann, Massachusetts	St. Martins, West Indies		

ORIGIN DATA				EFFECTS DATA		
Date	Lat. Long.	Eq. Mag.	Area	Location of Effects	Runup (m)	Deaths
1761 03 31 [12:05 LT]	37.0N 10.0W	MMI = IX	Lisbon, Portugal	Barbados	1.2	
1767 04 24 [6:00 UT]	14.4N 61.0W		Martinique and Barbados	Martinique Barbados		
1770 06 03 [19:15 LT]	18.3N 72.2W		Haiti	Golfe de la Gonave and Arcahaie		
1802 05 05	9.2N 61.5W		Venezuela	Venezuela: Orinoco River		
1823 11 30 [3:10 LT]	14.4N 61.0W		Martinique	Martinique: Saint-Pierre Harbor		
1842 05 07 [17:30 LT]	19.7N 72.8W	Ms 7.7	Haiti	Haiti:		~5,000*
				Mole St. Nicolas		
				Cap Haitien		
				Port-de-Paix	5.0	200-300
				Forte-Liberte		
				Santiago De los Caballeros		
				Dominican Republic		
				Santo Domingo	2.0	
				U.S. Virgin Islands		
				St. John	3.1	
				North coast of Hispaniola	2.0	
1843 02 08 [14:50 UT]	16.5N 62.2W	MMI=IX	Guadeloupe	Antigua	1.2	
1853 07 15	12.1N 63.6W	Ms 6.7	Venezuela	Venezuela: Cumana Puerto Sucre Sabana de Caiguire Sabana de Salgado		
1856 08 09	16.0N 88.0W	Ms 7.5	Honduras	Honduras: Rio Patuca Omoa Cortez Atlantida	5.0	

ORIGIN DATA				EFFECTS DATA		
Date	**Lat. Long.**	**Eq. Mag.**	**Area**	**Location of Effects**	**Runup (m)**	**Deaths**
				Trujillo		
1860 03 08	19.0N 72.0W		Hispaniola	Hispaniola:		
				Golfe de la Gonave		
				Les Cayes		
				Acquin		
				Anse –A-Veau		
1867 11 18 [18:45 UT]	18.0N 65.5W	Ms 7.5	St. Croix and St. Thomas, U.S. Virgin Islands	Guadeloupe:	19.8	
				Dechaies	18.3	23
				Basse-Terre	1.0	
				Sainte-Rose	10.0	
				Isles des Saintes		
				Grande Terre		
				Fond-du-Cure	1.0	
				Pointe-a-Pitre		
				U.S. Virgin Islands:		
				St. Thomas:		
				Charlotte Amalie	4.5-6.0	12
				Hassle Island	4.9	
				Altona		
				St. John		
				St. Croix:	7.0-9.0	
				Christiansted		
				Frederiksted	7.6	5
				Gallows Bay		
				Puerto Rico:	1.0-6.0	
				Arroyo	0.9-1.5	
				San Juan	0.9-1.5	
				Vieques Islands	6.1	
				Fajardo		
				Puerto Yabucoa	1.37	
				British Virgin Islands:		

ORIGIN DATA				EFFECTS DATA		
Date	Lat. Long.	Eq. Mag.	Area	Location of Effects	Runup (m)	Deaths
				Peter Island	1.2-1.5	
				Tortola		
				Road town	1.5	
				Netherrlands Antilles:		
				Saba		
				St. Kitts and Nevis:		
				St. Christoopher (St. Kitts)		
				Netherlands and France		
				St. Martin		
				France		
				St. Barthelemy		
				Antigua and Barbuda:		
				St. Johns	2.4-3.0	
				Martinique	3.0	
				St. Vincent and the Grenadines:		
				Becquina	1.8	
				Grenada:	3.0	
				St. Georges	1.5	
				Charlotte Town (Gouyave)	3.0	
				Venezuela		
				Maiquetia Island		
1882 09 07 [7:50 UT]	7.3N 77.8W	Ms 8.0	Panama	Panama: San Blas Archipelago	3.0	75-100
1883 08 27 [10:00 LT]	5.8S 106.3E		Krakatoa, Indonesia	U.S. Virgin Islands: St. Thomas		
1887 09 23 [12:00 UT]	19.7N 74.4W		Haiti	Haiti: Mole-Saint-Nicolas Jeremie Anse-d'Hainault Point Tiburon		
1900 10 29	10.9N 66.8W	Ms 8.4	Venezuela	Venezuela		

ORIGIN DATA				EFFECTS DATA		
Date	Lat. Long.	Eq. Mag.	Area	Location of Effects	Runup (m)	Deaths
				Macuto Puerto Tuy	 10.0	
1902 08 30 [21:25 LT]	14.4N 61.0W		Martinique	Martinique Fort-de-France	1.0	
1906 01 31 [15:36 UT]	2.4N 79.3W	Ms 8.9	Venezuela	Venezuela: Cumana Carupano Costas Nueva Esparta Rio Caribe Isla de Margarita		
1907 01 14 21:36 UT	8.1N 76.7W	Ms 6.5	Jamaica	Jamaica: Hope Bay Orange Bay Sheerness Bay St. Ann's Bay Annotto Bay Port Maria Ocho Rios Bluff Bay Port Antonia Kingston	 2.5 2.5 2.5 2.5 1.8-2.4 1.8-2.4 2.5	
1911 11 03	10.5N 61.2W		Trinidad	Trinidad		
1916 04 24 8:02 UT	11.0N 85.0W	Ms 7.6	Panama	Panama: Almirante Bocas del Toro Isla de Carenero Isla Bastimento		
1918 10 11 [4:14 UT]	18.5N 67.5W	Ms 7.5	Puerto Rico	Puerto Rico: Aguadilla Punta Agujereada Punta Higuero 800 m SE of Punta Higuero Punta Borinquen	 2.4-3.4 5.5-6.1 5.2 2.6-2.7 4.5	140* 32 8

ORIGIN DATA				EFFECTS DATA		
Date	**Lat. Long.**	**Eq. Mag.**	**Area**	**Location of Effects**	**Runup (m)**	**Deaths**
				Isla Mona	3.0	
				Rio Culebrinas	4.0	
				Bahia de Boqueron	0.9	
				800 m SE at bay entrance	0.4	
				Isabella	2.0	
				Cayo Cardona	0.75	
				Guanica	0.5	
				Mayaguez	1.5	
				Isla Caja de Muertos	1.5	
				Puerto Arecibo	0.6	
				Rio Grande	.10	
				Rio Grande de Loiza	1.0	
				Playa Ponce		
				St. Thomas		
				Krum Bay	1.2	
				Charlotte Amalie	.45	
				Dominican Republic		
				Santo Domingo (Rio Ozama)	0.7	
				U.S. Virgin Islands	0.3-0.6	
				Tortola		
1918 10 24 [3:43 UT]	18.5N 67.5W		Puerto Rico	Mona Passage		
				Puerto Rico		
				Texas		
				Galveston		
1929 01 17 [11:52 UT]	10.6N 65.6W	Ms 6.9	Venezuela	Venezuela:		
				Cumana		
				Manicuare		
				El Dique		
				El Barbudo		
				El Salado		
				Puerto Sucre		
1939 08 15 [3:52 UT]	22.5N 79.2W	Ms 8.1	Cuba	Cuba:		
				Cayo Frances		

ORIGIN DATA			EFFECTS DATA			
Date	Lat. Long.	Eq. Mag.	Area	Location of Effects	Runup (m)	Deaths
1946 08 04 [17:51 UT]	19.3N 68.9W	Ms 8.1	Dominican Republic, Haiti and Puerto Rico	Dominican Republic: Matancitas Julia Molina Cabo Samana Puerto Rico: San Juan Bermuda Florida: Daytona Beach New Jersey: Atlantic City	 2.5 4.0-5.0	1,790
1946 08 08 [13:28 UT]	19.5N 69.5W	Ms 7.9	Puerto Rico	Puerto Rico: Aguadilla Mayaguez San Juan Bermuda Florida: Daytona Beach New Jersey Atlantic City		75*
1969 12 25 [21:32 UT]	15.8N 59.7W	Ms 7.6	Leeward Is.	Barbados Antigua Dominica	0.46 0.30 0.12	
1985 03 16 14:54	17.0N 62.4W	Ms 6.8	Leeward Is.	Guadeloupe Basse-Terre	0.1	
1989 11 01 [10:25 UT]	19.0N 68.8W	Mb 5.2	Puerto Rico	Puerto Rico Cabo Rojo E Nuevo Dia		
1991 04 22 [21:56 UT]	9.7N 83.1W	Ms 7.4	Costa Rica	Panama: Bocas del Toro Isla de Carenero San Cristobal Island	 0.6	

ORIGIN DATA				EFFECTS DATA		
Date	Lat. Long.	Eq. Mag.	Area	Location of Effects	Runup (m)	Deaths
				Bastimento Cristobal	0.1 0.1	
				Portobelo Colon Coco Solo Costa Rica Limon Punta Cahuita-Puerto Viejo U.S. Virgin Islands St. Croix Limetree	0.6 0.8 2.0 0.07	
1997 07 09 [19:24 UT]	10.6N 63.5W	Mw 7.0	Venezuela	Venezuela: Isla de Margarita Tobago		
1997 12 26 [3:00 LT]	16.7N 62.2W		Montserrat	Montserrat	3.0	

Other Possible Tsunami Events 1498-2000

ORIGIN DATA				EFFECTS DATA		
Date	Lat. Long.	Eq. Mag.	Area	Location of Effects	Wave height (m)	Deaths
1498 08 02 or 3	9.9N 62.3W		Venezuela	Venezuela: Boca de la Sierpe Pedernales		
1539 11 24 [23:00 LT]	15.0N 86.5W	MMI = X	Northern Honduras	Northern Honduras: Cabo de Higueras		
1541 12 25	10.8N 64.2W		Venezuela	Venezuela: Cubagua Island Nueva Cadiz		
1543	10.7N 64.1W		Venezuela	Venezuela: Cumana		
1688 03 01 [Gregorian]	17.6N 76.5W		Jamaica	Jamaica: Port Royal		
1726	10.6N 64.2W		Venezuela	Venezuela: Araya Peninsula		
1750	10.7N 64.1W		Venezuela	Venezuela: Cumana		
1751 09 15 [19:00 UT]	18.5N 70.7W	Ms 7.3	Hispaniola	Haiti:		
1751 11 21	18.3N 72.3W		Haiti	Haiti Port-au-Prince		
1766 06 12 [4:45 UT]	20.0N 75.5W		Santiago de Cuba and Bayamo, Cuba	Jamaica		
1766 10 21 [9:00 UT]	7.4N 62.5W	Ms = 7.5	Venezuela	Venezuela: Cumana Orinoco Islands		
1769	18.5N 72.3W		Haiti	Haiti: Port-au-Prince		
1775 02 11	19.0N 72.4W		Hispaniola and Cuba	Hispaniola		
1775 03	19.0N 72.3W or		Hispaniola	Hispaniola		

ORIGIN DATA				EFFECTS DATA		
Date	Lat. Long.	Eq. Mag.	Area	Location of Effects	Wave height (m)	Deaths
	20.0N 15.8 W					
1775 12 18	9.2N 70.3W	MMI = VIII	Hispaniola and Cuba	Hispaniola Cuba		
1780 10 03 [22:00 LT]	18.1N 78.1W		Jamaica	Jamaica: Savanna La Mar	3.0	10
1781 08 01	18.2N 78.1W		Jamaica	Jamaica		
1787 10 27 [14:20 LT]	18.4N 77.9W		Jamaica	Jamaica: Montego Bay		
1798 02 22	10.2N 82.9W		Costa Rica	Costa Rica: Matina		
1802 03 19	10.4N 68W (5-20) 10.3N 64 W (8-15)		Leeward Is.	Antigua St. Christopher		
1812 03 26	8.6N 71.1W	Ms 7.7	Venezuela	Venezuela: La Guaira		
1812 11 11 [10:50 UT]	18.0N 76.5W		Jamaica	Jamaica: Annotto Bay		
1822 05 07	10.0N 84.0W		Costa Rica	Costa Rica: Matina,		
1824 09 13	16.7N 62.2W		Guadeloupe	Montserrat: Plymouth		
1824 11 30	14.4N 61.0W		Martinique	Martinique: St. Pierre,		
1825 02 (26)	11.2N 74.2W		Honduras	Honduras: Roatan Is.		
1825 09 20 [1:45 UT.]	10.4N 61.3W	Moderate MMI=VIII	British Guiana	British Guiana: Demerara County		
1831 12 03 [23:40 UT]	12.4N 61.5W		Trinidad and St. Christopher	Trinidad St. Christopher		
1837 07 26	18.2N 64.5W		Martinique	Martinique		

ORIGIN DATA				EFFECTS DATA		
Date	**Lat. Long.**	**Eq. Mag.**	**Area**	**Location of Effects**	**Wave height (m)**	**Deaths**
	(8-2 eq)					
1843 02 17	17.0N 61.8W		Antigua	Antigua		
1852 07 17 [7:25]	20.0N 75.8W		Cuba	Cuba: Santiago de Cuba		
1855 09 25 [10:45 LT]	15.9N 86.0W		Honduras	Gulf of Honduras Trujillo		
1867 (09 or 10)	18.0N 65.5W	Ms 7.5	Venezuela	Venezuela: Carupano Margarita Islands		17
1868	10.6N 66.9W		Venezuela	Venezuela: Cabo Blanco Maiquetia		
1868 08 13	18.5N 70.3W	Ms 8.5	Venezuela	Venezuela: Rio Caribe Margarita Island Juangriego		
1873 10 13 [18:05 LT]	30.1N 85.6W		Panama	Panama: Panama City Aspinwall		
1874 03 11 [4:30 LT]	18.3N 64.9W		Lesser Antilles	U.S. Virgin Islands St. Thomas Charlotte Amalie Dominica		
1881 08 12	19.9N 76.8W		Jamaica	Jamaica: Kingston	0.46	
1902 05 08	14.4N 61.0W		Martinique	Martinique: St. Pierre		
1906	10.6N 66.9W		Venezuela	Venezuela: Cabo Blanca Maiquetia		
1916 11 12	10.1N 66.8		Venezuela	Venezuela: Ocumare de la Costa		

ORIGIN DATA				EFFECTS DATA		
Date	Lat. Long.	Eq. Mag.	Area	Location of Effects	Wave height (m)	Deaths
1922 05 02 [20:24 UT]	18.2N 66.6W		Puerto Rico	Texas: Galveston	0.6	
1928 09 13	10.6N 63.2W		Venezuela	Venezuela: Carupano		
1931 10 01	21.5N 80.0W		Cuba	Cuba: Playa Panchita, Rancho Veloz, Las Villas		
1932 02 03 [06 16 UT]	19.5N 75.6 W	Ms 6.8	Cuba	Cuba: Santiago de Cuba		
1932 11 04	10.7N 64.1W		Venezuela	Venezuela: Cumana		
1950 08 03	9,8N 69.7W	Ms 6.8	Venezuela	Venezuela: Puerto Cabello		
1953 05 31 [19:58 UT]	19.7N 70.7W		Dominican Republic	Dominican Republic: Puerto Plata	0.06	
1955 01 18	11.3N 69.4W		Venezuela	Venezuela: La Vela		
1961 06 16	9.7N 71.5W		Venezuela	Venezuela: Lago de Maracaibo,		
1968 09 20 [6:09 UT]	10.7N 62.6W	Ms 6.2	Venezuela	Venezuela		
1979 09 13 [2 12 UT]	5.9N 82.5W	Ms 5.0	Venezuela	Venezuela: Puerto Cumarebo		

REFERENCES

Affleck, Capt., 1809. On the agitation of the sea at Antigua, Nov. 1, 1755, Royal Society of London, *Philosophical Transactions*, Abridged, Vol. 11, pp 9-10.

Arce, M.F., Molina, E. Havskov, J., and Atakan, K., 1998. Tsunamis in Central America, *Tech. Rep. 11 1-12*, Reduction of Natural Disasters in Central America, Earthquake Preparedness and Hazard Mitigation, Inst. Solid Earth Physics, Univ. Bergen, Norway, 34 pp.

Arnald, R. and Macready, G.A., 1956. Island forming mud volcano in Trinidad, British West Indies, *Bull. Amer. Assoc. Petroleum Geologists*, Vol. 40, No. 11 p. 2756.

Berninghausen, W.H., 1964. Tsunamis and seismic seiches reported from the eastern Atlantic south of the Bay of Biscay, *Bull. Seismological Soc. Amer.*, Vol. 54, No. 1, pp 439-442.

Berninghausen, W.H., 1968. *Tsunamis and Seismic Seiches Reported from Western North and South Atlantic and the Coastal Waters of Northwestern Europe*. Naval Oceanographic Office, Informal Rep. No. 68-85, Washington, D.C. 20396, p 41.

Bodle, R.R., and L.M. Murphy, 1948. Tidal Disturbances of Seismic Origin, *United States Earthquakes*, 1946, U.S. Dept. of Commerce, Coast and Geodetic Survey, Government Printing Office, Washington, D.C., 23 pp.

Calder, Eliza S., Simon R. Young, R. Steve, J. Sparks, Jenni Barclay, Barry Voight, Richard A. Herd, Richard Luckett, Gill E. Norton, Lutchman Pollard, Lucy Ritchie, Richard D. A.Robertson, and the Montserrat Volcano Observatory Staff, 1998. *Special Report 06, The Boxing Day Collapse, Dec. 26, 1997*, Montserrat Volcano Observatory, Montserrat, West Indies, http://www.geo.mtu.edu/volcanoes/west,indies/soufriere/govt/specrep/specrep06.html.

Camacho, Eduardo, 1994. The tsunami of April 22, 1991 in Central America, *Tsunami Newsletter*, Vol. 25, No. 1, pp 6-7.

Campbell, J.B., 1991. *Earthquake History of Puerto Rico*, Appendix I, Part A, Aguirre Nuclear Power Plant PSAR, Weston Geophysical Research, Inc., Weston, MA, 75 pp.

Centeno-Grau, M., 1969. *Estudios Sismologicos*, Bibloteca Academia Ciencias Frisicas, Matematicas y Naturales, VIII, Caracas, Venezuela, Segunda Edicion.

Coffman, J.L., and W.K. Cloud, 1970. *Miscellaneous activities, United States Earthquakes, 1968*, U.S. Dept. of Commerce, Coast and Geodetic Survey, Government Printing Office, Washington, D.C., p 73.

Davidson, C., 1936. *Great Earthquakes*, Thomas Murty and Co, London, 286 pp.

Deville, Ch. Sainte-Claire, 1867. Sur le tremblement de terre du 18 Nobembre, 1867 aux Antilles, *Extrait des Comptes Rendus des Seances de l'Academie des Sciences*, LXV, Séance du 30, Decembre, 1867, Institute Imperial de France, Academie des Sciences, Paris, p 1110.

Dunbar, Paula K., and Lowell S. Whiteside, 1994. Earthquake coupling with other natural disasters, Fall Meeting, American Geophysical Union, poster session, San Francisco, CA.

El Nuevo Dia, 1989. Puerto Rico, newspaper article, Nov. 2, p 11.

Feldman, Lawrence, H., 1984. A catalogue of historical documents pertaining to the earthquake damage in Panama and Costa Rica, unpublished manuscript.

Feldman, Lawrence H., 1993. *Mountains of Fire, Lands that Shake: Earthquakes and Volcanic Eruptions in the Historic Past of Central America*, (1505-1899), Labyrinthos Press, Culver City, CA.

Grases, J., 1971. La sismicidad historica del Caribe, *Documentos de Trabajo*, Informe que presenta a la Junta Directiva del Comite Conjunto del Concreto Armado, Oct., Caracas, Venezuela.

Hall, M., 1907. *The Great Earthquake of January 14th 1907*, Third Report of Earthquakes in Jamaica, Special Issue of the Weather Report, No. 337, Government Printing Office, Kingston, Jamaica.

Heck, N.H., 1947. List of seismic sea waves, *Bull. Seismological Soc. Amer.*, Vol. 37, No. 34, p 269.

Heilprin, Angelo, 1903. *Mont Pelee and the Tragedy of Martinique*, J.B. Lippincott Co., Philadelphia and London, 333 pp.

Henderson, 1852. *Jamaica Almanack for 1852*, p 36.

Herridge de Guerrero, Christine M., 1998. email communication, July 21.

Hess, H.H., 1932. Interpretation of gravity anomalies and sounding profiles obtained in the West Indies by international expedition in 1932, *EOS, Transactions, American Geophysical Union*, Vol. 13, pp 26-33.

Kirkpatrick, R.Z., 1920. Earthquakes in Panama up to January 1, 1920, *Bull. Seismological Soc. Amer.*, Vol. 10, No. 2, pp 121-128.

Lander, James F., and Patricia A. Lockridge, 1989. *United States Tsunamis (Including United States Possessions) 1690-1988*, Publication 41-2, National Oceanic and Atmospheric Administration, National Geophysical Data Center, Boulder, CO, 265 pp.

Lyell, Sir Ch., 1875. *Principles of Geology* 2, 12th Edition, 2 Vol., Murray, London, 146-154.

Lynch, J.J., and R.R. Bodle, 1948. The Dominican earthquakes of August 1946, *Bull. Seismological Soc. Amer.*, Vol. 38, No. 1, pp 1-18.

Lynch, Lloyd L., and John B.Shepherd, 1995. An earthquake catalogue for the Caribbean Part II. The macroseismic listing for the instrumental period 1900-1991, presentation at the Caribbean and Latin American Seismic Hazard Project Workshop, Melbourne, FL, 45 pp.

Mader, Charles, 1997. 1775 Lisbon Tsunami, CD video of modeling of travel times, shown at the Caribbean Tsunami Workshop, Mayaguez, Puerto Rico.

Mallet, R., 1853. *Catalogue of Recorded Earthquakes from 1606 B.C. to A.D. 1850*, Part I, 1606 B.C. to 1755 A.D. Report of the 22nd Meeting of the British Association for the Advancement of Science, held in Belfast, Sept. 1852, John Murray, London, 177 pp.

Mallet R., 1854. *Catalogue of Recorded Earthquakes from 1606 B.C. to A.D. 1850, Part II, 1755 A.D. to 1784 A.D.*, Report of the 23rd meeting of the British Association for the Advancement of Science, held in Hull, Sept. 1853, John Murray, London, pp 118-212.

Mallet, R., 1855. *Catalogue of Recorded Earthquakes from 1606 B.C. to A.D. 1850, Part III, 1784 A.D. to 1842 A.D.,* Report of the 24th Meeting of the British Association for the Advancement of Science, John Murray, London, 326 pp.

Mangeney, Anne, P. Heinrich, R. Roch, G. Boudon, and J.L. Cheminee, 1998. Numerical simulation of the December 1997 tsunami generated by a debris avalanche in Montserrat, Lesser Antillels, *Abstracts, International Conference on Tsunamis*, UNESCO, May, Paris, p 88.

Mercado, Aurelio, 1997a. "1987 Venezuela earthquake and tsunami," personal communication.

Mercado, Aurelio, 1997b. "1918 tsunami fatalities," e-mail communication.

Mercado, A., and W. McCann, 1998. Numerical simulation of the 1918 Puerto Rico Tsunami, Natural Hazards, Vol. 18, No. 1, pp 57-76.

Millas, Jose Carlos, 1968. Hurricanes of the Caribbean and Adjacent Regions, 1492-1800, Academy of Arts and Sciences of the Americas, Miami, FL, 328 pp.

Miller, Don J., 1960. Giant Waves in Lituya Bay, Alaska, U.S. Geological Survey Professional Paper 354c, Government Printing Office, Washington, D.C., 86 pp.

Milne, J. 1911. Unpublished notes relating to destructive earthquakes, *Brit. Assoc. Adv. Sci.,* 55.

Milne, J., 1912. A Catalogue of Destructive Earthquakes, A.D. 7 to A.D. 1899, 16th Report of the Committee on Seismological Investigations, Report of the 81st Meeting of the British Association for the Advancement of Science, held at Portsmouth, 1911, 92 pp.

Molina, Enrizue, 1997. *Tsunami Catalogue for Central America, 1539-1996, for Reduction of Natural Disasters in Central America, Earthquake Preparedness and Hazard Mitigation*, Technical Report No. II 1-04, Institute of Solid Earth Physics, University of Bergen, Bergen, Norway, 87 pp.

Monthly Weather Review, 1883. Hazen, W.B., Brig and Maj. Gen., ed., Vol. XI, No. 8, United States War Department, Washington, D.C., Aug., p. 191.

Murphy, Leonard M., and Franklin P. Ulrich, 1952. *United States Earthquakes 1950, U.S.* government Printing Office, Washington, D.C., Serial No. 755, p 19.

Murphy, L.M., and W.K. Cloud, 1955. *Miscellaneous Activities, United States Earthquakes, 1953,* U.S. Government Printing Office, Washington, D.C., p 29.

Murty, T.S., 1977. *Seismic Sea Waves*, Dept. of Fisheries and the Environment Fisheries and Marine Service, Ottawa. 336 pp.

Myles, D., 1985. *The Great Waves*, McGraw-Hill, New York, 206 pp.

Neumann, Charles J., B.R. Jarvenen, Arthur C. Pike, and Joe D. Elms, 1988. *Tropical Cyclones of the North Atlantic Ocean, 1871-1986* (with figures to 1992), National Oceanic and Atmosphheric Administration, National Climatic Data Center, Asheville, NC., 186 pp.

O'Loughlin, Karen and James F. Lander, A Five Hundred Year History of Tsunamis in the Caribbean, in preparation, 2002.

Olsen, P., 1988. Archivist for Denmark's translation from *Journal over det paa St. Thomas passerede*, Danish West Indian and Guinea Co. records (498); and from *Brev og dokumenter fra Vestindien, 1674-1698*, Letter from "Christiansfort of 8 April, 1690," by the governor of St. Thomas to the Danish West Indian and Guinea Co., West Indian Letters and Documents (98); personal communication, May 9.

Paiewonsky, I., 1979. History Corner, a series of 14 newspaper articles in The St. Thomas Daily News.

Palgrave, W.G., 1874. Earthquake in St. Thomas, Nature, Vol. 9, pp 483-484.

Parker, W.E., 1922. Unusual tidal registration of earthquakes, *Bull Seismological Soc. Amer.*, Vol. 12, No. 1, pp 28-30.

Perry, A., 1843. Note historique sur les tremblements de terre aux Antilles, *Comptes Rendus (hebdomadairies) Acad. Sci. de Paris* 16, 1283-1312 (French).

Perry, A., 1847. 1845-1846, Sur les tremblements de terre aux Antilles, Memoires de l'Academie des Sciences, Artes, et Belle-Lettres de Dijon, pp 325-392.

Preliminary Determination of Epicenters (PDE), Monthly Listings, United States Dept. of Interior, Geological Survey (USGS), National Earthquake Information Center, Golden, CO

Reid, H.F., 1917. Note on the earthquake at Almirante, Republic of Panama in April 1916, *Bull. Seismological Soc. Amer.*, Vol. 7, No. 1, pp 27-30.

Reid, H.F., and S. Taber, 1919a. *The Puerto Rico Earthquake of 1918*, House of Representatives, 66th Congress, 1st Session, Document No. 269, No. 19, 74 pp.

Reid, H.F., and S. Taber, 1919b. The Puerto Rico earthquakes of October-November 1918, *Bull. Seismological Soc. Amer.*, Vol. 9, No. 4, pp 95-127.

Reid, H.F., and S. Taber, 1920. The Virgin Islands earthquakes of 1867-1868, *Bull. Seismological Soc. Amer.*, Vol. 10, No. 1, pp 9-30.
Robson, G.R., 1964. An earthquake catalogue for the Eastern Caribbean, 1530-1960, *Bull. Seismological Soc. Amer.*, Vol. 554, No. 2, pp 785-832.
Rubio, Mario, 1982. *Occurrencia de tsunamis en el Caribe*, Investigationes Sismologicas en Cuba, Academia de Ciencias de Cuba, Instituto de Geofisica y Astronomia, No. 2, pp 170-180.
Scherer, J., 1912. Great earthquakes in the island of Haiti, *Bull. Seismological Soc. Amer.*, Vol. 2, No. 3, pp 161-180.
Schubert, C., 1994. Tsunamis in Venezuela: Some observations on their occurrence, *Journal of Coastal Research, Special Issue No. 13, Coastal Hazards*, pp 189-195.
Seismological Notes, 1929. *Bull. Seismological Soc. Amer.*, Vol. 19, No. 1, p 55.
Seismological Notes, 1955. *Bull. Seismological Soc. Amer.*, Vol. 45, No. 2, p 160.
Shepherd, John B., and Lloyd L. Lynch, 1992. An earthquake catalogue for the Caribbean, Part 1, the preinstrumental period 1502-1900, presentation to the Steering Committee, Latin American and Caribbean Seismic Hazard Program, Melbourne, Florida, 60 pp.
Sigurdsson, H.R., S.J. Sparks, S.N. Carey, and T.C. Huang, 1980. Volcanogenic sedimentation in the Lesser Antilles arc, *Journal of Geology*, Vol. 88, pp 523-540.
Sigurdsson, H., 1996. "Volcanic Tsunami," Summary Report IOCARIBE Tsunami Warning Workshop, St. Johns, Virgin Islands, May, UNESCO IOC Workshop Report, Paris.
Sigurdsson, H., 1997. personal communication.
Simkin, T., L. Siebert, L. McClelland, D. Bridge, C. Newhall, and J.H. Latter, 1981. *Volcanoes of the World*, Smithsonian Institution, Hutchinson Ross Publishing Co., Stroudsburg, PA, 233 pp.
Singer, A., C. Rojas, M. Lugo, 1983. *Inventario Nacional de Riegos Geologicos, Estado Preliminare,* Caracas: Fundacion Venezonana de Investigaciones Sismologicas, Serie Tecnica 03-83.
Sloane, H., 1809. Letter in the Royal Philosophical Society of London Transactions, Abridged, 3, pp 624-632.
Smithsonian Institution, 1997. *Bulletin Global Volcanism Network 1980-1997*, Washington, D.C., pp 5-22.
Southey, Capt., T.V., 1827. *Chronological History of the West Indies*, Longman, Rees, Orne, Brown and Green, London, 2, 407, 422, 472.
Stothers, Richard B., 1989. Volcanic Eruptions and Solar Activity, *J. Geophys. Res.* Vol. 94, No. B12, pp 17371-17382.
Stover, Carl w. and Jerry L. Coffman, 1993. Seismicity of the United States, 1568-1989 (Revised) p. 250
Taber, S., 1920. Jamaica earthquakes and the Bartlett Trough, *Bull. Seismological Soc. Amer.*, Vol. 10, No. 2, pp 55-89.
Taber, S., 1922a. The great fault troughs of the Antilles, *Journal of Geology*, 30, pp 89-114.
Taber, S., 1922b. The seismic belt in the Greater Antilles, *Bull. Seismological Soc. Amer.*, Vol. 12, pp 199-219.
Taylor, C.E. 1888. *Leaflets from the Danish West Indies*, Wm. Dawson and Sons, London 80-81; Reprinted by Negro Univ. Press, Greenwood Press, Inc., New York (1970).
Tomblin, J.M., and G.R. Robson, 1977. A Catalogue of Felt Earthquakes for Jamaica with Reference to other Islands in the Greater Antilles, 1564-1971, Ministry of Mining and Natural Resources, Special Publication, No. 2, Jamaica.
Van Housel, L., 1878. An earthquake experience, Scribners Monthly, Vol. XV, No. 5, Scribners and Co., New York, pp 662-672.

Von Hake, C.A., and W.K. Cloud, 1971. Miscellaneous Activities, *United States Earthquakes, 1969*, National Oceanic and Atmospheric Administration, Rockville, MD, 53 pp.

Watlington, Roy A., and Shirley H. Lincoln, 1997. *Disaster and Disruption in 1867: Hurricane, Earthquake and Tsunami in the Danish West Indies*, Eastern Caribbean Center, Univ. of the Virgin Islands, 134 pp.

Weissert, T.P., 1990. Tsunami travel time charts for the Caribbean, Science of Tsunami Hazards, Vol. 8, No. 2, pp 67-78.

Whiteside, L.S., D. Dater, and P. Dunbar, 1996. Seismicity Catalog CD-ROM, National Oceanic and Atmospheric Administration, National Geophysical Data Center, Boulder, CO, and U.S. Geological Survey, Golden, CO, also available at http://www.ngdc.noaa.gov/seg/hazard/tsu.shtml.

THE NEED FOR UNDERWATER LANDSLIDE HAZARDS PREDICTION

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ABSTRACT

As of early 2000, scientists were unable to assess many underwater landslide hazards, to predict their occurrence following a nearby earthquake, to evaluate their tsunamigenic potential, and to warn coastal communities of imminent danger. Underwater landslides pose a continuous threat to US coastal economic activity, including valuable offshore structures, communication cables, and port facilities. Underwater landslides can generate tsunamis reaching at least 30 m above sea level, surpassing bounds of tsunamis generated by earthquakes. In the 1990s, more than 2400 people perished from landslide tsunamis as villages were swept clean by walls of water moving faster than residents could run, notably during the 1992 Flores Island, Indonesia and 1998 Papua New Guinea events. Local tsunamis also threaten lives and property along most US coastal waters, including Southern California. This fact calls into question the preparedness of US coastal communities for such events and fuels the need for underwater landslide prediction. This report summarizes the motivation for a workshop funded by the US National Science Foundation and reports on the consensus finding of workshop participants.

INTRODUCTION

Underwater landslides or submarine mass movements are generic terms encompassing all sizes and shapes of sediment, rock, and reef failures. Can scientists predict the occurrence, location, and dimensions of underwater landslides for a given continental margin and earthquake trigger? This is the central question that the Workshop on the Prediction of Underwater Landslide Occurrence and Tsunami Hazards off of Southern California attempted to answer from March 10-11, 2000 at the University of Southern California, Los Angeles, California. The basic answer is yes: several methods have already been devised and several were described in presentations at the workshop. However, underwater landslide hazard assessment remains difficult because the accuracy of prediction techniques remains largely unknown, so there are no clear confidence limits. There is also a dearth of sensitivity analyses of existing predictive models, so key physical quantities remain to be identified. The number of case studies applying or comparing predictive models is quite small. The 1998 Papua New Guinea event provides one of the first complete tsunami case studies with modern seismic records, exhaustive onland investigation, several post-event marine surveys, and successful numerical simulations. Predicted probability distributions have rarely been compared with distributions of documented or historic events. A lot of fundamental research remains.

Tsunamis, a Japanese word meaning "harbor waves" or tidal waves, have been traditionally associated with nearshore earthquakes. The largest tsunamis readily propagate across an entire ocean to inflict significant damage and loss of life. From this perspective, either an earthquake generates a tsunami that threatens the entire Pacific Basin, or a credible tsunami threat only exists where the earthquake is felt. Locally, the earthquake is the only tsunami warning needed: the larger the earthquake, the larger the expected tsunami. The Pacific Tsunami Warning Center was created in the mid 1900s following several large transoceanic tsunamis to warn distant places, especially Hawaii, of pending tsunami arrival and potential tsunami amplitude. In contrast, the decade of the 1990s saw numerous modest earthquakes that generated devastating tsunamis without any significant transoceanic tsunamis. The term "local tsunami" was coined to distinguish these potentially surprising events from their transoceanic brethren.

Recent case studies of local tsunamis suggest that underwater landslides can be responsible for most of the devastating impact of local tsunamis. As if to underscore this point, remote tsunami sensors in the open ocean occasionally detect tsunamis following earthquakes where none were expected. Researchers now consider tsunamigenic landslides triggered by the earthquake. Consequently, the term "landslide tsunami" came into use to describe those events where underwater landslides generate the most hazardous local tsunami. The word tsunami can now encompass several tsunami sources generated by different geological events, e.g., earthquakes and landslides. The tsunami amplitude is no longer predictable from earthquake magnitude alone. On the one hand, few underwater landslides are tsunamigenic as they are either too small or too deep to generate an appreciable water wave. On the other hand, some of the largest tsunamis ever produced on earth were landslide tsunamis. Scientific observations and case studies are driving a paradigm shift in our understanding of underwater landslide and tsunami hazards. Effective hazards assessment and local tsunami warning demand that underwater landslide hazards, including tsunamis, be predicted.

WORKSHOP OBJECTIVES

Some invited scientists, both before and after the workshop, perceived that landslide tsunamis constitute a scientific discipline at the juncture of seismology, soil mechanics, marine geology, and fluid dynamics. The juncture is clearly more interdisciplinary and more complex than a simple boundary between two scientific disciplines. However, the perception of a distinct scientific discipline can only be validated by the response of fellow scientists to study natural hazards such as landslides and tsunamis. Is "underwater landslide hazards" an appropriate and desirable label for the collective research effort? A workshop is one mechanism whereby the enthusiasm of the scientific community can be assessed. Therefore, an informal workshop objective was to assemble a group of scientific leaders who could potentially form an established core for the scientific discipline. We canvassed four scientific disciplines to promote the synergies needed to consolidate underwater landslide hazards into one discipline. We eventually hosted 67 registered workshop participants, almost double the number planned for at the outset. The largest contingent of participants were marine geologists. Additional students and staff from the University of Southern California informally attended the workshop. Based on the workshop attendance and interest level of participants, underwater landslide hazards appear to have a promising future. The workshop had the following formal objectives:

- To present the state of the art in science and engineering disciplines related to underwater slope stability and landslide tsunamis;
- To establish the capabilities, accuracy, and sensitivity analyses of existing predictive models in order to hone in on requisite model inputs;
- To gather databases and case studies with which to validate predictive models;
- To focus future research activities on unavailable data and predictive model improvements;
- To write recommendations for research institutions and public agencies, notably the US National Science Foundation;
- To produce a volume summarizing workshop findings for scientific peers.

The workshop considered underwater landslide prediction from seven different perspectives: the probability of failure, the occurrence of failure, the location of failure, the size of failure, the landslide motion following failure, the landslide deformations following failure, and the tsunami features generated by failure. These seven perspectives have different affinities to seismology, soil mechanics, marine geology, and fluid dynamics as well as to existing prediction models. By acknowledging seven perspectives, we hoped to encourage participants to choose a form of underwater landslide prediction most suited to their traditional research.

WORKSHOP ACTIVITIES

The workshop was largely organized through a web site that still lists the participants and the activities: *http:rccg03.usc.edu/la2000/*. We summarize the workshop activities here. The workshop opened with short introductions given by 1) Cliff Astill, US National Science Foundation Program Manager, 2) Eddie Bernard, Director of NOAA Pacific Marine Environmental Laboratory, 3) Ed Clukey, scientist at BP Amoco Inc., and 4) the workshop hosts. The workshop goals were then outlined through case studies presented Tad Murty, Dave Tappin, Eli Silver, Jose Borrero, Costas Synolakis and the author. All but two speakers described various aspects of the 1998 Papua New Guinea event. The main body of the workshop consisted of four technical sessions:

1) Seismic Considerations, chaired by Emile Okal, Northwestern University
2) Sediment/Geotechnical Stability, chaired by James Mitchell, Virginia Tech
3) Mass Failure Field Work, chaired by George Plafker, USGS Menlo Park
4) Mass Failure Computations, chaired by Homa Lee, USGS Menlo Park

At the conclusion of the four technical sessions, Cliff Astill chaired a session devoted to formulating recommendations for the US National Science Foundation. This was accomplished by letting workshop participants join open discussions facilitated by the session chairmen and the workshop hosts. A compilation of these recommendations is featured below.

RESEARCH ISSUES

During the workshop, participants were asked to reflect on the following lists of questions. In many instance, these questions remain research topics that the reader may find worthwhile pursuing. Even questions with apparently simple answers may conceal a wealth of geological or mechanical complexity. We therefore encourage the reader to reflect on each question with an open mind. Answers that address landslide hazards prediction are not always evident from the current state of the art.

Seismic Considerations

How do near-field earthquake ground motions induce the failure of marine sediments? What is the influence of any episodic stress changes on excess water pressure and sediment failure along a margin? Does coseismic displacement during an earthquake correlate with bathymetric highs and lows, and could this help indicate the locations of sediment failure? How do seismic radiation characteristics from mass failure depend on mass failure material and dimensions?

Sediment/Geotechnical Stability

What physical mechanisms are capable of inducing failure of submarine masses? Which sediment parameters affect most failure calculations for various failure mechanisms? Which geotechnical methodologies are available for predicting slope instability? How do local sediment inhomogeneities influence or determine global mass failure characteristics? Given an unstable sediment slope, what mechanisms determine or control the width of failure?

Mass Failure Field Work

What do mass failure morphologies tell us about failure mechanics? Why do so many steep slopes persist adjacent to failed slopes? Is the geological formation of a sediment slope related to the mechanics and probability of submarine mass failure? Can one infer probability distributions for submarine mass failure from observations of failure scars and deposits? What role would borings play in assessing regional failure probabilities?

Mass Failure Computations

How many reasonably complete case studies can one assemble to validate predictive algorithms of submarine mass failure? Under what conditions can a specific failure mechanism be expected to dominate mass failure? What constitutes a reasonably effective stability analysis for a given failure mechanism? Do predicted submarine mass failure probability distributions agree with observed distributions? Which seismic, sedimentary, or geological inputs essentially control or dominate submarine mass failure?

WORKSHOP RECOMMENDATIONS

One of the workshop objectives was to produce a list of recommendations for the US National Science Foundation. These recommendations are intended to be used by the US National Science Foundation, as well as other research institutions. Recommendation have been derived from multiple sources and collated in a manner that gave equal weight to all sources. In addition to the lists of questions mentioned above and distributed on paper forms, we asked workshop participant to provide written answers to the following three questions. What institutions can we establish to promulgate this research community? How can the internet assist us in our goals? Who is the most effective audience for our recommendations? Feedback from all of these queries has been collected here under the rubric of workshop recommendations. Reports from the session chairmen are also summarized here, as are the recommendations formulated at the end of the workshop. These varied sources of recommendations often coincide, which reflects on the level of agreement achieved at the workshop.

Underwater landslide hazards pose research challenges at the intra-agency and inter-agency level to both the US National Science Foundation and the US Office of Naval Research. As an emerging discipline, research on underwater landslide hazards has yet to established its places and roles within institutional structures. Consequently, these recommendations are geared toward facilitating research on underwater landslide hazards. The list of recommendations is provided as a bulleted list.

• Underwater landslide hazards present research opportunities within multiple directorates and divisions of the National Science Foundation. As of now, underwater landslide hazards do not fall neatly into any one directorate. In order to facilitate funding opportunities within the current institutional structure, workshop participants recommended merging support from different divisions to fund underwater landslide hazards research.
• The US government already possesses a wealth of existing marine geology data, much of which can be made or already is publicly available. These data are often an untapped or underused source of information for underwater landslide research and hazard mitigation purposes because of the difficulties involved in finding and requesting the data. In order to facilitate the productive use of this data, workshop participants recommended establishing institutional links to locate and distribute archives from the US Navy, Mineral Management Service, US Geological Survey, etc. to researchers.
• The workshop assembled a new composite of landslide triggering theories. Yet, almost no sites of underwater landslide research either receive or are amenable to a thorough examination of the causes of and potential for underwater landslides. In order to perform a thorough landslide case study and site specific hazard assessment, workshop participants recommended choosing an intensive research site such as Santa Barbara, California. At this site, a thorough suite of tectonic and sedimentary measurements could yield invaluable insight into underwater landslide hazards, improve existing engineering models, validate underwater landslide stability analyses, and enable prediction of future landslide events.
• Underwater landslides form a complex and interdisciplinary research subject that could benefit from further synthesis of disparate modeling efforts. In order to facilitate such syntheses and promote sensitivity analyses of landslide hazards, workshop participants recommended developing a landslide failure community model in order to model 3D failure surface formation, to study early time landslide motion and deformation, and to examine the role of tectonic structures such as faults in failure.
• Landslide tsunami generation remains a poorly understood phenomenon for which there has recently been a proliferation of different numerical models with widely differing assumptions. In order to guarantee and promote tsunami hazard assessment, workshop participants recommended developing a tsunami generation community model including landslide tsunami sources and earthquake tsunami sources.
• Researchers present at the workshop perceived that underwater landslide hazards was a relatively young and rapidly changing scientific discipline. One workshop would not suffice to define the interests and needs of participating researchers. In order to further interdisciplinary collaboration as well as the development of the research community, workshop participants recommended funding another underwater landslide hazards prediction workshop.
• Tsunami warning centers are currently set up to mitigate the impact of distant tsunamis. A felt earthquake was considered sufficient warning for local tsunamis. Devastating landslide tsunamis can appear with little to no felt earthquake, and can possess an amplitude far in excess of any concurrent earthquake tsunami. In order to help save lives endangered by landslide tsunamis, workshop participants recommended developing a prototype local tsunami warning system. Among other goals, such a system would identify and characterize underwater landslides by seismic and acoustic techniques.
• Post-event tsunami surveys during the 1990s have revealed a wealth of information regarding landslide tsunami hazards. Nevertheless, significant events are sufficiently rare that there remains much to confirm and even more to learn. In order to further understand the onland impact of landslide tsunamis, workshop participants recommended continuing support of International Tsunami Survey Teams.
• Marine surveys are proving valuable tools for understanding and modeling landslide tsunami generation. However, only a handful of such surveys have been carried out and the inherent complexity of geological systems will require many more before patterns emerge. In order to further understand the offshore generation of landslide tsunamis, workshop participants recommended continuing support for marine surveys of tsunami source regions.

- The private sector has significant financial concerns exposed to underwater landslide hazards. In order to further prediction of underwater landslide hazards, workshop participants recommended seeking private research support, perhaps from oil and gas producers, insurance companies, or port facilities.
- There are a significant differences between the needs of researchers and the needs of disaster managers. In order to promote underwater landslide hazards mitigation, workshop participants recommended producing consumable tsunami hazard products such as underwater landslide hazards maps, probability distributions of landslide and tsunami events, observed landslide and tsunami recurrence rates, underwater landslide hazards risk analyses, hazard mitigation and preparation measures, cost/benefit analyses, and port survivability studies.
- Researchers need regular contact to keep their research up to date and to expand interest in their field. In order to promote common research interests and share the latest research results, workshop participants recommended organizing Special Sessions at AGU Meetings and other scientific events.
- Researchers need printed venues in which to publish their latest work. For a relatively new research discipline, this can be especially difficult. In order to promote common research interests and share the latest research results, workshop participants also recommended organizing special issues of recognized journals.
- Hazard mitigation in general often involves public education. In the case of tsunami hazards, public education has proven particularly effective at saving lives. In order to promote tsunami hazard mitigation, workshop participants recommended increasing public awareness of tsunami hazards through press releases, news conferences, television programs, web sites, tsunami animations, etc.

CONCLUSIONS

The workshop considered the state of the art in seismology, soil mechanics, marine geology, and tsunami generation as a starting point in underwater landslide hazards research. During the workshop, it became clear that new synergies are indeed providing opportunities to predict underwater landslide hazards. Landslide tsunamis motivate the urgent need for prediction, although other underwater landslide hazards are also of serious concern. Given the sparse temporal and spatial distribution of large underwater landslides, prediction is a crucial aspect of hazard assessment and hazard mitigation. On the one hand, relatively new marine geology tools enable a broader assessment of ocean floor stability, while on the other hand engineering models merge previously distinct aspects of landslide failure into predictive models. These interdependent opportunities feed the growth of a what some workshop participants termed a scientific discipline unto itself. The objectives of this discipline will include the prediction of the probabilities, locations, dimensions, motions, deformations, and hazards of prospective underwater landslides.

Landslide tsunamis pose the greatest local tsunami threat according to a consensus opinion of the 67 scientists attending the workshop. Tsunamis are one of the most important natural hazards facing the five Pacific US states, occasionally inflicting more damage and casualties than large earthquakes -- viz., the 1964 Alaskan earthquake. Local tsunamis have reached 15 m above sea level during the 1998 Papua New Guinea tsunami and 26 m above sea level during the 1992 Flores Island, Indonesia tsunami, both due to nearby underwater landslides. More than 2400 people perished from these tsunamis as villages were swept by churning walls of water moving faster than residents could run. The 1998 Papua New Guinea event has proven to be and will likely continue to be a valuable case study with which to validate models of underwater landslide hazards. To be sure, more case studies are needed, some of which should be based on the data and expertise acquired by oil and gas producers as well as the US federal government. Workshop participants have chosen the Santa Barbara, California continental slope as an ideal case study that can involve most interested scientists, agencies and institutions.

An interdisciplinary approach to underwater landslide hazards assessment will eventually yield probabilistic and deterministic predictions of submarine mass failure size and location. These predictions will enhance both underwater landslide hazards assessment and local tsunami warning capabilities. The capabilities and sensitivities of existing predictive models have established certain critical parameters that may control some underwater landslide hazards. Future research activities should focus both on reducing uncertainty and enhancing predictive model capabilities. Workshop recommendations have been written for public and private agencies and institutions. We are confident that the workshop has advanced our ability to assess underwater landslide hazards. We perceive our future goals as a continuation of the workshop goals: to predict underwater landslides, to assess underwater landslide hazards, to evaluate their tsunamigenic potential, and to warn coastal communities and other entities of imminent danger.

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OBSERVATIONS OF SELECTIVE AMPLIFICATION OF TSUNAMIS TO AZIMUTH OF THE SOURCE

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ABSTRACT

To study secondary undulation excited by tsunamis in bays we compared the spectra among 35 and 27 Pacific tsunamis observed at Ayukawa and Tosashimizu in Japan. As the most predominant periods 22±3 min(51%), 8±3 min(31%) for Ayukawa and 21±5 min (96%) for Tosashimizu were obtained. In the next step we eliminated background noises from the spectra assuming the same background noise to all the tsunamis. As the background noise sea-level records recently observed at the tide stations in quiet sea conditions were used. The result shows that predominant periods dispersed into 3-4 groups consisting of 42, 20, 15 and 8.6 min at Ayukawa, and 56, 33 and 18 min at Tosashimizu. From harmonic analysis with numerical models including the shelf regions the excitations are explained from resonant oscillations. The periods approximately correspond to those of the fundamental and the higher mode. The most predominant periods and amplitude of these predominant periods depend on azimuth angles of the epicenters as the tide stations. Particularly the shortest ones were much amplified in the same azimuth angles of epicenters to those of channels connecting the bays to the open ocean. Long ones are supplied from resonated wave in the shelf arrived in the oblique incidence. This fact suggests that there is a selective amplification of tsunami to the period component at bays. Thus we found tsunami responding to a shelf through eliminating the background noise from tsunamis observed in bays.

INTRODUCTION

Most part of tsunami observed in a bay is occupied by a local oscillation excited in the sea around the tide station. Counting time intervals of waves in some tsunamis, observed at Ayukawa tide station in Japan, Omori (1901) indicated predominant periods of 23-25 and 7.1-7.8 min, and he concluded that tsunami was a bay oscillation. Honda et al. (1908), noticing the secondary undulations in daily states, measured them at various places in Japan. It was pointed out that the secondary undulation was also excited by a strong wind (Ichie, 1956,Nakano and Unoki, 1962). After spectral analysis was introduced the predominant period was treated on the spectra. Takahashi and Aida (1963) found predominant periods of 8.5 and 20-22 min for Ayukawa and 21, 40 min for Tosashimizu in several tsunamis. Aida (1982) made a list of predominant periods of tsunamis and those of secondary undulations observed without tsunami for various tide stations, and emphasized that we need to discriminate the original period of the tsunami and that of the secondary undulation. Baptista et al. (1992) expressed the spectrum as a synthesis of source spectra and propagation spectra. Abe (1993) explained observed tsunami spectra from synthesized spectra of source and shelf response. As for the source spectra Yamashita and Sato (1974) obtained a formula on a constant depth. Rabinovich (1997) assumed the observed spectra as a synthesis for the source and the secondary undulation, which was observed just before the tsunami arrival, and called background spectrum, and separated the source spectra from the observed spectra. As for the tsunami in bays of which predominant periods are frequently same it is considered to be difficult to neglect propagation effects. To study the propagation effect it is important to eliminate the background spectra from the observed spectra. Thus, after the elimination it is expected that incident tsunami is separated from the observed tsunami. Noticing universal properties of the secondary undulation we apply one example of the secondary undulation to many tsunamis at a station in a bay and will eliminate the background noise from the observed tsunamis. As the secondary undulation we will use sea level oscillations observed at tide stations in the quiet sea without tsunami recently. We apply the method to two typical tide stations, Ayukawa and Tosashimizu, observing many Pacific tsunamis at which the same predominant periods are frequently observed.

TIDE GAUGE RECORDS OF TSUNAMIS AND THE SPECTRA

Ayukawa and Tosashimizu are tide stations located at bay heads facing to the Pacific in Japan. They are managed by Japan Meteorological Agency and have roles to watch tsunamis in the east and the west districts of Japan (Figure 1). Tide gauge records of 35 tsunamis in the period from 1894 to 1996 at Ayukawa and 27 tsunamis in the period from 1958 to 2001 at Tosashimizu (Table 1) are decomposed into the amplitude spectra. The tidal levels are reduced using assumed smoothed curves. The discrete sea levels starts at arbitrary time within 1 hour before the arrival and finishes at time 6 hours elapsed. Since the sampling time is 1minute, Nyquist frequency is 8.3 mHz(2 min in period). For a saturated record of the 1960 Chilean tsunami observed at Ayukawa the starting time was set to time after decaying into an unsaturated level.

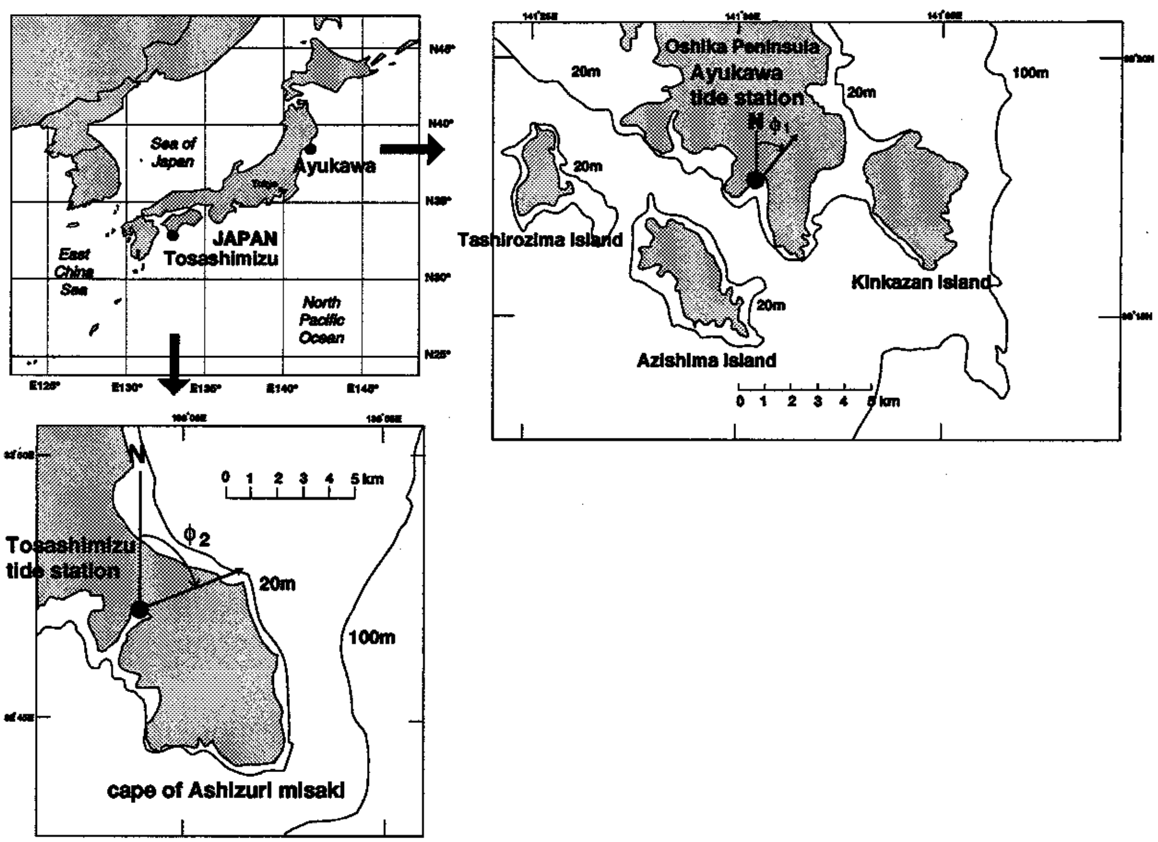

Figure 1. Locations of tide stations at Ayukawa and Tosashimizu. Definitions of azimuth angles of epicenter $\phi1$, $\phi2$ are illustrated in the figure.

Goertzel method, effective to discrete data, is used for the spectral decomposition (e.g.Abe, 1990). The spectral components are calculated in frequency range with interval of 0.02 mHz from 0.02 to 2.4 mHz and plotted with the same frequency interval after taking a running average. The raw spectra are calculated for all the tsunamis at each station. They are under a bias of background noises and the noises are eliminated through dividing amplitude of the raw spectra by one of the background-noise spectra (e.g. Rabinovich, 1996). Tide gauge records at quiet sea conditions are used as the background noises for all the tsunamis. They are time histories of sea levels from 15:30 to 19:00 on Nov. 3, 2000 at Ayukawa and from 13:00 to 19:00 on Aug. 24, 2000 at Tosashimizu. The calculation condition is the same as that for tsunamis. From the noise-eliminated spectra predominant periods are noticed and the properties are discussed. To compare predominant periods of the noise-eliminated spectra with those of models we use a numerical model of harmonic analysis. The same framework as that used by Abe (1986) is applied to shelf area including the tide stations. Plane sinusoidal wave of a frequency with unit amplitude is assumed to be incident to shelf margin and the frequency varies from 0.1 to 2 mHz with interval of 0.1 mHz. At the tide station amplitude is obtained as a function of frequency. This is a response of tide station to white noise incident to the shelf. The calculations are applied to Ayukawa and Tosashimizu including the shelves, independently.

MOST PREDOMINANT PERIODS OF NOISE-ELIMINATED SPECTRA

The background-noise eliminated spectra and the raw ones are shown with spectra of the background noise, in Figure 2 for Ayukawa and in Figure 3 for Tosashimizu. In the noise-eliminated spectra at Tosashimizu frequency response was not obtained for the component higher than 1.4 mHz because of instability due to a low level of the background noise. In this section we notice the most predominant period as a peak with the highest level of the spectra. The most predominant periods in the raw spectra tended to concentrate into some particular periods such as 22 ± 3 and 8 ± 3 min for Ayukawa and 21 ± 5 min for Tosashimizu. These values are within those before described but it is emphasized as a statistical result. The appearance is obtained as a rate of 51% for 22 ± 3 min and 31% for 8 ± 3 min at Ayukawa, and 96 % for 21 ± 5 min at Tosashimizu. The high concentration to 21 min and a low level in frequency higher than 1 mHz are noticeable at Tosashimizu. The low level is also observed for the background noise. The cutoff of high frequency is related to the bay with shallow water close in shore. On the contrary the cutoff is not observed for the background noise at Ayukawa. After the background noise elimination the most predominant periods were dispersed into 2-3 groups. It consists of 43±3 (14%), 20±1 (37%) and 8.1±0.9 (40%) min at Ayukawa, and of 33±1 (30%) and 18±1 (67%) min at Tosashimizu. Exceptional cases are 83 min (1960 Chile), 26 min (1968 Tokachi-oki) and 14 min (1933 Sanriku) for Ayukawa, and 27 min (1958 Iturup) for Tosashimizu. The appearance rates are shown in Figure 4 as functions of frequency because of emphasis of the periodic appearance. At Ayukawa 0.83 mHz (20 min) and 2.1 mHz (8.1 min) are first and forth higher modes of 0.39 mHz (43 min). A relation between the most predominant period after the elimination and the source location is illustrated in Figure 5 for Ayukawa and Tosashimizu. In the figures the most

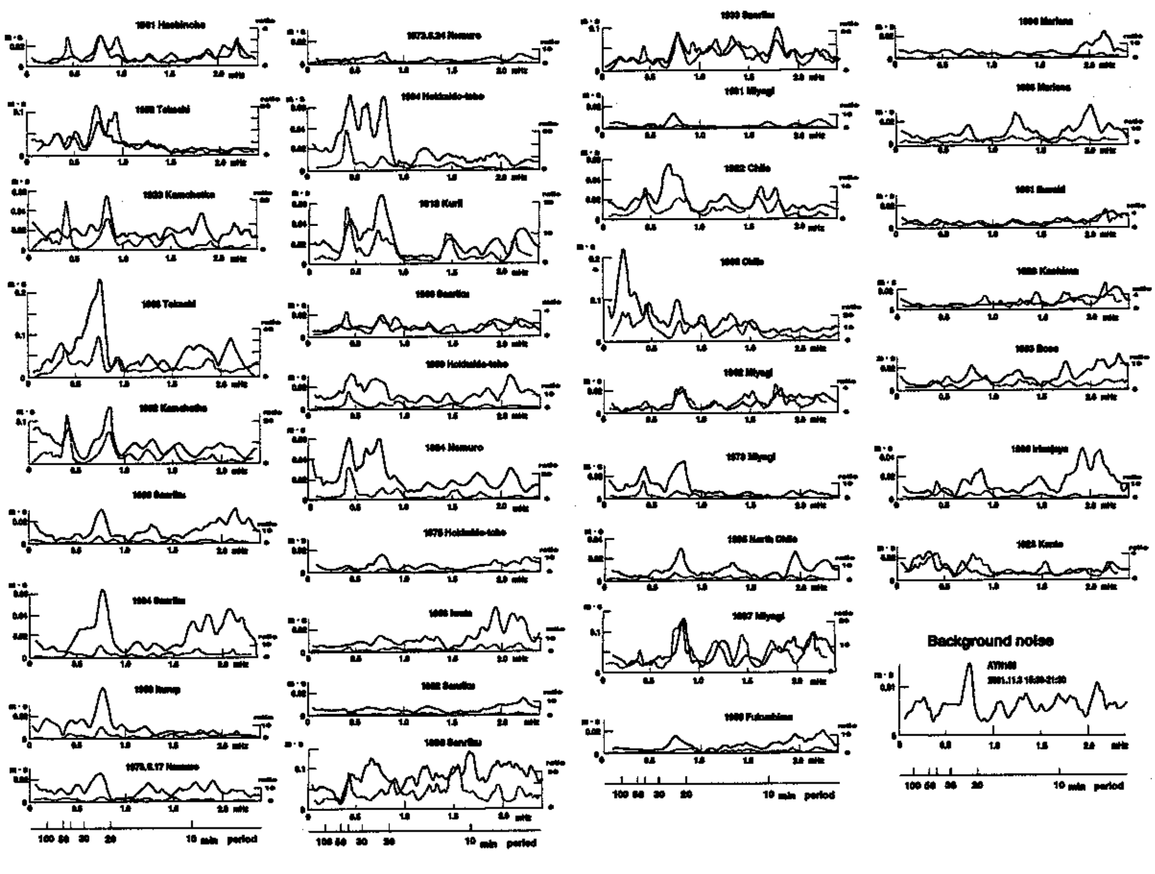

Figure 2. Raw amplitude spectra obtained for Ayukawa tide station and are shown in order of azimuth angle from left top to right bottom. The last one is a spectrum of background noise as used for the noise elimination.

predominant period is plotted using a circle of shade on an epicenter as the source and the earthquake magnitude is classified with the size. From the figure it is remarked that the sources are localized as for predominant periods. The magnitude dependence is not definite. The azimuth dependence is shown in Figure 6. In the figure directions of peninsula including the tide stations and those of channels connecting the stations to open sea are indicated. The direction of peninsula at Ayukawa is taken as the direction of a straight line connecting an east top of the peninsula and a south tip of the Kinkazan Island. It is commonly observed that the most predominant periods critically change at directions of the peninsula and decrease in directions of the open channels. It is shown that the most predominant periods are affected by azimuth angle of the source. But it should be interpreted to be caused by the incident angle of tsunami to the tide station. The azimuth angle of source coincides to that of coming direction of the tsunami

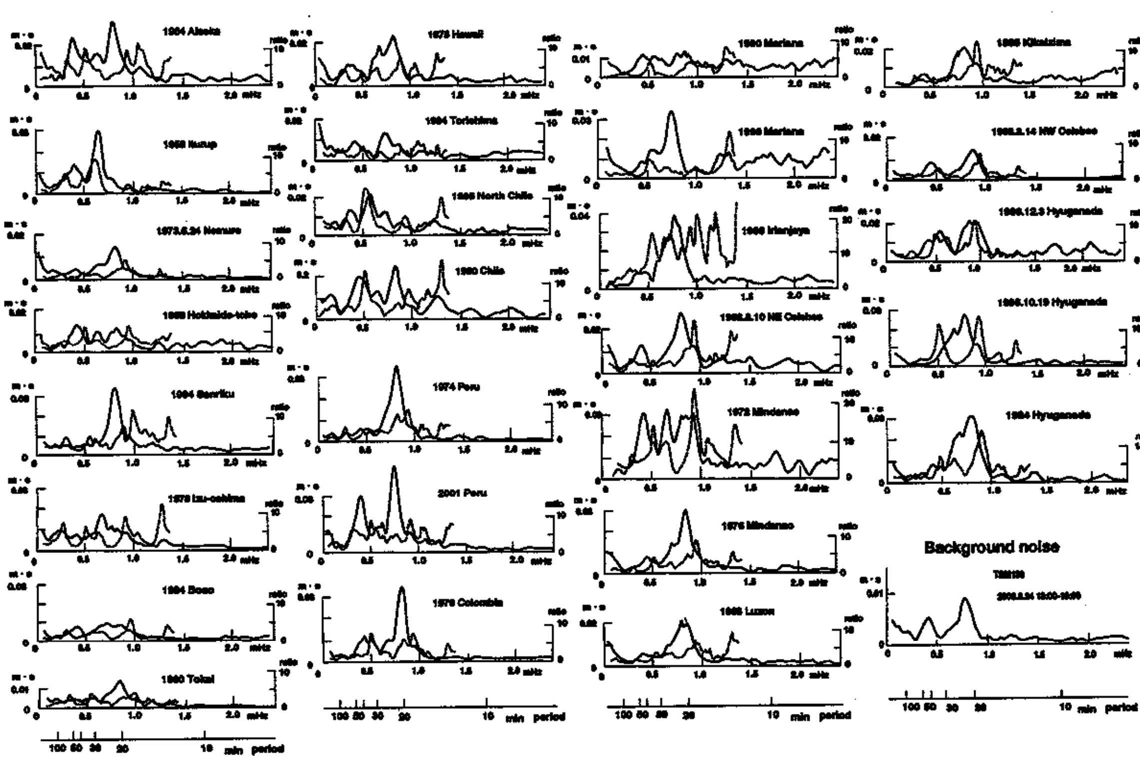

Figure 3. The same as Figure 2 for Tosashimizu tide station.

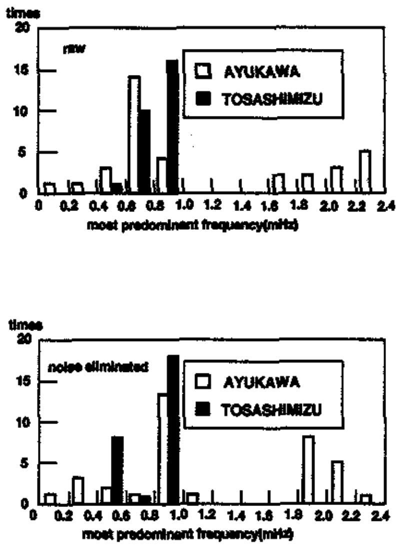

Figure 4. Frequency of appearance of the most predominant frequency in the raw spectra (top) and background-noise eliminated spectra (bottom) for Ayukawa and Tosashimizu, respectively.

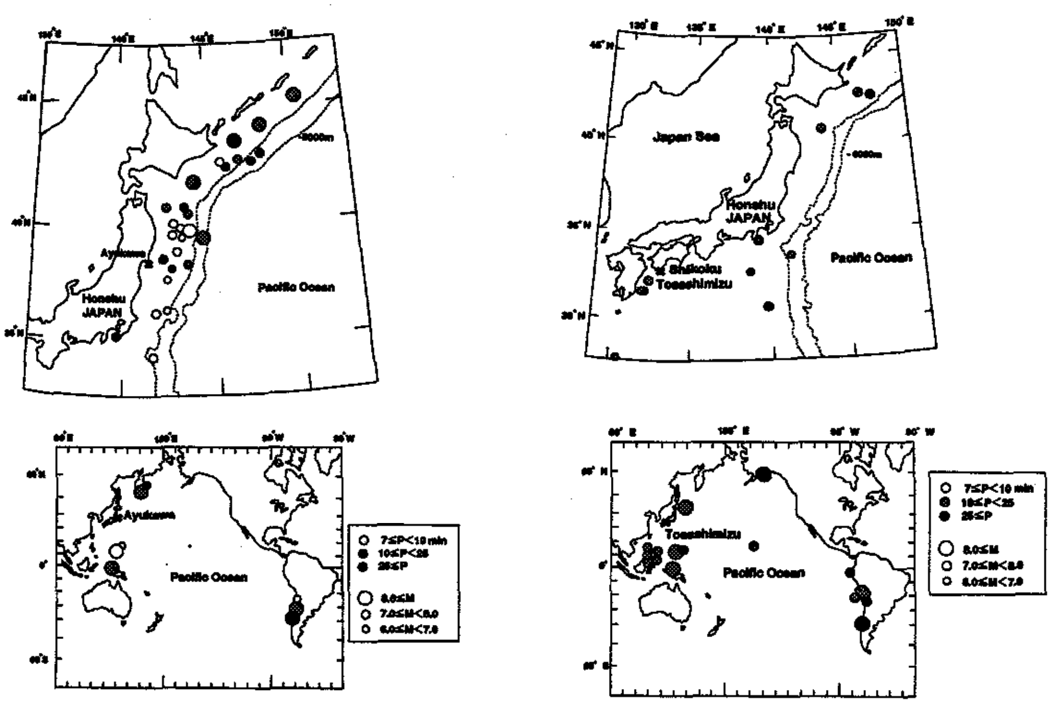

Figure 5. Most predominant periods in the background-noise eliminated spectra at Ayukawa (Left) and Tosashimizu (right), which are plotted at epicenters as the sources. It is classified with the period P and the earthquake magnitude M as shown in the corners.

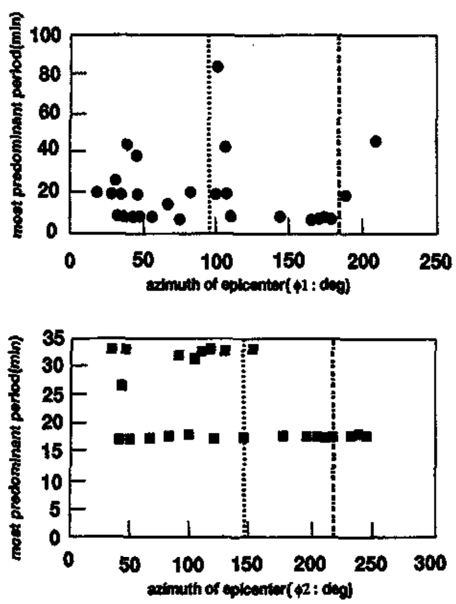

Figure 6. Azimuth angle dependence of the most predominant period in the noise-eliminated spectra at Ayukawa (top) and Tosashimizu (bottom). The azimuth angle of the epicenter is defined in Figure 1. Dotted and chain lines in the figure correspond with extension directions of peninsula and water channel to the tide station.

in a sea of constant depth. Slopes of the shelf cause a displacement from the coincidence.

AMPLITUDE OF PREDOMINANT PERIOD COMPONENTS

Some typical examples of the noise-eliminated spectra are shown in Figure 7. In the figure it is indicated that spectral peaks are common to all the tsunamis at each tide station. Periods of 42, 20, 15 and 8.6 min are identified as the common predominant periods for Ayukawa. On the other hand periods of 56, 33 and 18 min for Tosashimizu. Some of them correspond with the most predominant periods of the noise eliminated spectra. The predominant periods correspond to troughs of the background spectra and the amplitude is proportional to amplitude of the raw spectra. At Ayukawa the longest period component in the four predominant periods is predominant at the north tsunami and the shortest one is relatively predominant at the southeast tsunami. At Tosashimizu the shortest predominant period of 18 min predominates for south sources. A peak of 33 min is not observed in the 1995 Kikaizima tsunami and a peak of 18 min is notable in

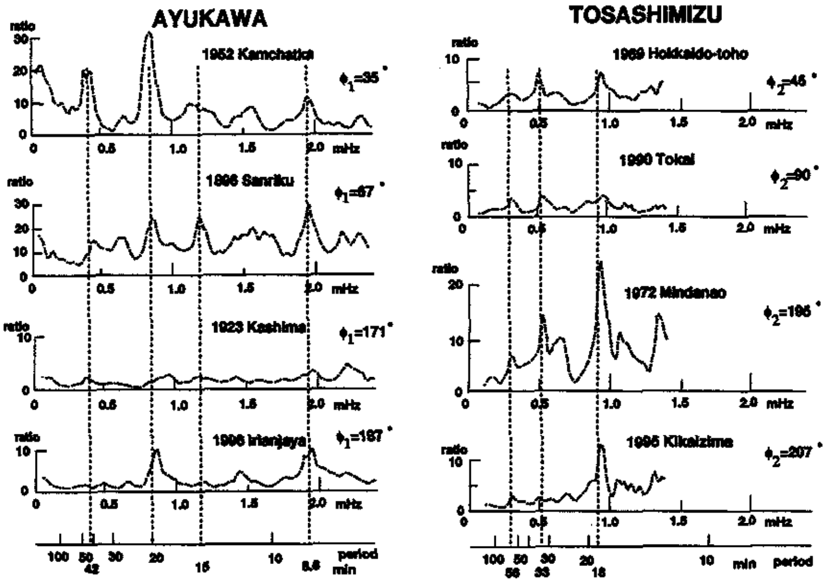

Figure 7. Some typical examples of the background-noise eliminated spectra for Ayukawa (left) and Tosashimizu (right). Dotted lines indicate predominant periods commonly observed, which are calculated as averages of the assumed groups for all the tsunami

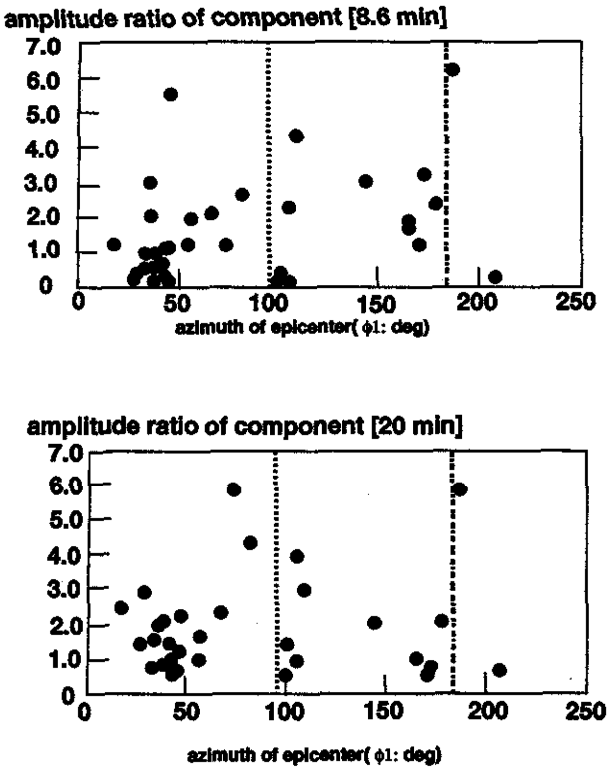

Figure 8. Amplitude ratio of spectral component of 8.6 min to one of 42 min (top) and another one of 20 min to one of 42 min (bottom) of Ayukawa. The same for dotted and chains lines as Figure 7.

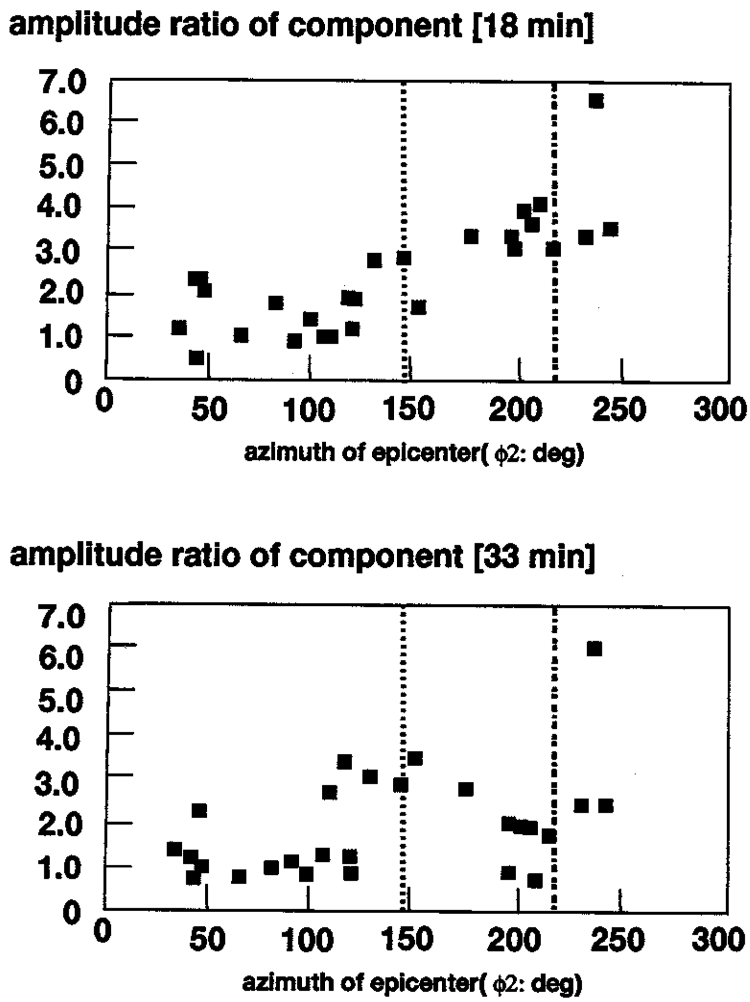

Figure 9. Amplitude ratio of spectral component of 18 min to one of 56 min (top) and another one of 33 min to one of 56 min (bottom) of Tosashimizu. The same for dotted and chains lines as Figure 7.

the 1972 Mindanao tsunami. In the next step we take relative amplitude of the predominant periods to that of the longest one to cancel the effect of earthquake magnitude. In this operation we assumed that a magnitude dependence of the spectral amplitude on the period is small. The results are shown in Figure 8 for Ayukawa and in Figure 9 for Tosashimizu. In the figures directions of peninsula and channels are also indicated as shown in Figure 6. It is approximately mentioned that the shortest period components, 8.6 min for Ayukawa and 18 min for Tosashimizu, are most amplified at approximate directions of the channels. It is suggested that peninsulas prevent the second longest ones to propagate from northeast directions in both the cases. This facts indicate that the observed tsunami have its azimuth dependence in the propagation.

NUMERICAL MODELS

Frequency (period) dependence of the amplification was studied with a finite element method. As the results the applied area, frequency dependence of the spectral amplitude at the tide stations and space distributions of the amplitude for some predominant frequencies are shown in Figure 10 for Ayukawa and in Figure 11 for Tosashimizu. In the applied area the tide stations and the shelves are included. Artificial boundaries are

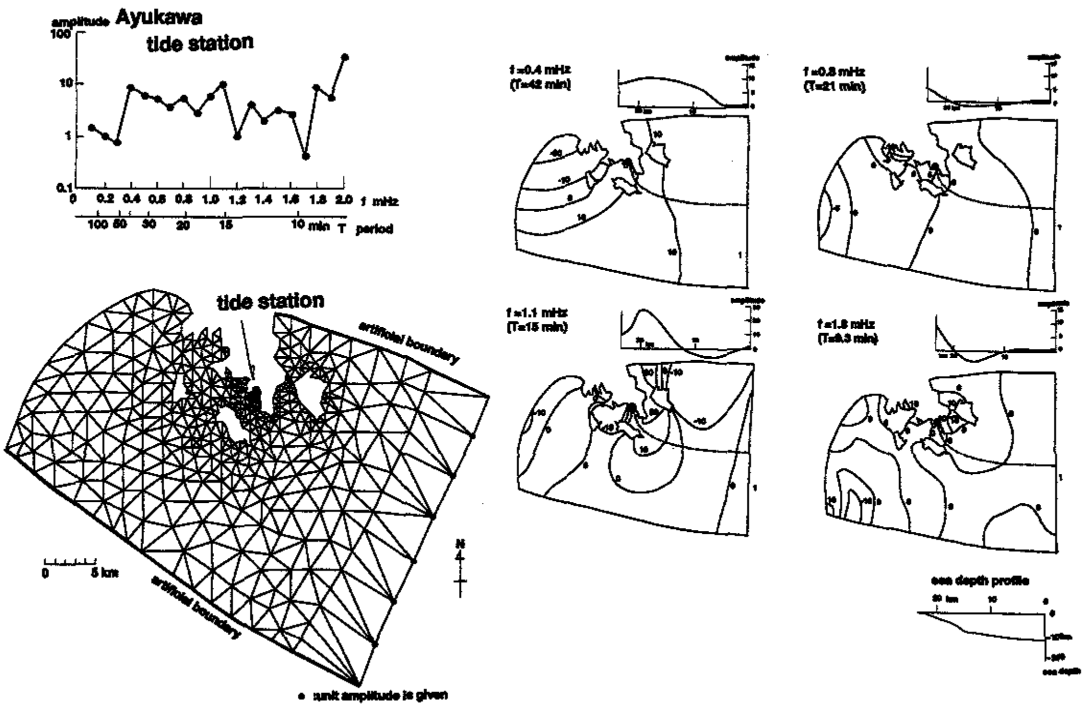

Figure 10. Finite element model for Ayukawa (left bottom) and the frequency response calculated at the tide station (left top). Space distribution of amplitude for the some predominant frequencies and the profiles along an assumed propagation path shown in a chain line (right side). The sea depth profile is also shown in the corner.

taken normal to general trends of the coastlines and distant from tide stations. The unit amplitude is given at boundaries of outer sea normal to the artificial boundaries. The frequency responses are plotted with logarithmic scale. Friction at sea bottom and finiteness of wave train are not considered in the results. From the frequency responses predominant frequencies of 0.4 mHz (42 min), 0.8 mHz (21 min), 1.1 mHz (15 min), 1.8 mHz (9.3 min) and 2.0 mHz (8.3 min) are identified for Ayukawa, 0.3 mHz (56

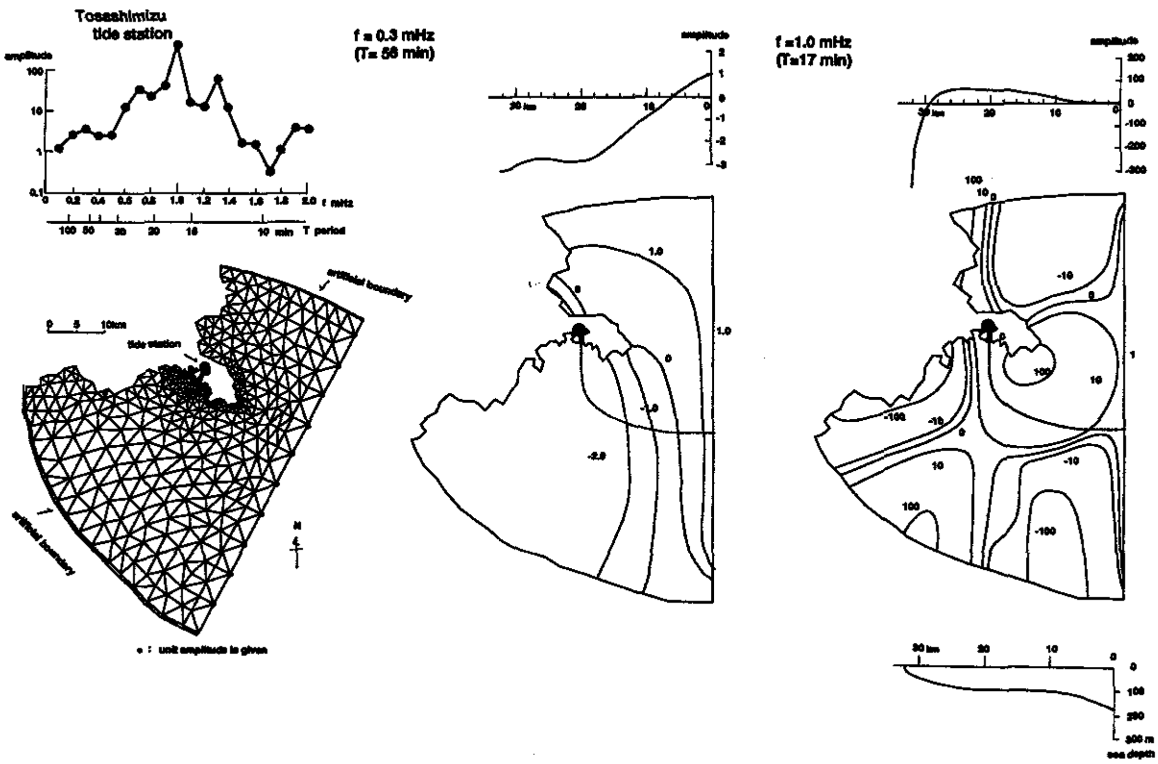

Figure 11. Finite element model for Tosashimizu. Other comments are same as those in Figure 10.

min), 0.7 mHz (24 min) and 1.0 mHz (17 min) for Tosashimizu. From the observations without noises predominant periods of 42, 20, 15 and 8.6 min were obtained for Ayukawa, and 56, 33 and 18 min for Tosashimizu. Except one case of 33 min in observation at Tosashimizu we can find coincidences of the predominant periods within error of 1 min in the numerical model. The coincidences prove that the observed predominant periods without noises are those of resonant oscillation in the shelf regions to sinusoidal incidences. Tsunami, generated out of the shelf, arrived at the shelf and was observed at tide station as multiple oscillations on the shelf. But intensity of the amplification depends on azimuth angles of the epicenters. This fact is interpreted as azimuth dependence of amplitude at the entrance of the tide stations. The azimuth angles should be interpreted as incident angle to the station. The azimuth angle of the epicenters is a first approximation of the incident angle.

DISCUSSION

In the raw spectra of tsunamis observed at Ayukawa the most predominant period of 22±3 min occupied 51 % of those of all the tsunamis. The period of 22 min reconfirms the predominant period of 20-22 min obtained from the spectral analysis of some tsunamis by Takahashi and Aida (1963). The result agrees the predominant periods of 6-10 and 22 min obtained from secondary undulations with atmospheric and seismic origins by Nakano and Unoki (1962). As for the background noise observed at Ayukawa and used for the noise elimination the most predominant period was 23 min and coincides with the tsunami predominant period of 22 min within an error estimated from the resolution. This fact is a proof of reproducibility of the background noise. But the background noise has a probabilistic property and is not defined as a unique solution. Accordingly the selection is accompanied with a probabilistic error. Taking into account of this fact we compromise the selection. This problem is maintained in the interpretation of the noise eliminated spectra.

In the raw spectra of tsunamis observed at Tosashimizu the most predominant period of 21±5 min occupied 96 % to those of all the tsunamis. The period of 21 min coincides with one of 21 and 39-40 min obtained by Takahashi and Aida (1963). It is within 20-24 min obtained by Nakano and Unoki (1962). Moreover the most predominant period of the background noise was 21 min and was equal to that derived from many tsunamis. The selection for the background noise is also agreed.

As for the secondary undulations of bays Honda et al. (1908) calculated the periods, which are interpreted as the resonance periods. They were 8.9 and 22.8 min for Ayukawa and Tosashimizu, respectively. In our result the predominant period of 8±3 min at Ayukawa occupied 31 % of those of all the tsunamis. It is considered that this value corresponds with the resonance period of 8.9 min obtained by them. The period component of 8.6 min was predominant in the noise-eliminated spectra for tsunamis of south origin. It is shown that these tsunamis contributed to an excitation of natural oscillation of the bay. It is interesting in the raw spectra that an excitation of the natural oscillation of 8 min occupies a small rate in comparison with an excitation of 22 min in the most predominant period. The main reason is in less tsunamis of south origin in comparison with northeast tsunamis. But it is possibly explained from relative location between the bay and Azishima Island. The latter is located in front of the former and the former receives tsunami from outer sea through a narrow channel at east of the latter. The narrow channel makes the excitation difficult because of a small chance to a normal incidence to the bay. The normal incidence has an advantage of excitation of the natural oscillation (Nakamura and Watanabe, 1961).

The space distribution of the most predominant period in the noise-eliminated spectra at Ayukawa (Figure 5) shows a group of predominant period shorter than 10 min existing at northeast of the tide station. One of possible explanations is trapping and leaking of the short period component by the Kinkazan Island. It is known that there is a focusing effect of island to tsunami (e.g. Abe, 1996a,b). The effect is explained with a refraction of tsunami around the shallow slope. In this case the trapping is explained from a kind of resonance of tsunami to the trapped wave around the island. In a rough approximation the Kinkazan Island is a circular island of 4 km in diameter and has a shallow sea of 50 m in depth around it. At that time the natural period, wavelength (circumference of the circle) divided by long wave velocity at the shallow sea, is about 9 min, which is almost equal to smallest one of the predominant periods. The wave trapped at the island was radiated to the energy toward direction opposite the sources. The frequent receiving at Ayukawa is attributed to the frequent radiation of wave. This mechanism is effective for some limited region in the sources.

As for the derivation of source mechanism of tsunami using a spectral superposition (e.g. Rabinovich, 1997) we only emphasize an importance of propagation effect in this stage. The fact that the same predominant period is observed at a limited region of the sources leads us to consider the propagation effect as a relative location between source and observation point instead of the generation effect.

CONCLUSION

We conducted spectral analysis of 35 and 27 Pacific tsunamis observed at Ayukawa and Tosashimizu, respectively. The most predominant periods obtained were 22 ± 3(51 %), 8 ± 3(31 %) for Ayukawa and 21 ± 5(96 %) for Tosashimizu. We eliminated the background noises from the raw spectra using spectra of time histories recently observed in quiet-sea conditions. As the result the most predominant periods of the tsunamis dispersed into 2-3 groups. It is shown that these periods were localized in the space distribution of the epicenters and depended on the azimuth angle. Period component of periods, 42, 20 and 8.6 min for Ayukawa and 56, 33 and 18 min for Tosashimizu, predominated. In the azimuth angle dependence it is observed that the shortest ones were much amplified in the azimuth angles same as those of bay axes and second shortest ones were prevented from propagating by peninsulas. Thus selective amplifications of tsunamis are verified for tsunamis which were observed in bays. It is suggested that the Kinkazan Island contributed the period component of 8.6 min to the propagation to Ayukawa. Noise-elimination of tsunamis observed in bays clarified a selective amplification to the incident angle. The azimuth angle dependence leads us to conclude that propagation effect is important in an analysis of tsunami.

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REFERENCES

Abe, K. (1986): An explanation of characteristic distribution of the tsunami maximum inundation heights observed at the small islands, Sci.Tsunami Hazards, 4,153-164.

Abe, K. (1990): Spectral characteristics of the 1983 Japan Sea Tsunami observed in Japan, Tohoku Geophysical Journ.33, 97-106.

Abe, K. (1993): Tsunami spectra as a synthesis of source spectrum and shelf response, Proceed.IUGG/IOC International Tsunami Sympo.,151-163.

Abe, K. (1996a): Focusing effect of islands on a tsunami, Part 1. A case of the 1993 Hokkaido Nansei-oki earthquake tsunami (in Japanese), Zisin, 2,49,1-9.

Abe, K. (1996b): Focusing effect of islands on a tsunami, Part 2. A case of the 1983 Nihonkai-chubu earthquake tsunami (in Japanese), Zisin, 2,49,11-17.

Abe, K. (2000): Predominance of long periods in large Pacific Tsunamis, Sci.Tsunami Hazards, 18,15-34.

Aida, I. (1982): Role of seiche in tsúnamis (in Japanese): Marine Sci. Monthly, Kaiyo Publishing, KK, 149,419-427.

Honda, K., T.Terada, Y, Yoshida and D.Isitani (1908): An investigation on the secondary undulations of oceanic tides, Jour.Coll.Sci.Imp.Univ.Tokyo, 24,1-113.

Ichie, T. (1956): On the secondary undulations caused by the typhoon "5415"(Ⅱ). Oceanogr.Mag.8, 107-122.

Miller, G.R. (1972): Relative spectra of tsunami, Hawaii Inst. Geophys. Univ. Hawaii, 72,1-6.

Nakamura, K. and H.Watanabe (1961): Tsunami forerunner observed in case of the Chile Tsunami of 1960, Report on the Chilean Tsunami, edited by Field Investigation Committee for the Chilean Tsunami, 82-99.

Nakano, M. and S.Unoki (1962): On the seiches (the secondary undulations of tides) along the coasts of Japan, Records of Oceanographic Works in Japan, Special Number 6, 169-214.

Omori, F. (1901): On tsunamis around Japan (in Japanese), Rep. Imp.Earthquake Comm., 34,5-79.

Rabinovich, A.B. (1997): Spectral analysis of tsunami waves: Separation and topography effects.J.Geophys.Res. 102,C6, 12663-12676.

Takahashi, R. and I.Aida (1963): Spectra of several tsunamis observed on the coast of Japan (in Japanese), Bull.Earthq.Res.Inst.Univ. Tokyo, 41,299-314.

Yamashita,T. and R.Sato (1974): Generation of tsunami by a fault model, J.Phys.Earth,22,415-440.