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TSUNAMIS AND TSUNAMI-LIKE WAVES OF THE EASTERN UNITED STATES

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ABSTRACT

The threat of tsunamis and tsunami-like waves hitting the eastern United States is very real despite a general impression to the contrary. We have cataloged 40 tsunamis and tsunami-like waves that have occurred in the eastern United States since 1600. Tsunamis were generated from such events as the 1755 Queen Anne's earthquake, the Grand Banks event of 1929, the Charleston earthquake of 1886, and the New Madrid earthquakes of 1811-1812. The Queen Anne tsunami was observed as far away as St. Martin in the West Indies and is the only known teletsunami generated in this source region.

Since subduction zones are absent around most of the Atlantic basin, tsunamis and tsunami-like waves along the United States East Coast are not generated from this traditional source, but appear, in most cases to be the result of slumping or landsliding associated with local earthquakes or with wave action associated with strong storms. Other sources of tsunamis and tsunami-like waves along the eastern seaboard have recently come to light including volcanic debris falls or catastrophic failure of volcanic slopes; explosive decompression of underwater methane deposits or oceanic meteor splashdowns. These sources are considered as well.

BACKGROUND INFORMATION

Notable Historical Events

Traditionally the East Coast of the United States has been thought of as an area that has been almost entirely free of tsunamis. Unlike the Pacific Ocean, the Atlantic Ocean is not surrounded by marked subduction zones where earthquakes with a relatively large vertical offsets are likely to occur. Classic thought about tsunamis has considered such subduction zone earthquakes to be the major generators of large tsunamis. However, in the last five years this idea has begun to change world-wide. For example, in 1998 a Mw 7.1 earthquake occurred in Papua New Guinea that generated a 15-meter tsunami. This tsunami resulted in about 2,200 deaths. This was a surprisingly large tsunami to have resulted from the Mw 7.1 magnitude earthquake. It was later determined that this tsunami was only indirectly related to the earthquake. An offshore earthquake- triggered landslide had generated this locally very-large tsunami.

One of the most notable earthquakes on the East Coast of North America occurred off the Burin Peninsula of Newfoundland in November 1929 caused much property damage and 29 deaths along the coast of Newfoundland. This 7.2 Ms earthquake caused a turbidity current that cut twelve transatlantic telegraph cables. It generated a local tsunami (perhaps a landslide-tsunami) that was recorded at Atlantic City, New Jersey, and Charleston, South Carolina, and possibly other places on the East Coast. The tsunami was recorded on tide gauges as far afield as the Azores and the coast of Portugal. The three to seven meter waves resulted in 29 deaths, but none of these fatalities were in the United States. (Ruffman, 1989)

The most destructive tsunami ever reported in the Atlantic Ocean was generated off the coast of Portugal on November 1, 1755. In addition to the local tsunami damage in Portugal, damage was reported at Funchal, Madeira Islands; Cadiz, Spain; Safi, Morocco; Praia da Vitoria, Azore Islands; Durham, England; and as far distant as La Martinique in the West Indies, and Santiago, Cuba. Modeling done by Mader (1997) has given us an appreciation of what may have happened on the United States East Coast in that event. Tsunami waves of three meters may have affected portions of the southeast coast of the United States in that event.

A number of smaller earthquakes (some of which were accompanied with cable breaks) have occurred in the Atlantic Ocean. De Smitt (1932) includes a list of 33 earthquakes most of which occurred in the Mid Atlantic Ridge area between 1755 and 1929. This table also includes a list of cable breaks that occurred during the same period. Although most of the cable breaks were not associated with earthquakes, the cable breaks show that slumping and landsliding is a frequent occurrence on the continental slope and shelf. Any of these events could have resulted in a tsunami.

Methane and Pressurized Water Deposits

Recent discoveries along the East Coast of the United States' continental slope have demonstrated the existence of pressurized hydrates and pressurized water layers in the continental shelf, and have produced speculation on possible triggers that could cause sudden and perhaps violent releases of this compressed material, along with the resultant landslides and tsunamis.

Two off-shore areas are under close investigation. Enormous cracks northeast of Cape Hatteras could be an underwater landslide in the making. This area off the coast of North Carolina and Virginia along with a second area of mysterious submarine canyons about 150 kilometers east of Atlantic City, New Jersey, have been areas of intense scrutiny. (Driscoll et al., 2000, Flemings and Dugan, 2000)

It has been suggested that large scale submarine slope failure is possible along the East Coast of the United States' continental slope. "The outer continental shelf off southern Virginia and North Carolina might be in the initial stages of large-scale slope failure. A system of en echelon cracks, resembling small offset normal faults, has been discovered along the outer shelf edge. Swath bathymetric data indicate that about 50m of down-to-the-east (basinward) normal slip has occurred on these features." (Driscoll et al., 2000). Further investigation has shown that the cracks are in areas of large deposits of methane hydrate and pressurized water. The sudden release of the water or methane may have produced the cracks and slope failures.

One possible cause for the sudden release of hydrates would be a quick warming of the waters. Another might be the sudden lowering of pressure with the passage of a hurricane. Should the passage of a hurricane trigger the release of methane hydrates and cause offshore landslides, the ‘Hurricane Wave’ would clearly be a tsunami.

A tsunami scenario, is suggested by Driscoll et al. (2000) for the nearby coastal zone based on the estimated volume and nature of the potential slide. Although maximum tsunami height of a few to several meters is predicted, the actual extent of flooding would depend on the tidal state at the time of tsunami arrival as well as the details of the hinterland topography. The low-lying coasts of Virginia-North Carolina and the lower Chesapeake Bay would be most as risk, since these area are close by. (Driscoll et al. 2000.)

Landslides from Volcanic Islands

The discovery of massive amounts of rock debris around the Hawaiian Islands that probably resulted from gradual or rapid collapses of portions of these islands, has stimulated the search for similar landslide activity around other volcanic islands. One of these island groups is the Canary Islands, located in the eastern Atlantic, an area that could give rise to tsunamis that might affect the east coast of the United States. Evidence for collapses on the Canary Islands includes a large amphitheater on the western island of La Palma. Other amphitheaters--possible collapse sites–are found throughout the islands. Ocean floor imagery northwest of El Golfo (island of El Hierro) shows a huge landslide (100 km^3) extending 80 km from the island that contains blocks as much as 1 km across. Further south a much younger volcano appears ready to collapse at any time. (McGuire, 1999)

Collapses in the Canary Islands apparently occur when the flanks of the volcanoes become too steep to support themselves and slide into the sea. This mechanism for producing landslides in the Canary Islands differs from that which probably occurs in Hawaii. In the Canary Islands the rock probably falls as a coherent blocks. In Hawaii, the rock may break up and enter the ocean in the form of a disaggregated mass. (McGuire, 1999) A solid block of rock is more efficient in generating a large tsunami. These tsunamis would probably be directed toward the United States East Coast.

There is evidence that large tsunamis have been generated by these Canary Island landslides. For example, on the Bahamian Island of Eleuthera, boulders of coral limestone “as big as houses and weighing thousands of tons” have been deposited 20 m above sea-level and as much as 500 m inland. On the other end of the Bahamas archipelago are large sand wedges several kilometers long and up to 25 m high–probably also formed by large waves in the area. The estimated ages of these features in the Bahamas seem to match the collapse at El Gulfo on the island of El Hierro in the Canary Islands. (McGuire, 1999) Tsunamis capable of leaving such artifacts in the Bahamas would doubtless cause much devastation in the Caribbean and also along the East Coast of the United States.

Bolide Impact Tsunamis

Perhaps the least likely source of tsunamis has the potential for causing the greatest tsunami: that of a meteor or comet impact. While many previously scoffed at the idea of an extra-terrestrial object hitting the earth, that has recently changed. Models have recently shown that an asteroid hitting the ocean can cause a large tsunami that would inflict catastrophic damage to coastal cities even at great distances.

An ocean impact is more likely than an impact on land since the Earth is seventy percent covered with water. At the same time human populations and assets are largely concentrated in coastal cities that were established historically from shipping, and trade near ports. Searches for large tsunamis in the geological record have begun in the coastal areas of the Atlantic in the 1990's. Because large earthquake-induced tsunamis are rare in the Atlantic is likely that many of those detected in the geologic record would probably be due to bolide collision.

Currently estimates are that an asteroid-induced tsunami exceeding 100 meters in height along the entire Atlantic coast line probably occurs once every few thousand years, which slightly exceeds written history in most of these ocean coastal regions. Modeling shows that a 100 meter tsunami would travel inland about 22 km (14 miles) and a 200 meter tsunami would travel inland about 55 km (34 miles) Such a tsunami would cause unprecedented damage to now-developed low lying areas all along the United States East Coast, and may totally submerge vast areas in Europe such as in Holland and Denmark.

There is evidence that at least one such an impact occurred in an Atlantic Ocean coastal area about 35 million years ago. A crater at Chesapeake Bay, Virginia, was caused by an asteroid or comet traveling at about 70,000 miles (113,000 kilometers) an hour, that splashed through several hundred feet of water and several thousand feet of mud and sediment. It is thought that billions of tons of ocean water were propelled into the air as high as 30 miles and vaporized. Millions of tons of debris and rocks were also ejected into the atmosphere.

The incident probably incinerated everything along the East Coast, triggered gigantic tsunamis affecting coastal areas on both sides of the Atlantic, and decimated marine life in the surrounding areas. Although remote, the potential is there for a tsunami of gigantic proportions along the Atlantic coastline from a bolide impact. wysiwyg://26/http://news.national geograp.m/news/2001/11/1113_chesapeakcrater.html
http://www.atlantisrising.com/issue6/ar6comets.shtml, http://www.permanent.com/a-impact.htm

This research suggests tsunamis may be generated in ways previously undefined in the literature. The historical record shows that tsunamis and tsunami-like events have occurred in this area. What follows is description of these events. The major locations affected by these waves are shown in Figure 1.

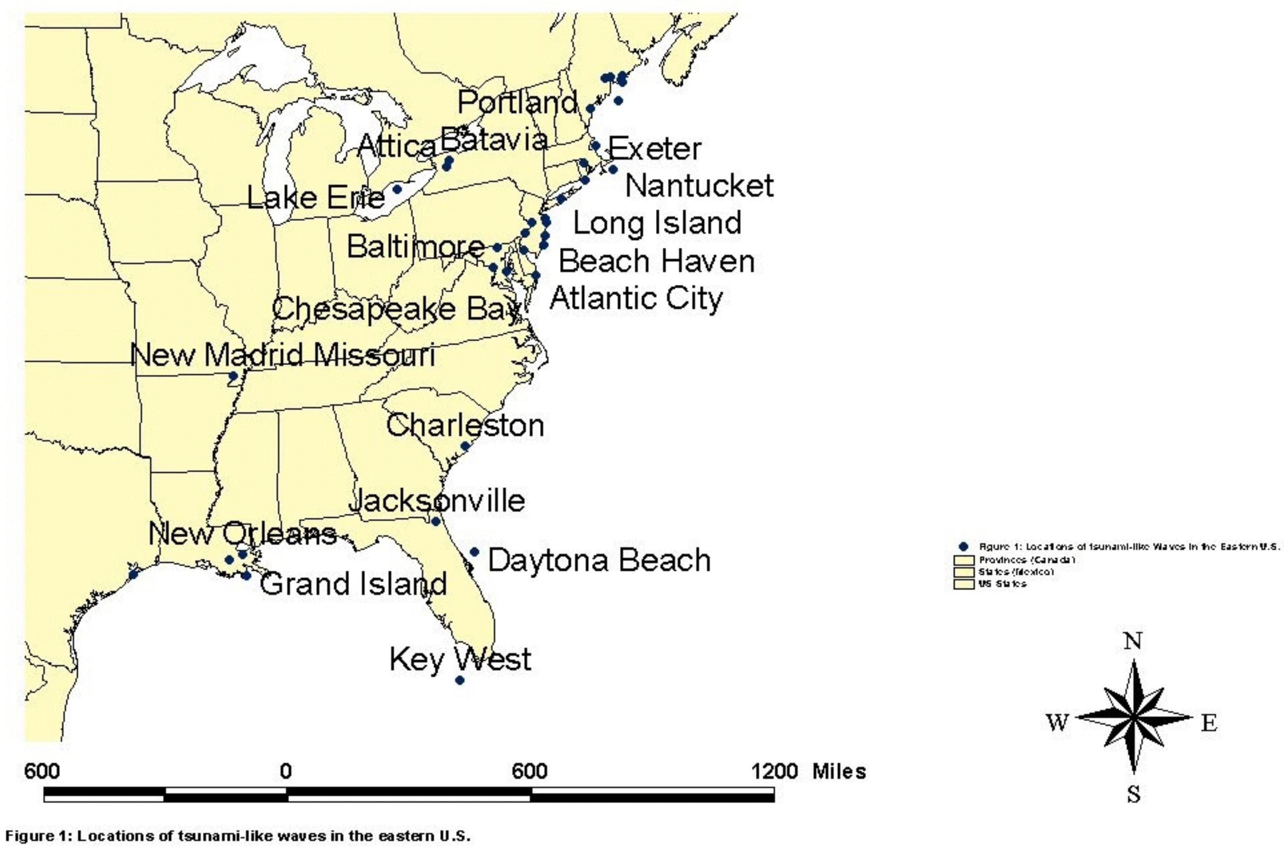

Figure 1. Locations of tsunami-like waves in the eastern United States.

DESCRIPTION OF TSUNAMI EVENTS

1668, April 13, 9:00**.** An earthquake of intensity IV occurred in the Boston and Salem, Massachusetts area. A river was reportedly swallowed up and Indians say that the river course was altered. (Winkler, 1978) Validity 1.

1755, October 4? In Lake Ontario between 10:00 and 11:00 A.M. the water repeatedly rose in an unusual way to the height of five feet. No shock is mentioned. (Dawson, 1860; Mallet, 1851) Validity 2.

1755, November 1, 09:50. A great Ms 8.0 earthquake occurred off Portugal's coast. Charles Mader's computer modeling suggests that the east coast of the U.S. was probably affected by 3-m (ten-foot) waves. The harbor drained at Cape Bonavista, Newfoundland. After ten minutes the water returned, overflowing parts of the community. This earthquake also generated a 7m tsunami that was measured at Saba, Netherlands Antiles. At St. Martin, the runup was 4.5 m. At Martinique, the water was reported to have withdrawn 1.6 km and returned to inundate the upper floors of houses. Since tsunami effects were measured in Newfoundland and in the Caribbean, it is highly likely that the east coast of the United States was also affected by the tsunami. (Mader, 1997; Berninghausen, 1968) Validity 3.

1755, November l8, 09:12. A ml 7.0 earthquake at 4:11 A.M. threw down chimneys and walls in Boston. Gabled ends of buildings collapsed, and stone walls were shaken down. *United States Earthquake History* notes that a sea quake was experienced by a ship located near the epicenter east of Cape Ann, Massachusetts. The shock was felt over a 300,000-square-mile (777,000 km^2) area from the Chesapeake Bay to Nova Scotia. Aftershocks continued for more than a month. (Coffman et al. 1982)

The earthquake was reported to have produced a noticeable sea wave. Reportedly "On the day of the first shock, nine hours after it was felt at Cambridge, or about two o'clock in the afternoon, the sea withdrew from the harbor of St. Martin's in the West Indies, leaving vessels dry, and fish on the banks where the depth of water was usually three or four fathoms. ... If the 'tidal wave' at the West Indies' [is] a result as well as a consequence of this New England shock, we shall have a line nearly nineteen hundred miles long." (This may be the only teletsunami generated by an earthquake on the western shores of the Atlantic off the United States East Coast.) (Berninghausen, 1968; Brigham, 1871; Rothman, 1968) Validity 1.

1811, December 16 08:15; **1812, January 16** 08:15; **1812, February 7** 09:45. The New Madrid earthquakes generated several waves in the rivers. "At first the Mississippi seemed to recede from its banks, its waters gathered up like mountains, leaving boats high upon the sands. The waters then moved inward with a front wall 15 to 20 feet (5 - 7 m) perpendicular and tore boats from their moorings and carried them up a creek closely packed for a quarter of a mile. The river fell as rapidly as it had risen and receded within its banks with such violence that it took with it a grove of cotton wood trees. A great many fish were left upon the banks. The river was literally covered with the wrecks of boats." (Fuller, 1912)

"A bursting of the earth just below the village of New Madrid, arrested this mighty stream in its course, and caused a reflux of its waves, by which in a little time a great number of boats were swept by the ascending current into the mouth of the bayou, carried out and left upon the dry earth, when the accumulating waters of the river had again cleared their current. On the Mississippi great waves were created, which overwhelmed many boats and washed others high upon the shore, the return current breaking off thousands of trees and carrying them out into the river. High banks caved and were precipitated into the river, sand bars and points of islands gave way, and whole islands disappeared. (Fuller, 1912) (See Figure 2, next page.)

Unusual lake water level rises were seen at Lake Bistineau near Texas-Louisiana border. Lake Caddo, in the same area, was probably formed as a result of the earthquake and accompanying subsidence.
(http://www.lakebistineau.com/history/1919article.html, http://www.ops.tamu.edu/x075bb/caddo/caddo.html.)

At Orchard Lake, Michigan, it was reported that on December 17, 1911 "the Indians said the waters of the lake began to boil, bubble, foam and roll about as though they had been in a large kettle over a hot fire, and that in a few minutes up came great numbers of turtles, and hurried to shore, upon which they had a great turtle feast." (Hobbs, 1911; Bricker, 1977) Validity 3.

Figure 2. Rough waves on the Mississippi River, New Madrid, Missouri Earthquakes of Feb. 7, 1812, and aftermath. Jan T. Kozak Collection: Images of Historical Earthquakes, National Information Service for Earthquake Engineering.

1817, January 8. A earthquake in the Philadelphia area caused "the most important disturbance and was sort of a tidal wave, its effects being much more powerful on the water though the houses and churches of the city were rocked." (*Philadelphia Inquirer*) "The river was much agitated by the earthquake on the southward, tossing about vessels, and raising the water one foot." (Pennsylvania Department of Internal Affairs, 1944) Validity 2.

1821, September 3. A hurricane passed over the North Carolina Outer Banks, and over the Delmarva Peninsula (Delaware and Maryland, and entered Cape May County, New Jersey, where it traveled up the present Garden State Parkway. Miles of sandbars were exposed the next morning. A dull roar approached and then a solid mass of wind and rain came tearing great pines from the ground and cutting houses from foundations. A monstrous wall of water struck, carrying away men and horses. One man and his grandson were carried six miles inland. Another family was carried away by the tidal wave. The husband was found the next day hanging by his belt from a tree 6.2-m (twenty feet) from the ground. (Source: http://www.ocmuseum.org/shipwrecks/storms.asp)

This is one of several events that are connected with hurricanes. However, typically a hurricane does not produce a recession first and then a "wall of water." The hurricane may have triggered an off-shore landslide that in turn generated a tsunami. Validity 1.

1823, May 30. There was a slight shock and the water rose nine feet (2.7 meters) in Lake Erie. (Brigham, 1871)

1840, November 14. A severe shock ml 5.2 MMI = VII felt at Philadelphia. A noise was also heard. A large and unusually sudden swell in the Delaware River was observed. (Brigham, 1871; Berninghausen, 1968; Coffman and Stover, 1982; *Philadelphia Inquirer; Burlington Gazette:* Friday November 20, 1840, 2:4) Validity 3.

1871, June 18. Reportedly there was an earthquake induced tsunami that was experienced on Long Island. Also it was said that a storm raged on the 'Sound' during the convulsion on land. There was no meteorological storm on the Sound. "Long Island, in short, appears to have received the full benefit of the tidal wave, and various stories are told of honest citizens frightened almost out of their wits by the strange phenomenon." No earthquake is listed in the historical catalogs for that date. (Information provided by Harry Woodworth, National Weather Service, *New York Times*, June 20, 1871) Validity 3.

1872, November 17. Fluctuations were registered on the tide gages at North Haven and on the Fox Islands in Penobscot Bay, Maine. The fluctuations continued from midnight until nearly 6:00 A.M. at somewhat irregular intervals of about 17 minutes from crest to crest, with an average vertical range of about 23 cm. The largest wave at 3:00 A.M. had a height of 50.8 cm. A moderate earthquake of MMI = V (ml 3.7) was recorded in SE Maine on Nov. 18, 1872, which may have been related. (Berninghausen, 1968) Validity 2.

1879. The following are excerpts from the experiences of a sailing party in 1879 as published in the *New York Times*.

“The party [was composed] of young men who delighted in tough sailing, and as often as possible, sought the turbulent waters where the tides meet on The Rips, off Nantucket (Massachusetts) shores. They planned to sail through the channel between Nantucket and Tuckernuck Islands out into the broad ocean to the south...The current between these islands were usually dangerously strong. Sailing outward, the light breeze on the glorious Saturday afternoon gradually died down as the boat rounded into the channel and the current carried the vessel toward the ocean in a dead calm...”

“Suddenly, the Captain stiffened up into a whirl of action, lashed his helm for a second while he adjusted his sail, and flying back to his post called out in stern excitement, ‘Hold fast,’ causing the young men to jump to their feet to seek the cause of his unwonted commotion. The cause was a vast, huge wave stretching ‘shore to shore’ approaching the vessel. This huge green wave was topped by a white foaming crest, which curled and threw off white froth, and yet did not curl over frontward....”

“The passengers were mesmerized by the marvelously beautiful sight, until the distressed tome of the Captain aroused them. ‘Great God, if only we could get a little breeze it would carry us over before we are swamped. Hold fast! Hold fast! It is a blind breaker!’, shouted the Captain. Then no one spoke during the tense moments, as they stared into the great green wall of water now upon them, which struck with great force, seeming to boil and seethe around them, swaying all to and fro, confusing and blinding them by the spray, which almost took their breath away. It was quickly over, leaving foam-spread, swirling water with here and there a frenzied fish leaping out of the water in search of a clear space for progress...”

“It took three hours and more to make harbor, drifting most of the way. The Captain's mouth remained closed like a clam when the men said good night and spoke fervently of their appreciation in carrying them safely through the peril.” (August 16, 1924, Letter to the Editor of the *New York Times*, by a Mr. Holbrook) There is no record of the wave reaching land and doing damage there. (Information provided by Harry Woodworth, National Weather Service.) There was an earthquake at 41.3N, 72.9W on October 24, 1879, and an aftershock on October 26 at 42.9N, 71.9W. Although these earthquakes are too small to generate a tsunami, they could have disturbed the sediments and caused a landslide tsunami. Validity 1.

1884, August 10. An earthquake (19:07 UT, 40.6N, 74.0W, Ml 5.6) generated a tsunami that was reported from Philadelphia, Trenton, and Highlands, New Jersey. In Philadelphia “The large ships loading petroleum on the Schuykill River snapped their hawers, and were only prevented from going ashore by the united efforts of their crews. Several large steamers were thrown strongly against the wharves in the lower section of the city and the crews thrown out of their bunks. Huge waves backed up by the rising tide, overflowed many of the wharves, and considerable property was flooded thereby. In several instances where persons were watching the river from the docks they found themselves suddenly overtaken by the waves and were thoroughly soaked. Deeply laden steamers lying in the Delaware [River] trembled without apparent injury during the existence of the shock.” (*New York Times,* Monday, August 11, 1884.) Water in the Housatonic River was violently agitated. (Stover and Coffman, 1993)

At Trenton, New Jersey, “the water in the city reservoir was agitated, and a small tidal wave was noticed on the canal and feeder.” (*New York Times,* Monday, August 11, 1884.) At Highlands, New Jersey, “two gentlemen who were out fishing at the Highlands said they experienced a sensation as though the water had all gone out from under their boat and it was grating on the sand. The water boiled about them, and they felt a distinct shock, though not like that which visited the people on shore.” (*New York Times,* Monday, August 11, 1884.)

The *Philadelphia Inquirer* reported that the water in the Delaware River suddenly rose and waves of nearly two meters (five or six feet in height) dashed over the banks immediately after the vibrations were felt. Several boats were upset, and without warning the occupants found themselves floundering in the water. The *Inquirer* also mentions a steamer in New York Harbor that was lifted four times by the waves and set in motion.

The *Mount Holly Herald* reported that Captain Porter noticed that the *Doron* reared up slightly on her keel about the time the shock occurred. This report, along with the other river front towns mentioned suggests that the *Doron* was docked on the Delaware River in Burlington County. The wave was apparently small in this area of the river because the river is relatively straight here. The *Herald* also reported that the waters of Stop-the-Jude Creek were visibly affected.

The report from Philadelphia suggests that the waves were particularly troublesome where the Schuykill River empties into the Delaware River. The report from Trenton confirms this. A small tidal wave was observed on the Delaware River and Raritan Canal and feeder. (This canal extends from the Delaware River north eastward through Trenton and Mercer County connecting with the inland Millstone River.) The Highlands, New Jersey, report suggests the possibility that the tsunami affected the entire mid-Atlantic coast. (Newspaper reports provided by Harry G. Woodworth, National Weather Service, Mount Holly, New Jersey.) Validity 4.

1884, September 19. In the Detroit River a wave or "ground swell" was reported. (Hobbs, 1911) Validity 2.

1886, August 31. There was a tsunami associated with the Charleston earthquake (21:50 UT 32.9 N, 80.0 Mw 7.7 on this date. The *Florida Times Union* gives the following report: "Dr. J. M. Fairlie came up from Mayport (suburb of Jacksonville, Florida) yesterday with his family. The doctor was seated on the front porch of his cottage at the beach at 9 o'clock standard time, Tuesday evening, enjoying the cool southeast breeze. Most of the family had retired to rest. The tide was coming in at the time and the new moon had just disappeared behind a tier of red-tinted western clouds. There was a brief calm on the river; then a sudden wave dashed high over the beach and a rumbling noise was heard, the earth and houses shook like the leaves on the trees. The inmates of the cottage were aroused, saying their beds were shaking..." (*Florida Times Union*, Jacksonville, Florida, Sept. 2, 1886.)

Martin gives the following account: "The silence ended just before 9:00 P.M. when a tidal wave smashed along the Jacksonville [Florida] beaches and thrust itself up the St. Johns [River] past Mayport. Jacksonville literally began to shake. People already asleep woke up holding fast to beds that seemed to be rocking like boats in the wake of a large ship. Pictures on walls slipped to crazy angles. Gas lights hanging from ceilings began to swing and sway. Lightning-like cracks jabbed their way across plaster walls. Houses tipped on their foundations. Dishes rattled, jumped from tables and shelves and shattered on floors. What was described variously as a moan, an unearthly wail, a thundering and a threatening rumble, groaned through the city, torturing it out of shape for seconds that seemed like minutes or hours. Jacksonville was in the grip of the worst earthquake in its history...Before long, the middle of Bay Street was crowded with excited people, among them sailors who dashed ashore as their vessels rocked and heaved on violent waves that whipped against the shore." (Martin, 1972) The Charleston earthquake may itself have been tsunamigenic or this event may be related to a local sub-marine landslide caused by the earthquake. (Information provided by Harry G. Woodworth, National Weather Service, Mount Holly, New Jersey.) There was a wave of some height on the Copper River in South Carolina. (Dombroski, 1973) Validity 4.

1895, September 1 (6:09 A.M. local time, 11:09 UT, 40.7N 74.8W). At Arverne-by-the-Sea an early morning earthquake awoke a few guests. (Arverne-by-the-Sea is the part of Long Island on the spit of land south of Jamaica Bay.) The surf seemed to subside for a minute or so and the waters became smooth. "A few seconds later they were gathered up in a monstrous wave *which swept oceanward*.." "Subsided" could have referred to the activity of the surf as it became more quiet or to a slight recession of the sea. The report gives the impression that the monstrous wave formed at the shoreline and went out. The recession could have been more dramatic and noticeable than the more gradual influx of the sea that preceded it. Or the wave trough could have arrived first. (Information provided by Harry G. Woodworth, National Weather Service, Mount Holly, New Jersey.) (*New York Times*, Mon. Sept. 2, 1895) Validity 4.

1895, October 31. The Charleston, Missouri Earthquake (6.2 ml) caused extensive damage to schools, churches, homes and commercial buildings in Charleston. This was the largest earthquake to occur in the central Mississippi River valley since the 1811-12 series in the area of New Madrid, Missouri. A slight earthquake shock was felt at

Green Bay, Wisconsin. There was a slight tidal manifestations on the bay. (Street, Couch, Konkler, 1986; Stover and Coffman, 1993) Validity 1.

1909, September 22. "Refugees who reached New Orleans today from the coast declare that a 'tidal wave' which swept from Grand Island and eastward to Vermillion Parish, has claimed hundreds of lives. The most conservative estimates place the deaths at 300, while others more radical say many more were lost. *The tidal wave followed the gale and storm which had been sweeping the coast for several days*. The waves swept along the coast just as the gale was dying away and the people were beginning to think their troubles were over. There was no chance to escape, as the wall of water burst upon the little villages along the coast and swept everything before.

"My God, it was terrible," exclaimed one of the refugees who arrived here today. "Just as the poor people were trying to bring order out of chaos following the terrible storm, the 'tidal wave' came and swept them away. I saw so many corpses that I believed for a time that I was the only survivor."

"Houma, [Louisiana,] was reached by telephone today and the information reveals a terrible condition. The coast line for twenty-five miles was lapped by the 'tidal wave' and in some places the angry watch rushed into the inland for a distance of two miles."

"As the waters rushed into the little homes along the coast there was no chance for the escape of the inhabitants. The wave rose suddenly, as one of the witnesses described it, 'It shot up as if from the ground and started rolling up the hill.' Thousands of fisherman and planters' homes were swept away like as many straws."

"New Orleans is a city of desolation. After struggling through a night in which the city was almost completely dark, the residents are beginning to realize the enormous damage the storm has wrought."

"Three hundred city squares are under water, and it is believed that the toll of life will be heavier than was at first supposed."

"Many fine homes are under water along the Mississippi River and merchants of the poorer classes will probably lose their all. Telegraph lines leading into New Orleans are still down. The only outside communication possible by telephone says the loss to property along the Mississippi coast will reach more than $10,000,000."

"Four hundred persons held up for two days on two Louisville and Nashville trains by a washout were brought into New Orleans last night by boat. Some of them were almost exhausted from hunger. The suffering among the poor is a great problem for the city." (*Elizabeth Daily Journal*, Elizabeth, New Jersey, November 10, 1909.)

This was possibly a landslide triggered tsunami. The timing of the wave was not appropriate for a storm surge. Typically a storm surge should come in during or before the storm rather than after the storm. Various authors have suggested that storms may trigger off-shore landslides in loose sediments which in turn generate tsunamis. Such may have been the case here. (Newspaper reports provided by Harry G. Woodworth, National Weather Service, Mount Holly, New Jersey.) Validity 2.

1912, April 13. Lake Erie ports reported that an immense 'tidal wave' swept the southern shore of Lake Erie last night. The steamer *Sahara* of Duluth broke from her moorings and was thrown against the Schoonmacher, the largest freighter on the lakes smashing the Schoonmacher's light upper works. No one was injured. Ice was washed 184.6 m (600 feet) back up the river at Painesville, and large icebergs were observed out in the lake. (*New York Times,* April 14, 1912) (Newspaper report provided by Harry G. Woodworth, National Weather Service, Mount Holly, New Jersey.) Validity 2.

1913, June 9. Longport, New Jersey. There was $10,000 damage at Longport as a bank caved into the bay. Waters, rushing in, washed out 40 m (250 feet) along railroad track.

Damage occurred at Longport's Thoroughfare waterfront when a 77-m (250-foot) section of the embankment at 23rd Street was carried away. The washout extended to within 4.6 m (15 feet) of the near rail line. The tide tore away the wharf at the Schurch chandlery store (see alternate spelling in quote below) and at the same time undermined the soil from beneath the building. After the unusually high tide, the chandlery store was standing isolated at least 9.2 m (30 feet) from dry land, and only upheld by the timber piling, that threatened to give way at any moment. Other properties were damaged.

The Lavine wharf was completely torn away, and 4.3 m (14 feet) of water was left where there had been solid embankment further inshore, while the Henreesie (see alternate spelling in quote below) house stood along on its piling but isolated 9.23 m (30 feet) away from land. The Henreesie house was next to the chandlery store. At the following low tide, there was 3.7 m (12 feet) of water under both the "marooned" buildings, with 2.5 (8 feet) in the clear. A special meeting was held that night on the disaster which had overtaken part of the town. Another meeting was to be held on repair money, which had to be furnished by the property owners. The loss to lost land and wharves, to say nothing of the inroads on the driveway, is considerable. (*Atlantic City Daily Press*: June 10, 1913, front page)

Heavy tides played havoc on the thoroughfare side of Longport, washing out large sections of the bulkhead, undermining the houses occupied by Mr. and Mrs. Frederick Klein and Mr. and Mrs. Henry Hennici (see spelling above). of Philadelphia, and carried away the foundation from beneath the store owned by William H. Church (see misspelling above). Two women caught in the swirling tide about their homes faced the dangers pluckily, and were still smiling when a hastily constructed gangway made it possible for them to reach the shore. Church, who remained in his store trying to save his stock, had to be rescued in the same manner. The tide at 24th Street, where the Atlantic City and Shore Railroad tracks are close to the water, carried away a pole, tying up the service for a time on the line to the lower end of the island and crippling the Longport lighting service. (*New York Times*: Jun 10, 1913, p 4.) (Newspaper reports provided by Harry G. Woodworth, National Weather Service, Mount Holly, New Jersey.) Validity 3.

1918, October 11, 14:14. This Ms 7.5, Mw 7.3 earthquake occurred about 15 km off the northwest coast of Puerto Rico. “The sea waves had an unobstructed sweep across the deep waters of the North Atlantic and were registered on the tide gage at Atlantic City, New Jersey, about 2,200 km north of the origin. The disturbance appears to have begun at 2:00 P.M., 75th meridian or Eastern Standard Time, with a depression [and then an elevation] of the sea...and the oscillations of water level lasted for several hours. The amplitude of the waves was between 3 and 6 cm, and the period between 10 and 15 minutes. The tide gage at Atlantic City is not in an enclosed basin, but is on the open coast where no ordinary seiche could occur. Nor can...the periodic movements be a seiche set up between the coast and the edge of the continental shelf, for the period is much too short. They [the periodic movements] are more probably auxiliary waves following a short group [of waves] started by a sudden disturbance, but the matter is still obscure.” (Reid and Taber, 1919a)

“The tide gages in New York Harbor, at Key West, Florida, and Colon, Canal Zone, did not register the waves. The first is apparently too well protected to register small waves with periods as low as 10 or 15 minutes; the second is protected by the great Bahama bank; and the comparatively shallow water of the Mona Passage may have reduced the wave too much for registration at Colon.” (Reid and Taber, 1919a) Validity 4.

1918, October 25, 03:43. (No magnitude is available.) This aftershock of the October 11, 1918, earthquake occurred at 11:43 P.M. October 24 (local date). A small wave was recorded on the tide gage at Galveston, Texas. However, there are no reports of a tsunami being observed in Puerto Rico. (Heck, 1947; Berninghausen, 1968) Validity 4.

1922, May 2, 20:24. A small earthquake with an epicenter near Isla de Vieques, Puerto Rico, reportedly produced a 0.6-m wave at Galveston, Texas (Berninghausen, 1968). Parker (1922), then the director of the United States Coast and Geodetic Survey, observed a train of three waves with a period of about 45 minutes on the Galveston tide record, followed eight hours later by a similar but smaller train of waves. He associated it with the Vieques earthquake occurring approximately four hours earlier. The earthquake was felt in Vieques in masonry buildings, but according to Campbell (undated), it was a slight shock lasting only two seconds, an unlikely candidate to produce a tsunami. Other sources for the waves are not known. (Parker, 1922; Campbell, undated) Validity 2.

1923, August 6. Rockaway Park, Queens, New York. “Huge wave drowns two crippled children playing on beach —three others saved. A high-rolling wave swelled out of the surf and broke on the beach. It had come wholly unexpected. No such wave preceded it, and no high wave followed it. But that one was enough to engulf five little crippled children, patients at the Convalescent Home for Hebrew Children at the foot of Beach 110th St, and two of them were drowned...Twenty-two crippled children in all were taking their morning "water cure." They were placed on the sands where only little rippling waves could reach them...Then came the wave, unnoticed by the three nurses, until it broke on the shore. Five of the 22 children were swept from their feet, with three grabbing a rope leading to a float. When the children were retrieved from the water, the Higgins and Levin girls were unconscious. Crews tried artificial respiration while physicians worked hard to revive them, but to no avail." (*New York Times*: August 7, 1923.) (Newspaper report provided by Harry G. Woodworth, National Weather Service, Mount Holly, New Jersey.) Since this wave can not be directly linked to either an earthquake or landslide, it is given a validity of 1.

This event prompted Mr. Robert Adger Bowen to write a Letter To The Editor of the *New York Times*, published August 9, 1923, entitled "Triplicate Waves:"

"Your editorial note does not mention what frequently repeated experience through many years of familiarity with surf bathing on the Rockaway beaches has led me to accept as a curious fact - namely, the almost invariable following of an exceptionally large wave by two others in immediate succession." (*New York Times* Aug. 8, 1923, Topics of the Times)

This letter to the editor gives the impression that larger waves were a common occurrence in this area and that for frequent bathers, their behavior was actually quite predictable.

1924, August 8. Coney Island, New York. A wave from a [seemingly] calm sea hits Coney bathers; hundreds felled, four hurt; crowd in panic. There was wild excitement at the west end of the beach at Coney Island early in the evening, when wave 4.6 m (15 feet) high and extending more than ½ mile broke on the shore with such force that hundreds of bathers were knocked down."

"Four were so badly bruised that an ambulance carrying two physicians from Coney Island Hospital was sent to the scene. One explanation offered of the wave was that it was caused by the churning of the screw of a liner about a mile off shore, much closer than the usual course of big ships. The water, witnesses said, was as calm as a mill pond when the sudden disturbance occurred shortly after 6 o'clock.

In the backwash several children were drawn under and life guards and other strong swimmers were kept busy rescuing them. One bather dragged six lads to safety after they had been swept several feet from shore. (*New York Times*: August 9, 1924, Front Page). (Newspaper report provided by Harry G. Woodworth, National Weather Service, Mount Holly, New Jersey.) Here is another wave with an undetermined cause. Validity 1.

1926, January 9. No earthquake was reported or recorded on January 9, 1926. A 'tidal wave' was reported at Bernard, Mt. Desert Island, Maine. The following was taken from the Associated Press Wire Services Bulletin of January 9, 1926: "Unexplained in its origin, the phenomenon which occurred about noon caused the sudden emptying of Bass Harbor, followed a minute later by a 3.0-m (10-foot) rush of water, and then two smaller waves. No one was injured, but about 50 fishing boats were hurled ashore, and two men in a dory had a narrow escape from falling cakes of ice when their craft suddenly grounded. "The first sign of something wrong was a rumbling from the direction of the harbor. Townspeople ran to the piers to see their harbor emptied with a rush. William Kelley, who has a fish-packing plant on the eastern shore of the harbor, told what happened next: 'It was about low tide when the first wave came,' he said. 'It flowed in steadily like the even flow of a river. Then came two lesser ones, and in less than ten minutes the whole harbor was filled to near high water mark. Great whirlpools were formed. Small boats were tossed about at their moorings, and the 21-m (70-foot) fishing boat *Fish Hawk* broke from her lines at the Underwood Dock and crashed against the pilings. The entire harbor was a mass of foam." 'The water left the harbor so rapidly that a waterfall was created at the harbor mouth. In less than 15 minutes it was all over.'" (Associated Press Wire Service Bulletin, January 9, 1926, 8:45 A.M.)

"...In Vinalhaven, an island in Penobscot Bay 25 miles (40 km) southwest of here, rumbling noises were heard four or five hours before the Bass Harbor disturbance, and an hour before it the islanders felt what they thought were slight earthquake shocks. A fisherman reported seeing a 10-inch (0.25-m) ripple on the waves, although the sea was calm, and he said the water was roily and peculiar in appearance. A steamer captain said that the occurrence at Bernard was probably what natives call a 'bore' wave, peculiar to coves and harbors of a certain shape.

"From the head of the cove (of Bass Harbor), which is the inner extreme of the harbor, to Parker's wharf is a distance of a quarter of a mile (0.42 km). This whole area was drained entirely." [The water had previously been 2.4 to 3 m (8 to 10 feet) deep in the drained area.] "Bar Harbor, summer resort for many wealthy persons also on the island, did not feel the tidal wave."

"Prof. Kistlay F. Mather, dean of the observatory at Harvard University, said the University seismograph showed no record of any earth disturbance. He believed it possible that the outgoing tide had carried enough ice with it to form a dam at the head of the ragged inlet which forms the harbor, and that the incoming tide had broken this dam and caused the sudden inrush of water."

However, the Associated Press wire release of 8:07 A.M. January 14, 1926, indicates a wider source. "From the remote fishing village of Corea on the northeastern Maine coast comes news that at about the same time Saturday that the phenomenon was observed at Bass Harbor, a monster wave smashed lobster cars, tore boats adrift, and washed thousands of flounder from their winter beds in the Harbor bottom mud. These fish were gathered up in barrels by the natives. The tidal wave came at 11 A.M. and was preceded by a rushing flood tide several hours earlier." An explanation for this event is not known. However, the offshore sediments contain glacial deposits and trapped gas, and a non-seismically generated submarine slump or landslide is a possibility. Validity 2.

1929, August 12, 6:25 A.M. An earthquake (Ml 5.8, 42.9, 78.4) occurred at Attica, New York and the Batavia area that rattled windows and rocked buildings for about half a minute. A big wave rolled from the south to the north of Horseshoe Lake and over the road during the tremors. This may have been a lake seiche. (*New York Times*, August 13, 1929) Validity 2.

1929, November 18, 20:32. A tsunami generated by the Ms 7.2 Mw 7.4 Grand Banks earthquake swept up several inlets to a height of 15 m, destroying villages and causing heavy loss particularly on the Burin Peninsula on the south coast of Newfoundland and at Cannso, Nova Scotia. The tsunami reached the shore when an abnormally high tide was expected, and there was a gale at sea. Twenty eight persons died in Newfoundland, and one person drowned in Nova Scotia. (Johnstone, 1930; Lynch, 1929) The earthquake was felt as far south as Washington, D.C., Baltimore, Maryland..

Twelve trans-Atlantic cables were broken, all more than once for a total of 28 breaks over a large area, indicating a turbidity current. (Keith, 1930; Smith, 1968) This event was recognized in 1952 as the first documented turbidity current. The underwater slump of about 200 cubic kilometers of material moved at speeds of up to 70 km/hr. Material in the slump moved some 1,100 kilometers and was redistributed over an area of 150,000 square kilometers on the Sohm Abyssal Plain in the deep ocean. The tsunami moved at 400 km/hr south and east to Bermuda and Portugal, and impinged at 140 km/hr on southern Newfoundland and Nova Scotia. It did minor damage in Bermuda and was seen on tide gages down the east coast of the United and in the Azores and in Portugal. (Alan Ruffman, Hailfax, Nova Scotia) In the New England area the records were complicated by waves produced by a severe storm. (Heck, 1947) Newspaper reports mention waves not necessarily attributable to the storm alone.

Bar Harbor, Belfast, and Portland, Maine, reported waves. Exeter, New Hampshire; Barnstable, Massachusetts; and Block Island, Rhode Island, reported high tides. The Ocean City, Maryland, tide gage recorded a change of approximately 0.3 m. (Berninghausen, 1968) Tide gage records show that it was recorded at Atlantic City, New Jersey, with about the same height as Ocean City. The tsunami was also recorded on the tide gage at Charleston, South Carolina. (Associated Press Reports) Validity 4.

1931, August 19. Atlantic City, New Jersey. There was a sudden and brief onset of 4.62-m (15 foot waves) in Atlantic City, New Jersey. The *Atlantic City Daily Press* reported "Backwash Of Waves Cause of Drowning; Two Others Missing as Sudden Drag of Towering Combers Catches Hundreds Only Waist Deep; Life Guards Rescue Scores In Trouble Impeded by Excited Crowds in Efforts to Save Bathers. Several hundred bathers were swept off their feet by the back-wash of a line of huge breakers on the beach at South Carolina Avenue...Many [who were] rescued needed medical attention for shock or immersion. Four persons brought in unconscious were revived. Rescue work was impeded by fright which gripped all those thrown from their feet. Lifeboats going to the aid of those being carried out were grabbed by bathers being buffeted about in shallow water and overturned. The boats came to shore laden with persons unable to fight their way through the water. Guards and beach surgeons, assisted by civilian swimmers, made repeated trips into the surf with can buoys and often brought back two or three persons ashore at once."

"Although the surf was rough all day, the temperature of 76 degrees attracted hundreds. The sudden series of waves, about 3.1 m (ten feet high), rolled in shortly before noon. Traveling toward shore the waves did little damage, but when they washed back the force of the water was irresistible and persons only waist deep were unable to make headway and a few were carried out to the end of Steeplechase Pier. Dr. Charles Bossert, chief of the beach patrol, declared he had never witnessed such powerful combers in his 25 years on the beach. He ordered all bathers ashore while the waves lasted which was only ten minutes."

"Rumor on the beach attributed the waves to an earthquake at the bottom of the sea, but seismographs recorded nothing. Walcott L. Day, veteran head of the Atlantic City weather bureau, attributed the disturbance to a tropical storm north of Puerto Rico. The waves arrived at high tide, which served to intensify their force." (*Atlantic City Daily Press:* August 20, 1931).

The *New York Times* also ran an article on the Atlantic City waves, and on the severe weather which occurred later in the day. The article related how the weather bureau observers were unable to account for the disturbances along the New Jersey beaches. Mentioning the drowned Mr. McKenna, it also mentioned two other drownings that day, one being John Birch, 28, a contestant in a dance marathon at Wildwood, who lost his life while trying to save a 15-year-old boy from the surf there. [Wildwood, New Jersey, is about 30 miles south of Atlantic City.] This suggests the possibility that the huge waves came into shore from Wildwood to at least Atlantic City. Perhaps the best description of the waves themselves and the nature of the wave event came from the *Pleasantville Press* and *Ventnor News*:

"Beach Disaster Big Mystery To The Scientists; Cause of Phenomenon Sought Among Forces of Nature; Quake or Storm? Was it hurricane, earthquake, or the breaking down of the 'ridge' frequented by fishermen that caused the phenomenon at Atlantic City when one person drowned, three were reported missing, four were seriously hurt and 70 rescued? The water swept shoreward at about 11:30 am. It appeared to rise to a height of 3.1- 4.6 m (10 to 15 feet) between the Central and Steeplechase Piers about 61.5 m (200 feet) off the strand and rushed landward with express-train speed. The first wave was followed by a half dozen others, creating the appearance of a solid wall of water that toppled shoreward. While the waves went but a few feet past the ordinary tide lines of the beach, the havoc was wrought when the waters receded. Some of the bathers were hurled on the beach as the waves struck, only to be carried out to sea again by the undertow."

"Hardly had the excitement died down when a similar oceanic freak occurred two blocks distant, at the foot of New York Avenue, shortly after 1:00 P.M.. Cries from men and women bathers knocked down and carried to sea in the same kind of miniature whirlpool brought squads of lifeguards, some already fatigued, from the three stations along the beach. While the first series of waves were about 4.6 m (15 or more feet) in height, these were only about half that size. The excitement from the second disturbance was hardly quieted when cries for help were heard along another section of the beach, when a third disturbance at 3:00 P.M. carried six more bathers out to sea off the foot of Virginia Avenue."

"Dr. James H. Kimball, of the New York Weather Bureau, said the origins of the waves was a mystery to him, a wind of only 12 mph having been reported offshore. Of the two ships nearest the resort, the *Christobal*, 75 miles SE, reported a 6-mile SW breeze, while the *Virginia*, an oil tanker in the same region, reported a 10-mile wind."

"Besides the storm and earthquake theories, another is the settling of a reef out in the ocean. An interesting theory, which in a measure might support the sub-oceanic disturbance possibility, was offered by fishermen, who have traveled the waters off the coast for years. They advanced the idea that the 'ridge,' a sort of under-the-ocean hill near the edge of the Gulf Stream off Atlantic City, has been breaking down all summer. This, they say, has caused the unusual deposits of marine flora and fauna that have washed up on the coast during recent months. The disturbance, they said, might be due to the same force which has been breaking down the "ridge," where they fish for market."

"In the Asbury Park newspaper dated August 20, 1931, Mr. Day (see above explanation by Day) said that the disturbance must have been to a greater or lesser extent all along the coast, although no other resort reported similar disturbances. The drowning in Wildwood extended the possibility of the wave coming ashore from Atlantic City to Wildwood. A small article on page two in the Asbury Park paper stated that a bather was injured while at a local beach in Point Pleasant Beach, when she was knocked down by a huge wave. [Point Pleasant, New Jersey, is 50 miles north of Atlantic City.] She fractured a bone in her right knee was and was taken to the Point Pleasant Hospital where she was treated and released."

It is highly probable that the waves came in along the entire New Jersey shore, and possibly also the south shore of Long Island as well. An earthquake of Mb 5.6 had occurred on August 16 near Bermuda. This event could be a belated landslide-triggered tsunami. *Pleasantville Press* and *Ventnor News*, August 21, 1931 Front Page; *Asbury Park Evening Press*, August 20, 1931, Front Page; August 21, 1931 1:3, 2:5; August 22, 1931, 3:4; *Atlantic City Press*, August 20, 1931, Front Page; *Atlantic City Evening Union*, August 20, 1931, Front Page; *New York Times,* August 20, 1931, 3:6) The above newspaper accounts were taken from a web site developed by Harry Woodworth for the National Weather Service: http://205.156.54.206/er/phi/tsunami.htm. Validity 1.

1932, November 10, 6:30 P.M. EST. There was an invasion of the sea to a height of 5.4 meters at Willetts Point, New Jersey, from 6:30 P.M. EST to 9:40 P.M. on November 11th. (Annales...1933 p. 55) Validity 1.

1938, September 21. "Remarkable" waves occurred along the New Jersey coast in the wake of the September 21, 1938, hurricane, also known as The Long Island Express. On September 22, just before dawn at Port Washington, NY, one person heard a rumble and felt a slight tremor. (Neumann, 1938)

The following was taken from a web site developed by Harry Woodworth for the National Weather Service: http://205.156.54.206/er/phi/tsunami.htm: Some have suggested that this is the 1929 Grand Banks earthquake, which caused the destructive Newfoundland tsunami. Any evidence that the tsunami moved into New England and points southward is disguised by the exceptionally high tides from a severe coastal storm that was raging along the northeast coast. Tides were 5.7 m (18 ½ feet) above the norm in Boston harbor at high tide, which occurred a few hours before the quake hit. Other wave events that happened later in the day could have been tsunami related, but the storm made it impossible to say for sure. This was also stated in the newspapers of the time. Because of this concept, one would never think to review hurricanes in the search for possible tsunamis, and especially a hurricane that brought such great death, destruction, and huge storm surges to Long Island and New England. In the search for tsunamis, the Monmouth County Historical Society sent an article from the Asbury Park Press that, with further newspaper article gatherings, began to reveal an extraordinary event along the New Jersey coast, an event that seems to have been amazingly forgotten with time. Whether the waves were true tsunamis or hurricane generated, it is interesting to review the details of this amazing event.

"The hurricane remained offshore New Jersey, about 100 miles from Atlantic City, and 75 miles from Sandy Hook. A blocking North Atlantic high pressure system prevented a recurve out to sea from the Carolinas, and the storm moved almost due north. Exceptionally strong steering winds moved the storm at an average speed of 55 mph, but could have been traveling as fast as 78 mph off New Jersey. Being on the west, or "weak" side, the New Jersey shore did not experience hurricane force winds. The strongest wind at Atlantic City was 58 mph between 2:05 P.M. and 2:10 P.M., with the lowest pressure of 28.99 inches recorded at 2:10 P.M.. New Jersey was on EDT. At 3:30 P.M., the hurricane began to move across Long Island, and by 5:30 P.M. was in western Massachusetts. Up to this time, there had been much damage in New Jersey on land. Torrential rains the previous four days had super-saturated the soil. The additional hurricane rains caused massive flooding as well as mud slides, the worst in Mt Holly up to that time.. Many trees were uprooted by the wind, since their roots were surrounded by saturated soil. The falling trees took out power lines and electricity, as well as crashing down on cars and houses."

"Along the shore, the ocean was disturbed, and the gales did damage to some boats, but nothing the shore people couldn't handle. Because of the forward speed of the hurricane, the storm really didn't last that long. With the storm moving quickly northward into New England, the gales died down very rapidly, and a few brave souls headed to the boardwalks to see what had happened. The shore had survived in fairly good shape up to 5:30 P.M.. Then the terror began."

"Looking down from the boards at the churning surf of an almost high tide, people's attention was suddenly turned upward, and they became mesmerized and then terrorized as they looked at a wall of water 15.4 m (50 feet) high moving toward them. The wave was terraced at the front, and non-breaking. People began to run; but, it was too late, because the wave was upon them, and they were engulfed. This wave was so big that the top of it was visible to an observer in Bayville, Ocean County, which is about three miles inland. From the shoreline, the wave continued its westward journey, moving into coastal Monmouth County, passing completely over the barrier islands of Ocean County to the south, and extended down into Cape May county as well. After the wave reached maximum runup, shore residents then had to go through its equally or even more damaging back-wash. But, there was more to come. Altogether, there were three waves during this event, none less than 9.2 m (30 feet) high, the first being the biggest. Most of the shore damage occurred within a one-hour period with these three waves, when the hurricane was already well into Massachusetts. Councilman George Peek of Manasquan who lived on Beachfront St, fronting on the boardwalk, said that one wave larger than the rest did the most damage. When it hit, it lifted everything before it. 'I was out front and saw it coming,' he declared. 'I started for the house, and it arrived at the front door with me. When I opened the front door, I let it in with me.'"

Damage From The Waves

Newspaper articles have been obtained from the Asbury Park and Atlantic City newspapers. The waves probably extended south as far as Cape May County. From Atlantic Highlands to Seaside Park, more than 30 miles, the Atlantic washed from one to several blocks inland, heaving boardwalks, piers, bulkheads and boats. Witnesses at several points agreed there were three tremendous waves 'which seemed like tidal waves' at high tide, which engulfed beachfront dwellings. Police rescued many people from their beach bungalows at Manasquan (north of Point Pleasant.) A six-mile stretch of boardwalk, almost continuously through Avon, Belmar, Spring Lake, Sea Girt, Manasquan and Point Pleasant, was either twisted or washed away. Throughout the resort area, cottages were carried to sea, piers and floats damaged, and roads flooded by the 9.23-m (30-foot) waves. To describe the damage we will start at the northern-most mentioned community, and work southward. If a community is not listed, it simply means that no information was available to the researchers.

Monmouth County:
Keansburg: Flooded roads (probably from the torrential rains).

Atlantic Highlands: Considerable damage to small boats, bulkheading and docks.

Long Branch: A section of the municipal fishing pier was wrecked, and the south end of the boardwalk was carried away together with some bulkheads. Estimated damage $10,000.

Allenhurst: Cabana colony, owned by the municipality, wrecked, causing $10,000 in damage.

Asbury Park: North end of boardwalk completely destroyed, and other sections were buckled or lifted from the supporting pilling. Parts of the boardwalk was buried in sand, and lamps were washed away. A section of the municipal fishing pier was also wrecked. Estimated damage was $50,000.

Ocean Grove: One half mile of boardwalk was lost, and two fishing piers were washed into the sea.. Storm damage was estimated at $15,000 to the boardwalk, fishing piers and pavilions fronting the ocean.
Bradley Beach: The boardwalk was badly damaged. The north part was washed into Fletcher Lake.

Avon: Half the boardwalk was gone. The entire boardwalk has to be replaced. The towering waves moved the bell buoy designating the entrance to Shark River from its position of Washington Avenue, Avon, to about 150 yards offshore at the end of Brinkley Avenue, Bradley Beach. Public damage was estimated at $50,000, in addition to the private damage to many parked automobiles which were smashed by the wind and then waves and by flying bits of the boardwalk.

Belmar: Half the boardwalk was removed, including parts of a new section being rebuilt under the WPA. Estimated public damage $100,000. In the inlet ten boats were sunk and the Coast Guard had to raise them. A large electric pump used to draw salt water from the ocean was tossed to the west side of the street by the towering waves.

Spring Lake: One third of the boardwalk was carried away. Pieces broke open the doors of two municipal swimming pavilions, and filled the cellars with 2.15 m (seven feet) of sea water.

Sea Girt: One hundred fifty-four meters (five hundred feet) of a private boardwalk at the Stockton Hotel was picked up and thrown through the front of the hotel's enclosed cocktail garden. The break let in the waves and piled up sand even in the hotel lobby. Damage was estimated at $5,000.

Manasquan: "There were three waves, just like tidal waves," said Patrolman Job Francis. One mile of the boardwalk went into the sea. Fourteen blocks of the boardwalk were turned into driftwood and deposited two blocks inland. On the way, the debris crashed into casinos and pavilions fronting the ocean, and into cottages on the side streets. Porches were torn away and doors and windows smashed open. The sea left about one meter (three feet) of sand behind it, burying Ocean Avenue for its entire length. One man was swept inland for a block. Another man was seriously hurt when pinned against a wall by boardwalk wreckage. House movers were needed in putting wave-tossed bungalows back on their foundations. A doctor driving to a call was riding north on First Avenue when the wave, carrying a large section of the boardwalk, struck his machine and forced it into a cottage on the northwest corner of the intersection. The doctor had to crawl from a window of the car. The water on First Avenue, which is ordinarily several hundred yards from the water line, was about one meter (three feet) deep.

Brielle: Several hundred pleasure craft, charter fishing boats and private fishing boats, normally moored side-by-side in the yacht basin, were badly buffeted. A 13.85-m (45-foot) craft broke away and was driven against the Manasquan causeway.

Ocean County:
Point Pleasant: Sixty-two meters (two hundred feet) were swept away from the end of the newly completed municipal fishing pier, at Point Pleasant Beach at a cost of $5,000. A mile of the boardwalk was washed away, causing $50,000 in damage. Ocean Avenue was covered by sand. Private damage was estimated at $200,000, due to the smashing of beach front pavilions and casinos, and to private homes from pieces of the boardwalk hurled inland by the sea.

Point Pleasant Beach: In his book, David D. Oxenford mentions that "this violent storm sent the boardwalk, (parts of) hotels, and plenty of water rushing down Arnold Avenue."

Bay Head: Boats were strewn along the shores of Barnegat Bay, their masts snapped off and cabins staved in. One and one half miles of boardwalk were completely destroyed. There was considerable damage to many summer homes.

Mantoloking: The ocean rolled *across* this peninsula town.

Chadwick: Preliminary damage set at $10,000.

Seaside: Boats were strewn along the shores of Barnegat Bay, their masts snapped off and cabins staved in. Below Seaside two new inlets were cut through Island Beach, known as Phipps estate. The ocean sprawled over the Seaside Park boro, scattering it with wood and debris. Police estimated $45,000 in damage - $25,000 in the loss of ten blocks of boardwalk; $10,000 in boats swept to sea; and $10,000 in wrecked boat sheds. Two houses washed out to sea, one injured resident was rescued while clinging to his house.

Atlantic County:
The big news of the day for Atlantic County/City was the collapse into Absecon Inlet of a 92.3-m (300 foot) section

of the Atlantic City-Brigantine bridge, nearest Atlantic City. No exact time of the event was given. The article mentioned 'last night', and that scores of cars carrying several hundred Atlantic City workers had crossed the bridge in the two hours before its collapse. The bridge tenders halted traffic when the bridge appeared to wobble. The buckling caused a short circuit which first extinguished lights and then set the wooden bridge on fire. The wife of a bridge tender notified City Hall, and firemen and police cars responded. When they arrived, there was no fire to put out. The burning structure was already in the water and floating away, having collapsed with a roar. Six hundred people were stranded and kept from getting to their homes.

The bridge was built in 1924 at a cost of $800,000. There were strong tides in the inlet that the bridge was built over, as well as in another inlet about 615.4 m (2,000 feet) away at Rum Point Island. After the bridge had been built, the War Department eventually ordered the second inlet to be filled in. This created a tide race in the channel under the bridge, which undermined the pilings. The tremendous speed of the outgoing tides, at least as great, if not greater, than the speed of the Gulf Stream, struck especially hard on the Atlantic City side, creating erosion. A runaway barge had crashed into the bridge on the Atlantic City side a little more than a year previous. No article made mention of any huge or tremendous waves in the region. One sentence hints at the possibility when it mentions a section of the boardwalk between Rhode Island and Vermont Avenues was near collapse, due to 'the fury of the ocean.' This echoes the boardwalk wave damage further north. Perhaps the giant waves bypassed this section of the shore, or came in at lower heights. High tide at Atlantic City was about 6:00 P.M.. If the waves came into southern New Jersey around or after 6:00 P.M., the still tremendous back-wash of the waves in conjunction with the strong ebb currents in this channel could have been the final contributing force for the collapse of the bridge. Since the collapse happened the day the hurricane hit, this is a very plausible explanation.

Cause of the Waves

The probable cause was theorized by a reporter of the Asbury Park newspaper. He suggested that the NW gales (hurricane force over the waters nearer the hurricane) were keeping the high tide from coming in. When the wind suddenly [became] calm, in came the ocean...taking the form of 9.23-15.4-m (30-50 foot) waves. Using the USGS publication *Hurricane Floods of September 1938,* it appears that the reporter, in a general sense, hit the nail on the head. This article states that, except at five places, the time which the storm wave reached it maximum height is not definitely known. 'Storm wave' used here means the storm surge associated with the hurricane; and, storm surge is the height of the water above the reference level of Mean Lower Low Water (MLLW). Indeed, trying to compare times in the article discussions, and the times mentioned in the charts and tables proved difficult, until it was realized that the discussions were using EDT, and the charts and tables were in EST. All times mentioned here will be in EDT. The Corp of Engineers, United States Army, and the Coastal and Geodetic Survey provided much information to the USGS report. This could be the cause of the time discrepancies.

The surge reached the southern Long Island coast as the eye came ashore about 3:30 P.M., along with the lowest pressure. Sandy Hook, New Jersey, and New York Harbor, respectively, peaked at one and one-half and two hours later than on the southern Long Island coast. In contrast, normal high tides at Sandy Hook and New York harbor occur, respectively, only about 15 and 45 minutes after Long Island. All surges occurred on an incoming spring tide, but before the time of high tide. USGS suggests the surge could have been slightly higher if it had occurred at the exact time of high tide. The surge reached 2.5 m (8.2 feet) above MLLW at 5:00 P.M. at Sandy Hook, and 8.7 feet above MLLW at the Battery at 5:30 P.M.

The USGS article states that it is probable that the surge peak in the New York harbor region was the effect of the hurricane winds upon the water in the open sea to the east, where the surge reached its peak nearly simultaneously with the passage of the hurricane. Also, the surge in the New York harbor region was a reflection of the wave that the storm had built on the Long Island shore. Two other surges occurred in New York harbor on a lowering tide, one about 9:00 P.M., and the other about 11:00 P.M.. The USGS article suggests the first might have resulted from oscillations set up by the release of the water piled up on the southern Long Island shore. The second was further complicated by the particular configuration of the harbor, and by the inflow of water into the harbor through the draining of excess water in Long Island Sound via the East River.

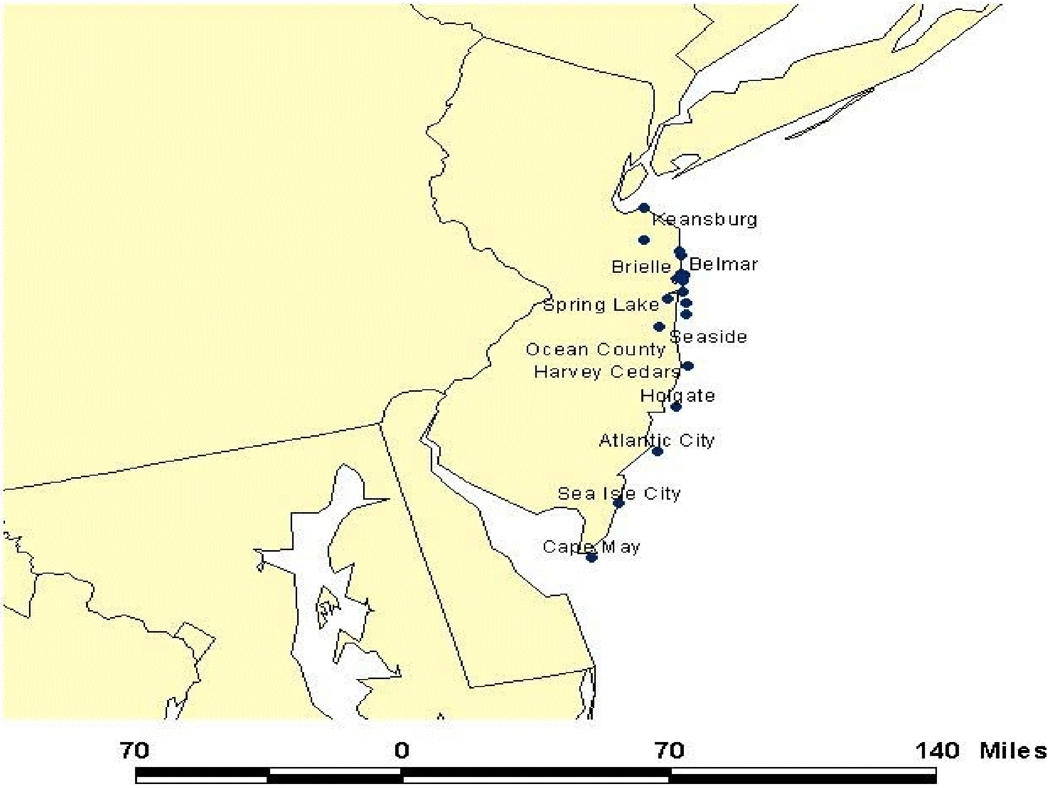

Figure 3. Locations of tsunami-like waves during 1938 and 1944.

The USGS article infers that the tremendous waves were hurricane-induced. These occurred on the "weak" side of the storm, and were at least as large as the waves riding the much higher storm surges that moved into the coastal regions to the east of Sandy Hook. Nine-meter (30 foot) waves on the surge were reported from eastern Connecticut to Massachusetts, with a 15.4-m (50 foot) wave reported in Gloucester, Massachusetts. New Jersey's 15.4-m (fifty foot) wave seems to have washed away from memory as fast as it receded from land. In fact, even though over one million (1938) dollars in damage from the hurricane's waves occurred along the New Jersey shore, two days later, New Jersey residents began raising funds for New England relief. There is another theory about what could have caused the giant waves, and that is an offshore landslide, or, slump.

On August 23, 1938, an earthquake of intensity MMI V, occurred in central New Jersey. The previous July 15th, an MMI VI hit Pennsylvania. The day before the hurricane, an MMI III hit southern Connecticut. This series of quakes may have left a section of the unstable offshore canyons 'teetering on the brink,' with the extremely low pressure of the speeding hurricane providing 'the straw that broke the camel's back.'

The only way to prove this would be by comparing a scan of the ocean floor before, and then after, the hurricane passage. Otherwise, if we accept the first theory, a large hurricane racing northward off New Jersey and making landfall in New England doesn't mean an 'all clear' can be given to the New Jersey coastal regions, just because the hurricane has passed. Residents would have to remain on guard for at least two hours afterwards, as shown by the Long Island Express.

The above was largely taken from a web site developed by Harry Woodworth for the National Weather Service: http://205.156.54.206/er/phi/tsunami.htm#1 (References included: Monmouth County Historical Society; *Atlantic City Evening Press*: Thursday, September 22, 1938; Ibid Friday, September 23, 1938; Ibid Saturday, September 24, 1938; The *New York Times*: Friday, September 23, 1938; Ibid Saturday, September 24, 1938; *Asbury*

Park Evening Press: Thursday, September 22, 1938; Ibid Friday, September 23, 1938; USGS, 1940; Oxenford: 1992) Validity 1.

1944 Summer. This letter came to our office in 1988. At that time we had never heard of such an event but notice the similarity with the 1944 September event that follows. "During the summer of 1944 (possible '43 or '45), in Brooklyn, New York, my sister and I were vacationing with our mother on the beach at Sea Gate or Coney Island (both of which are Brooklyn communities.) On one beautiful, sunny day, when the beach was crowded with bathers, a great wall of water suddenly came toward us and everyone had to run off the beach. Later, we were told it was a tidal wave." (Craig, 1988) Validity 1.

1944, September 14-15. A ML 5.9 earthquake hit upstate New York on September 5, 1944, at 8:20 UT. It was felt at MMI IV from Newark, New Jersey to Philadelphia and at MMI III southward along the coast to Virginia. Although the following event seems to have the hurricane as its immediate cause, this earthquake could have loosened sediments before the hurricane arrived and contributed to the intensity of the waves. The following information is taken from a Web site developed by Harry Woodworth for the National Weather Service. Another site has information on all the paths taken by hurricanes in 1944. See the path for the September 14-15 hurricane at http://www.nhc.noaa.gov/.

"We saw the wave come over the island and go across to the mainland...A single wave. Just one big wave. I think as the crest of the wave passed by our house, it was probably 2.5 to 2.8 m (eight or nine feet) high. You could see it coming from way out, and it came at one shot. The beach at that time was relatively steep and wide, and to come across the beach and pass by our house at 2.5 to 2.8 m (eight or nine feet) - that was a h--- of a wave. When that wave got to the mainland, it turned around and came back. I think people at that time said that the return of the wave did more damage. It just sucked everything out. The boats from the bay were now on the beach."

This is an observation from the New Jersey shore, made during the 1944 off-shore hurricane. This event was witnessed by a Mr. Ellwood Barrett, his mother, aunt and ten-year old sister, from a second-floor apartment near the ocean on Seventh Street in Beach Haven. (Savadore and Buchholz, 1993)

Megan Sprignate of the Monmouth County Historical Association mailed the initial article from the *Asbury Park Evening Press* on the giant wave event that occurred during the 1938 hurricane. She then sent an article on the 1944 hurricane, mentioning that the description of the wave event that accompanied this hurricane sounded remarkably similar to the 1938 storm. Upon further research, indeed, a series of monstrous waves accompanied this 1944 hurricane as was the case with the 1938 hurricane! This hurricane passed offshore a little closer than 1938, moving at an accelerating forward speed along a path from the North Carolina outer banks to eastern Long Island. Estimated wave crest heights were given by witnesses along the entire New Jersey shore. (*New York Times*, the *Asbury Park Evening Press*, and Savadore and Buchholz, 1993.)

North Jersey resorts declared this storm as its "worst storm in history" for 25 miles, from Deal to Bay Head. A series of three tidal waves near 15.4 m (fifty feet) high swept over the beachfront, carrying everything in front of them. At Harvey Cedars on Long Beach Island, Reynolds Thomas, a borough commissioner, watched the first wave strike. "It lifted itself 7.7 m (25 feet) above the dunes and advanced toward the boulevard in a solid wall of water, no foam." On the southern end of Long Beach Island, the wave height was estimated at 9.2 m (30 feet). Cape May witnesses estimated the height at 12.3 m (40 feet). The time of occurrence varied, with the waves striking around 5 P.M. in the extreme south, to a time given as between 9 and 10 P.M. in the north. From north to south along the shore, the boardwalks were taken away for a ride as in 1938. In Beach Haven, the wave hit the Spray Beach Hotel, which was near the beach. An enormous flow of water and sand entered the hotel, even through the third floor windows. In Asbury Park, within seconds the boardwalk was destroyed, buildings on the ocean side flattened, and fishing piers swept away. A car driven by Frank H. Rowland, Civil Defense Coordinator, was caught in the backwash of the biggest wave on Fifth Avenue and carried 23.1 m (75 feet). In Stone Harbor, Mayor John Biggs watched part of the boardwalk ride the crest of the wave over the top of a house, then crash onto First Avenue. In Cape May, the entire two mile long boardwalk was destroyed in a matter of minutes. Unlike 1938, these waves caused fatalities.

On Long Beach Island, the bodies of two women were recovered from the surf. Three island residents reported missing were never recovered. In Sea Isle City, a nurse running for aid was washed away. She was found buried beneath more than a foot of sand and debris. As with the 1938 event we have listed the damage by county moving from north to south along New Jersey's shore.

Monmouth County:
Asbury Park: Parts of the Casino were torn from the steel and concrete foundations and the sub floor developed a giant crack. The wooden floor of the roller skating rink buckled and rose one meter (three feet). Because of the damage, the Casino was closed for nearly ten years. The municipal fishing pier, extending out hundreds of feet on 10 cm (twenty-four inch) thick pilings, was swept away, including a restaurant, shooting gallery and gift shop. Parts of the floor of Convention Hall buckled. The Hall and the Paramount Theater were swamped by water. The waves swept into the sewage treatment plant, knocking it out of service for more than two weeks. Logs and wreckage were all over Ocean Avenue, and toilets, stoves and other fixtures that had washed out of boardwalk shops covered Kingsley Street.

Ocean Grove: The boardwalk was reduced to rubble, with benches and boardwalk carried a block inland, some a block beyond Ocean Avenue. The South End Pavilion was uprooted and destroyed. The boardwalk Homestead Restaurant at the North End Pavilion was torn off its pilings and thrown against the front of the North End Hotel. The Barnegat Bay Seafood Restaurant opposite the hotel was wrecked.

Long Branch: The boardwalk was smashed to kindling. Ocean Avenue was undermined in many places, with the pavement and sidewalks disappearing. Chelsea Baths on Ocean Avenue was destroyed.

Deal: Eighty-nine meters (two hundred feet) of a pier at the foot of Phillips Avenue were carried away. Much sand from the beach was washed onto Ocean Avenue.

Avon: Large sections of the boardwalk were destroyed. Water rushing across Ocean Avenue entered the Avon Inn. The west wall of the Norwood Avenue Pavilion was knocked into Ocean Avenue by the rushing waters.

Belmar: The then-new 10th Avenue Pavilion and a mile of boardwalk were torn apart and carried westward to settle on lawns along Ocean Avenue. The ocean went as far west as A Street in spots. Piers at 8th and 16th Streets were heavily damaged. The fishing pier lost 107.7m (350 feet) of its 261.6 m (850 feet)-long span.

Spring Lake: The boardwalk was swept across Ocean Avenue onto residents' lawns.

Manasquan: The boardwalk was ripped from end to end.

Brielle: Sections of the boardwalk were found floating in Wreck Pond.

Sea Girt: Heavy timbers being used in jetty construction at the north end broke loose, pounding against several houses. The boardwalk was severely damaged, with bath houses totally wrecked. Tons of sand scoured out around the Stockton Hotel.

Ocean County:
Point Pleasant Beach: The boardwalk between Jenkin's Pavilion and Manasquan Inlet was ripped to pieces, as was the PP Fishing Club's pier at the foot of Central Avenue.

Mantoloking: Waves filled the bay. Garages were smashed, with winter-stored furniture floating everywhere. A small house at the foot of Dower Avenue was deposited on Rt 37. Ocean front homes were badly damaged.

Bay Head: One and a half miles of the boardwalk were wrecked, with some pieces found two blocks back from the ocean. Many homes directly on the oceanfront were damaged, and porches and bulkheads were washed away.

Long Beach Island: Hundreds of cottages and automobiles were swept away and many others damaged. Throughout the area, many intact pleasure boats were found miles away from their anchorages, often high and dry some distance from the water.

Southern end of Long Beach Island: The monstrous waves washed across, popping off roofs of houses, with some houses collapsing. Some houses floated whole, hitting other buildings and jamming up, forming islands of debris.

Harvey Cedars: The monstrous wave “about eight meters (twenty-five feet) above the dunes” broke a huge, oceanfront home in two.

Holgate: Shows a combination of events. The wind lifted a house off its foundation, but it sank back down. Then, the gigantic wave took the house into the bay. The house broke up when it was washed back.

Atlantic County:
Atlantic City: Eight teenage boys rode a (12.3-m) forty foot section of the destroyed boardwalk down Madison Avenue, ending up against the front of a barber shop. The Heinz Pier was split in two. The Atlantic City to Brigantine bridge, which had been damaged in the 1938 hurricane and then rebuilt, was destroyed.

Cape May County:
Sea Isle City: Twenty-five houses were washed from their foundations. Between Sea Isle City and Strathmere, more than one hundred bungalows vanished into the channel, as the wave passed over the land on its way to Ludlam's Bay.

Cape May: Beach drive washed out and buried to a depth of at least 1.2 m (four feet) with sand and debris.

The shoreline of New Jersey has had at least two bouts with monstrous waves, causing considerable and nearly instantaneous damage. These were the hurricanes of September 1938 and September 1944. Both hurricanes passed offshore, with the New Jersey waters being on what mariners call the ‘navigable,’ or, ‘safe side.’ The wind is weaker, and the storm surge lower, on the left side than around the center and to the right of the storm.

Both storms were waning and were only a CAT 1 at the most when they passed offshore. A ‘standard’ CAT 1 storm surge is estimated to be 1.2-1.5 m (4-5 feet). If the tide caused by the hurricane was 0.9-1.2 m (3-4 feet) above normal, the total tide height would be 2.1-2.8 m (7-9 feet) above normal.

The tide at Atlantic City peaked at 2.8 m (9.2 feet), one of the highest tides ever recorded there. The 1938 hurricane might have given similar readings, if the gage had been working. The normal waves riding this elevated ocean would be large and impressive, and capable of producing damage. Yet, both hurricanes produced a distinctive series of devastating waves, with descriptions of them using words usually associated with a great tsunami.

In the book *Atlantic Hurricanes*, by Dunn and Miller, this phenomena is called the Hurricane Wave. It is a "very important (though rare) sea effect which may occasionally be superimposed upon the usual hurricane tide--usually with disastrous results. This hurricane wave is sometimes called a ‘tidal wave,’ although it has nothing to do with tides. It is nearly always described as a ‘wall of water’ advancing with great rapidity upon the coast line." This definition reflects the witness reports for the 1938 and 1944 hurricanes. It also defines the effects of a tsunami.

Dunn and Miller further state that authenticated cases are relatively rare, with some authorities even doubting their existence. Recent correspondence shows this continues to be true to the present. Dunn and Miller, and another book, "Hurricanes,” by Tannehill, both give a few examples of hurricanes which produced the ‘Hurricane Wave.’ Neither book, published after 1944, mentions the New Jersey shore 1938 and 1944 events. Perhaps the 1938 and 1944 events are “hurricane waves” or they may be actual tsunamis.

As in 1938, there was earthquake activity along the East Coast previous to the passage of the hurricane. As was previously mentioned in the introduction to this event, a ml 5.9 earthquake occurred on September 5th. This quake occurred just nine days before the passage of the hurricane, and does present the possibility that the effects from the hurricane could have been the final trigger in the creation of an offshore landslide and resultant tsunami. (Woodworth, http://205.156.54.206/er/phi/tsunami.htm#1) Validity 1.

1946, August 4, 17:51. This Ms 7.8, Mw 8.1 earthquake occurred about 65 km off the northeast coast of the Dominican Republic. The waves were recorded at Daytona Beach, Florida, at Atlantic City, New Jersey, and at Bermuda. Travel time from the earthquake epicenter to Atlantic City was 4.8 hours, and 4.0 hours for Daytona Beach. (Bodle and Murphy, 1948) Validity 4.

1946, August 8, 13:28. This Ms 7.4, Mw 7.4 earthquake, an aftershock of the August 4, 1946, earthquake, produced a small tsunami that was recorded at Daytona Beach, Florida, at Atlantic City, New Jersey, and at Bermuda. Travel time was 4.7 hours at Atlantic City and 4.0 hours at Daytona Beach. (Berninghausen, 1968) Validity 4.

1952, May 6. A seiche "similar to a small tidal wave at sea, swept the shores of southern Lake Huron today, sending three walls of water over the banks. At Lexington, Michigan, the water poured through the windows of a marine restaurant. A huge log smashed a boathouse as it rode in on the wave. A boat livery at Harbor Beach, Michigan was damaged. Grounds of the Coast Guard station here were flooded. Many fashionable homes were flooded briefly in Port Huron. Water in the St. Clair River rose twelve inches and then dropped within a few minutes." Although this event was attributed to a rapid change in barometric pressure, it might have also been produced by an offshore landslide. (1952) Validity 1.

1954, June 26. At least eight persons drowned when a wave struck nearly twenty-five miles of Chicago's Lake Michigan shoreline. The wave swept over an eight foot sea wall at Loyola University close to Chicago's northern boundary, but caused no damage. Normally it was widely believed that a seiche in this area would never exceed a 4- or 5-foot rise or fall in the water level. While such seiches result from squall lines that contain significant pressure changes and occur each year in the Great Lakes, this 1954 event was at least twice as large as any that had occurred up to that time. Seiche related deaths have also occurred in other events. The 1954 event may have had a under-water landslide in connection with the event that augmented the wave. (*New York Times,* 1954, *Chicago Tribune*, 1985) Validity 1.

1964, May 19. A disturbance that probably originated near the northeastern end of Long Island was widely recorded in the area from Providence, Rhode Island to New Jersey. At Plum Island, New York, the record shows an impulsive beginning with an amplitude of 0.28 m and a period of 4 minutes at 5:25 P.M. EST. The short period waves continued over 10 cycles with decreasing amplitude. Waves of about 0.11 m maximum amplitude began impulsively also at Montauk, Long Island, New York, and the wave activity continued for eight or more hours. Smaller amplitudes were observed on nine other tide gage records. The source of these waves is not known, but there are no reports of recordings from local seismic stations, and the waves do not appear to be of meteorological origin. A submarine landslide or an explosion are possible causes. (Lander and Lockridge) Validity 3.

1992, July 3,4. At midnight, a three-meter (ten foot) wave suddenly surged onto Daytona Beach, Florida. It injured 75 people, damaged 100 vehicles, and caused some property damage. It lasted only about one minute. It was recorded on the tide gage at St. Augustine, Florida, 75 miles north of Daytona Beach and was reported to have extended as far south as New Symrna Beach, Florida. The wave has been explained as a "shallow-water gravity wave forced by a propagating squall line." (Nickerson, 1993; Churchill, 1995). This wave was probably meteorologically induced. Validity 0.

SUMMARY

In summary, several new tsunami events have come to light as the United States East Coast history is being scrutinized by those interested in historical tsunamis. At the same time sonar is revealing new features that may have been the source of tsunamis in the past. Modeling of the waves generated by the 1755 earthquake off the coast of Portugal suggest that the waves would have had a major impact on the East Coast had the area been densely populated at the time. The East Coast of the United States was formerly thought to be relatively free from tsunamis. Today several lines of research are suggesting a different picture. These theories coupled with the history of large waves on the United States' East Coast should cause us to rethink and reevaluate the tsunami hazard for this heavily populated area.

Hurricane Waves

A number of United States East Coast wave events could not be directly associated with earthquakes. Some events were not clearly linked to any cause. Other events such as September 3, 1821, September 22, 1909, August 19, 1931, September 21, 1938, and September 14-15, 1944 occurred in association with hurricanes.

Some authors have claimed that these events may be examples of "Hurricane Waves"--large waves caused by meteorological conditions. These waves are described by Dunn and Miller (1964): "There is one additional and very important (though rare) sea effect which may occasionally be superimposed upon the usual hurricane tide–usually with disastrous results. This is the hurricane wave, sometimes erroneously called a 'tidal wave,' although it has nothing to do with tides. It is nearly always described as a 'wall of water' advancing with great rapidity upon the coast line.

These unusually large waves may not be typical storm surges. (Nickerson, 1993) Some of the waves are preceded by recessions–withdrawals of the water from the shoreline. If it can be shown that a hurricane in itself can not produce an ocean recession, then these events require a different explanation.

One possible explanation is that these rare waves are actual tsunamis, with the hurricane being the trigger which induces offshore slumps or landslides in the canyons or continental slopes. In the 1938 and 1944 events, earthquake activity affected the region before the passage of the hurricanes and may have produced the slope instability that eventually resulted in the landslide-generated tsunami.

Other Unusual Tsunami Sources

Recent surveys of the continental slope off the United States East Coast has revealed unstable areas. These areas may have the capacity to generate landslide tsunamis. In addition a number of historical storm events were accompanied by waves that were atypical for such meteorological events. These hurricanes may have triggered landslides in unstable areas which, in turn, may have caused real tsunamis that accompanied or followed the hurricanes. All this information has increased the appreciation of the tsunami hazard on the east coast of the United States.

Driscolland others examining the continental slope about 100 miles off the northern New Jersey coast show that water trapped in sediments there may be highly pressurized and, if expelled violently, could cause undersea landslides which in turn could produce tsunamis. Another suggestion is that large quantities of natural gas are trapped in sediments off the Virginia coast. The use of sonar discovered cracks and gas eruption craters along the edge of the continental shelf. Landslides were found on the continental slope. Most, however, believe that the waves (tsunamis) produced by the release of water or gas under pressure would be no bigger than those waves produced by hurricanes that occur much more frequently in the region. (Driscoll, Weissel, and Golf, *Geology*, May, 2000)

There is a substantial danger of tsunamis along the East Coast of the United States that may have been underestimated previously. It is hoped that the information contained in this paper will provide hazard mitigators with needed information to protect the populations in their respective areas. It is also hoped that this information will stimulate further study of many of the phenomena contained in the paper so that the tsunami hazard can be more clearly defined.

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Appendix 1: LIST OF EARTHQUAKES AND CABLE INTERRUPTIONS IN THE ATLANTIC 25º - 50º N Latitude[1]

(Longitude 40º W to North American Coast)

Year-Date-Time	Earthquake Epicenter	Cable Break Time	Position	Remarks
1755, Nov. 18 04:15	42.6ºN 66.0ºW			210 n/m off Cape Ann
1831 July				Murray Bay, Bay of St. Lawrence.
1838 Sep. 27 03:20	31.7ºN 42.2ºW			"LaClaudine" shocks
1856 Jan. 6 10:30	25.4ºN 48.3ºW			"Fusilier" - 12 shocks
1869, Oct. 22 05:00				Ship enroute from Boston to New Brunswick
1881, Sep.			37º - 44ºW	
1883, May 10 06:00	29.9ºN 41.7ºW			"Arethusa" shock
1884, Oct. 3		21:15	46º-50ºW	
1884, Oct. 4		4:00	46º-50ºW	
1885, Nov. 6			48.1º- 43.8ºW	
1885, Apr. 18		20:00	37º-44ºW	
1885 Aug. 28 11:00	57.0ºN 46.3ºW			"Tjalfe" shocks
1887, Jan. 24	27.6ºN 43.9ºW			
1887, July 15		8:00	37º-44ºW	
1888, June			37º-44ºW	
1889, Sept.			37º-44ºW	
1889, Sept.			46º-50ºW	
1891, Aug. 23 10:30	36.7ºN 59.8ºW			"R. Harrowing" seaquake
1893, July 9			49.7ºN 40.2ºW	
1894, June 10			37-44ºW	
1894, June 11 7:22			46-50ºW	
1892, July			37-44ºW	
1895, Feb. 8			40.3ºN 72.7ºW	
1896, Apr. 11			43.7ºN 48.9ºW	
1897, July 3			44.0ºN 48.9ºW	
1897, July 30			43.9ºN 49.0ºW	
1898, Aug. 27			44.5ºN 58.9ºW	
1899, Feb. 12			40.8ºN 65.4ºW	

Year-Date-Time	Earthquake Epicenter	Cable Break Time	Position	Remarks
1899, Dec. 4			43.9ºN 49.9ºW	
1901, July 11			44.4ºN 58.8ºW	
1901, Aug. 27			44.1ºN 48.7ºW	
1902, Mar. 24 17:58	31.0ºN 80.0ºW			
1902, Sept. 24	31.0ºN 80.0ºW			
1903, June 14 19:39	32.0ºN 44.0ºW		44.4ºN 58.8ºW	
1903, Jan. 17 16:12	25.0ºN 88.0ºW			
1903, July 27 10.34	33.0ºN 57.0ºW			
1903, July 27 12.32	33.0ºN 57.0ºW			
1903, Sept. 14			43.0ºN 49.7ºW	
1904, May 5			43.0ºN 49.8ºW	
1904, Dec. 21			43.3ºN 49.4ºW	
1905, Apr. 6			42.7ºN 50.0ºW	
1906, July 15			44.7ºN 59.4ºW	
1906, Sept. 24			45.0ºN 48.9ºW	
1906, Oct.			48.1ºN 43.7ºW	
1908, Feb. 1 23:22	26.0ºN 67.0ºW			
1908, Mar. 21			47.3ºN 45.0ºW	
1908, Nov. 11			43.4ºN 49.2ºW	
1910, May 28			40.8ºN 65.5ºW	
1910, Aug. 11			40.0ºN 71.3ºW	
1911, Sept. 25			44.7ºN 61.0ºW	
1911, Dec. 2			42.6ºN 61.1ºW	
1912, Jan. 3			40.2ºN 67.5ºW	
1912, May 1			53.4ºN 40.5ºW	
1912, Jun. 12			25.1ºN 95.5ºW	
1914, Mar. 3			43.8ºN 61.1ºW	
1914, Oct. 22	29.3ºN 65.2ºW			
1914, Nov. 10	38.0ºN 70.0ºW			
1915, Aug. 28			51.1ºN 42.5ºW	
1915, Sept. 13			48.3ºN 41.5ºW	

Year-Date-Time	Earthquake Epicenter	Cable Break Time	Cable Break Position	Remarks
1915, Oct. 20			41.0ºN 65.0ºW	
1916, Mar. 10			44.7ºN 61.0ºW	
1917, June 7			39.8ºN 69.9ºW	
1917, Oct. 13			43.9ºN 57.0ºW	
1917, Nov. 7			44.7ºN 54.1ºW	
1918, Jan. 8			42.7ºN 61.1ºW	
1919, Jan. 8 1:47	25.0ºN 46.0ºW			
1919, Sept. 2			42.2ºN 61.8ºW	
1920, Aug. 12 6:12	25.0ºN 46.0ºW			
1920, Sept. 8			43.9ºN 56.5ºW	
1920, Sept. 17 23:51	32.5ºN 42.0ºW			
1921, Jan. 21			41.0ºN 64.8ºW	
1921, Mar. 7			39.8ºN 69.8ºW	
1921, Apr. 20 18:46	32.5ºN 48.0ºW			
1921, Aug. 19 8:34	34.5ºN 77.5ºW			
1921, Aug. 21 1:09	26.0ºN 50.0ºW			
1921, Oct. 28		13:30	48.6ºN 52.3ºW	
1921, Dec. 12		17:30	46.8ºN 55.4ºW	
1922, Jan. 3			46.3ºN 60.1ºW	
1922, Jan. 12		15:26	44.5ºN 63.1ºW	
1922, Apr. 21			39.8ºN 70.0ºW	
1922, July 26 6:31	50.0ºN 50.0ºW			
1922, July 28 23:43	32.5ºN 42.0ºW			
1922, Aug. 25				
1923, Mar. 31			49.0ºN 50.8ºW	
1923, May 31 22:06	31.3ºN 41.0ºW			
1923, July 19			40.2ºN 67.3ºW	
1923, Oct. 1		19:50	46.8ºN 55.8ºW	
1923, Oct. 2			46.5ºN 59.7ºW	
1923, Dec. 30			40.6ºN 41.5ºW	
1924. Feb. 29			46.1ºN 56.9ºW	

Year-Date-Time	Earthquake Epicenter	Cable Break Time	Position	Remarks
1924, July 12			39.9ºN 69.3ºW	
1924, Oct. 19 23:52	27.0ºN 42.0ºW			
1925, Nov. 15			39.9ºN 70.5ºW	
1925, Nov. 27		9:50	48.1ºN 53.2ºW	
1926, Jan. 7 14:31	33.0ºN 40.5ºW			
1926, Mar. 23			48.8ºN 52.3ºW	
1926, Aug. 19			44.6ºN 63.5ºW	
1927, Aug. 24			43.6ºN 61.1ºW	
1927, Aug. 24			44.8ºN 61.0ºW	
1929, Nov. 18 20:33	44.5ºN 55.0ºW			12 cables in 28 places

[1]de Smitt, V.P., 1932, *Earthquakes in the North Atlantic Ocean as Related to Submarine Cables*, Western Union Telegraph Company, NY, NY.

Appendix 1: TABLE OF TSUNAMIS AND TSUNAMI-LIKE WAVES OF THE EASTERN UNITED STATES

ORIGIN DATA			VALIDITY	CAUSE	TSUNAMI DATA							
DATE (GMT)	Time (UT) Latitude Longitude Magnitude [authority] Depth (km)	Area			MAG & INT	LOCATION OF EFFECTS	MAX RUN UP/ AMP (m)	1ST MOTION	PERIOD	ARRIVAL TIME (DAY-HR:MIN)	TRAVEL TIME (HRS)	COMMENTS
1668 05 13	9:00	Massachusetts	1	E		Boston and Salem, Massachusetts						River course was "swallowed up" and altered.
1755 10 04	10:00 AM	Lake Ontario	2			Lake Ontario	1.5					Water rose in an unusual way.
1755 11 01	10:24 36.0N 11.0W 8.0 (Mw)	Portugal	3	E		East Coast	3.0					Modeling results
1755 11 18	09:12 42.7N 70.3W 7.0 (ml)	Cape Ann, Massachusetts	1	E		Northeast coast of U.S.						Confused report for wave from Nov. 1, 1755, Lisbon earthquake at St. Martin, West Indies. Not observed in U.S.
1811 12 16 1812 01 16 1812 02 07	08:15 08:15 09:45 36.0 N 90.0W	New Madrid Earthquakes	3	E		Mississippi River						Boars torn from moorings by "great" waves
1817 01 08	39.95N 75.1W		2	E		Philadelphia, Pennsylvania	OBS					"Sort of a tidal wave"
1821 09 03		North Carolina Maryland New Jersey	1	M		Cape May County, New Jersey	OBS					Ocean withdrew. A wall of water carried one man 6 miles inland.
1823 05 30		Pennsylvania	1	E		Lake Erie	OBS					The water rose nine feet.
1840 11 14	39.8N 75.2W 5.2 (ml)	Pennsylvania	3	E		Philadelphia, Pennsylvania	OBS					Great swell on Delaware.

ORIGIN DATA		V A L I D I T Y	C A U S E	TSUNAMI DATA							
DATE (GMT)	Time (UT) Area Latitude Longitude Magnitude [authority] Depth (km)			MAG & INT	LOCATION OF EFFECTS	MAX RUN UP/ AMP (m)	1ST MOTION	PERIOD	ARRIVAL TIME (DAY-HR:MIN)	TRAVEL TIME (HRS)	COMMENTS
1871 06 18	Long Island 40.5N 73.9W	3	E		Long Island	OBS					"Tidal wave" struck Long Island
1872 11 17	New England 43.2N 71.6W 3.7 ml	2	E		Fox Islands, Maine	0.3		17			Fluctuations on tide gages.
					North Haven, Maine	0.3		17			Fluctuations on tide gages.
1879	Massachusetts	1			Nantucket, Mass	OBS					Wall of water observed by small craft in channel between islands.
1884 08 10	19:07 New England 40.6N 74.0W 5.6 ml	4	E		Philadelphia, PA	OBS					Huge waves...overflowed many wharves and considerable property was flooded. Several persons soaked by waves.
					Trenton, New Jersey	OBS					Water in the city reservoir was agitated and a small tidal wave was noticed on the canal and feeder.
					Highlands, New Jersey	OBS					Two gentlemen who were out fishing experienced wave effects
1884 09 19	Michigan	2	E		Detroit River	OBS					A wave or ground swell was reported
1886 08 31	21 50 Charleston South Carolina 32.9N 80.0W 7.7 (Mw)	4	E		Mayport, Florida (suburb of Jacksonville)	OBS					"...a sudden wave dashed high over the beach and a rumbling noise was heard, the earth and houses shook like leaves on the trees."
					Jacksonville, Florida	OBS					"...sailors dashed ashore as their vessels rocked and heaved on violent waves that whipped against the shore."

ORIGIN DATA			VALIDITY	CAUSE	TSUNAMI DATA							
DATE (GMT)	Time (UT) Latitude Longitude Magnitude [authority] Depth (km)	Area			MAG & INT	LOCATION OF EFFECTS	MAX RUN UP/ AMP (m)	1ST MOTION	PERIOD	ARRIVAL TIME (DAY-HR:MIN)	TRAVEL TIME (HRS)	COMMENTS
1895 09 01	11:09 40.7N 74.8W	Long Island, New York	4	E		Arverne by the Sea Long Island, New York	OBS					"monstrous wave swept oceanward"
1895 10 31		Charleston, Missouri	1	E		Green Bay, Wisconsin	OBS					Slight "tidal" wave on the bay.
1909 09 22			2	M		Grand Island	OBS					300 lives lost - coast line lapped by tidal wave for twenty-five miles. "Just as...people were trying to bring order out of chaos following the terrible storm, the tidal wave came and swept them away."
						Houma, Louisiana	OBS					Large number of homes destroyed.
						New Orleans, Louisiana	OBS					"A city of desolation"
1912 04 13		Lake Erie	2	M		Lake Erie						"Immense tidal wave swept the southern shore of Lake Erie." "Ice washed 600 feet back up river at Painesville"
1913 09 09		New Jersey	3	L		Longport, New Jersey						Cave in caused $10,000 damage. Waters washed out 250 feet along railroad track.
1918 10 11	14:14 18.5N 67.5W 7.3 (Mw)	Puerto Rico	4	E	2.0	Atlantic City, N.J.	<0.1	F	15	10-19:00		Registered on tide gage.
1918 10 25	03:43 18.5N 67.5W	Puerto Rico	4	E		Galveston, Texas	OBS.					Recorded on tide gage; not reported in Puerto Rico.
1922 05 02	20:24	Puerto Rico	2	E		Galveston, Texas	0.6		45			Unlikely that waves were produced by this earthquake. Not reported in Puerto Rico.

ORIGIN DATA			V A L I D I T Y	C A U S E	TSUNAMI DATA							
DATE (GMT)	Time (UT) Latitude Longitude Magnitude [authority] Depth (km)	Area			MAG & INT	LOCATION OF EFFECTS	MAX RUN UP/ AMP (m)	1ST MOTION	PERIOD	ARRIVAL TIME (DAY-HR:MIN)	TRAVEL TIME (HRS)	COMMENTS
1923 08 06		New York	1	?		Rockaway Park, Queens, New York						Two children drowned by huge wave.
1924 08 08		Coney Island, New York	1			Coney Island, New York						15 ft wave injured several. Hundreds knocked down.
1926 01 09		Maine	2	L	1.5	Bernard, Maine	3.0	F	<10			Boats broke moorings.
						Corea, Maine	OBS					Lobster cars smashed, boats set adrift, flounder washed from winter beds.
						Vinallhaven, Maine	0.2					Felt "earthquake" shock
1929 08 12	11 24 42.9N 78.4 W 5.8 ml	Attica, New York	2	E		Horseshoe Lake, New York						A big wave rolled from the south to the north of Horseshoe Lake and over the road.
1929 11 18	20:32 44.5N 56.3W 7.4 (Mw)	Grand Banks, Newfoundland	4	E	3.0	Atlantic City, New Jersey	OBS					Recorded on tide gage
						Bar Harbor, Maine	OBS					Waves reported; severe storm in progress.
						Barnstable, Mass.	OBS					High tides.
						Belfast, Maine	OBS					Waves reported.
						Block Island	OBS					High tides.
						Charleston, South Carolina	OBS					Recorded on tide gage.
						Ex[illegible]r, N[illegible]	OBS					High tides.
						Ocean City, Maryland	0.3					
						Portland, Maine	OBS					Waves reported.
1931 08 19	6:30 LT	Atlantic City, New Jersey	1 2	M		Atlantic City, New Jersey						15 ft waves drowned one, two missing

ORIGIN DATA		V A L I D I T Y	C A U S E	TSUNAMI DATA							
DATE (GMT)	Time (UT) Area Latitude Longitude Magnitude [authority] Depth (km)			MAG & INT	LOCATION OF EFFECTS	MAX RUN UP/ AMP (m)	1ST MOTION	PERIOD	ARRIVAL TIME (DAY-HR:MIN)	TRAVEL TIME (HRS)	COMMENTS
					Wildwood						One death
					Point Pleasant Beach	OBS					Bather injured.
1932 11 10	6:30 EST		E		Willetts Point, New Jersey	5.4					Invasion of the sea
1938 09 21	New Jersey	1	M		New Jersey	10-15					30-50 ft waves
					Atlantic Highlands	OBS					Waves washed blocks inland
					Seaside Park						Waves washed blocks inland, $90,000 in damage to boats, houses, and boardwalk.
					Avon	9					Boardwalk washed out, $50,000
					Belmar	9					Boardwalk washed out, $100,000 damage, boats sunk.
					Spring Lake	9					Boardwalk washed out
					Sea Grit	9					Boardwalk washed out, $5,000 damage
					Point Pleasant	9					Boardwalk washed out
					Keansburg	OBS					Roads flooded
					Atlantic Highlands	OBS					Considerable damage to boats & docks
					Long Branch	OBS					Pier wrecked
					Allenhurst	OBS					$10,000 damage
					Asbury Park	OBS					$50,000 damage
					Ocean Grove	OBS					$15,000 damage

ORIGIN DATA		VALIDITY	CAUSE	TSUNAMI DATA							
DATE (GMT)	Time (UT) Area Latitude Longitude Magnitude [authority] Depth (km)			MAG & INT	LOCATION OF EFFECTS	MAX RUN UP/ AMP (m)	1ST MOTION	PERIOD	ARRIVAL TIME (DAY-HR:MIN)	TRAVEL TIME (HRS)	COMMENTS
					Bradley Park	OBS					boardwalk damaged
					Manasquan	OBS					3 waves, water 1 meter deep several hundred meters inland.
					Brielle	OBS					Boats buffeted
					Point Pleasant	OBS					Fishing pier swept away about $255,000 damage
					Point Pleasant Beach	OBS					Boardwalk destroyed
					Bayhead	OBS					Boats damaged
					Mantoloking	OBS					Flooding
					Chadwick	OBS					$10,000
					Seaside	OBS					Boats damaged
					Seaside Park						$45,000 in damage. Two houses washed out to sea, one injured resident was rescued while clinging to his house
					Atlantic City	OBS					Collapse of bridge into Absecon Inlet, $800,000 damage.
					Sandy Hook	OBS					
					New York Harbor, NY	OBS					
					Gloucester, MA	15.4					
1944 Summer		1	?		Sea Gate or Coney Island, Brooklyn	OBS					Sudden wave comes on shore in good weather.
1944 09 14		1	?		Asbury Park	OBS					Damage to Casino, roller skating tink and convention Hall. Flooding

ORIGIN DATA		VALIDITY	CAUSE	TSUNAMI DATA							
DATE (GMT)	Time (UT) Area Latitude Longitude Magnitude [authority] Depth (km)			MAG & INT	LOCATION OF EFFECTS	MAX RUN UP/ AMP (m)	1ST MOTION	PERIOD	ARRIVAL TIME (DAY-HR:MIN)	TRAVEL TIME (HRS)	COMMENTS
					Ocean Grove	OBS					Pavilion destroyed, two restaurants wrecked.
					Long Branch	OBS					Chelsea Baths destroyed
					Deal	OBS					89 m of pier destroyed.
					Avon	OBS					Part of Pavilion knocked into street
					Belmar	OBS					Pavilion destroyed, piers heavily damaged.
					Spring Lake	OBS					Boardwalk swept onto lawns
					Manasquan	OBS					Boardwalk totally destroyed.
					Brielle	OBS					Sections of boardwalk destroyed
					Sea Grit	OBS					Boardwalk and bath houses wrecked.
					Point Pleasant Beach	OBS					Boardwalk destroyed.
					Mantoloking	OBS					Garages smashed, homes badly damaged.
					Bay Head	OBS					Homes damaged.
					Long Beach Island	OBS					Hundreds of cottages and cars swept away.
					Southern end of Long Beach Island	OBS					Roofs removed from houses. Houses jammed into other buildings
					Harvey Cedars	8					Large home destroyed
					Holgate	OBS					House washed into bay.
					Atlantic City	OBS					The Brigantine bridge was destroyed (again)

ORIGIN DATA		VALIDITY	CAUSE	TSUNAMI DATA								
DATE (GMT)	Time (UT) Latitude Longitude Magnitude [authority] Depth (km) / Area	VALIDITY	CAUSE	MAG & INT	LOCATION OF EFFECTS	MAX RUN UP/ AMP (m)	1ST MOTION	PERIOD	ARRIVAL TIME (DAY- HR:MIN)	TRAVEL TIME (HRS)	COMMENTS
					Sea Isle City	OBS					24 houses washed off foundations
					Cape May	OBS					Beach drive washed out
1946 08 04	17:51 18.9N 68.9W 8.1 (Mw) Dominican Republic	4	E		Atlantic City, New Jersey	OBS				4.8	Recorded on tide gage.
					Daytona Beach, Florida	OBS				4.0	Recorded on tide gage. (See also Puerto Rico/Virgin Islands section.)
1946 08 08	13:28 19.7N 68.5W 7.4 (Mw) 16 Dominican Republic	4	E		Atlantic City, New Jersey	OBS				4.7	Recorded on tide gage.
					Daytona Beach, Florida	OBS				4.0	Recorded on tide gage. (See also Puerto Rico/Virgin Islands section.)
1952 05 06	Lake Huron	1	?		Lexington, Michigan	1.5					Water poured through the windows of a marine restaurant.
					Harbor Beach, Michigan	OBS					A boat livery at Harbor Beach, Michigan was damaged. Coast Guard grounds flooded.
					Port Huron, Michigan	0.3					Many homes flooded briefly
1954 06 26	Lake Michigan				Chicago, Illinois	2.0					Wave swept over an eight foot sea wall at Loyola University. Total of 8 persons dead.
1964 05 19	Northeast Coast U.S.	3	L ?		Atlantic City, New Jersey	OBS?					High frequency noise, unreadable.
					Battery, New York	OBS?					Feeble recording.
					Montauk, New York	0.1	R	15.0	19-22:42		Activity continues for over 8 hours.
					New London, Connecticut	OBS			19-22:39		Feeble.
					Newport, Rhode Island	<0.1	R	11.0	19-22:39		

ORIGIN DATA		VALIDITY	CAUSE	TSUNAMI DATA							
DATE (GMT)	Time (UT) Latitude Longitude Magnitude [authority] Depth (km) / Area			MAG & INT	LOCATION OF EFFECTS	MAX RUN UP/ AMP (m)	1ST MOTION	PERIOD	ARRIVAL TIME (DAY-HR:MIN)	TRAVEL TIME (HRS)	COMMENTS
					New Rochelle, New York	OBS			19-22:14		Feeble.
					Plum Island, New York	0.3	R	4.0	19-22:25		Contrast on record poor but initial 10 cycles of short period waves visible.
					Port Jefferson, New York	OBS			19-23:10		Weak beginning
					Providence, Rhode Island	OBS					Weak.
					Sandy Hook, New Jersey	OBS					Feeble.
					Willets Point, New York	<0.1			20-00:00		
1992 07 03	Daytona Beach, Florida	0	M		Daytona Beach, Florida	3					
					St. Augustine, Florida	OBS					
					New Symrna Beach, Florida	OBS					

THE TSUNAMI HISTORY OF GUAM: 1849-1993

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ABSTRACT

The great (Mw 8.1) tsunamigenic earthquake of August 8, 1993, about 50 km to the east of Guam, has created renewed interest in the tsunami hazard for the island of Guam. We examine this hazard from two perspectives--historical and mechanistic. Guam has had only three tsunamis causing damage at more than one location--in 1849, 1892, and in 1993, and only two to six other locally-generated tsunamis which were observed on the island in the past 200 years. Five of these six events have low validities and may not be reports of true tsunami. On the other hand, dozens of storm surges related to typhoons have caused millions of dollars of damage on Guam. The island of Guam is located west of the Marianas Trench. The trench is caused by the subduction of old, cold, and dense lithosphere of the Pacific plate under the Philippine plate. Steeply dipping old material is unlikely to trigger tsunamis because (1) the two plates are decoupled and (2) the motion is too slow to allow large amounts of stress to build up before earthquakes occur, resulting in less violent earthquakes. A small section of the Marianas Trench near Guam, however, has shallow subduction. This is where the 1993 event occurred, and a quiet area south of this may be the site of a similar future tsunamigenic earthquake. Most of the damage from a local tsunami would occur on the relatively unpopulated east coast; the likelihood of a local tsunami from the west is minimal. However, a repeat of the 1848 tsunami with a southern source could affect both the east and west coasts. The 1993 earthquake occurred coincident with the passage of Typhoon Steve. We show that this may not be coincidental as there is a substantial statistical correlation between earthquakes and typhoons at Guam. The close encounter of a typhoon with Guam doubles the probability of an earthquake with magnitude greater than 5.0 occurring on that day.

INTRODUCTION

Guam, located about 50 km west of the axis of the Marianas Trench, one of the world's deepest at 9650 m, has a history of strong seismic events. Major earthquakes were reported in 1809, 1822, 1825, 1834, 1837, (Degraz, 1838) 1849, 1892, 1902, and 1909 (Repetti, 1939). An unconfirmed tsunami has also been reported from the late 18^{th} Century as having caused severe damage in Agana and Umatac with several fatalities. This event has been reported as having occurred in 1767 (Farrell); 1769 (*Guam Reporter*, Jan. 1929, p 217); 1779 (?) and 1799 (Maso 1910). Degraz (1838) reported that in the month of October 1837, an extraordinary movement of the sea was experienced. A type of tempest disturbed it and it flooded raised portions of the banks, caused landslides and considerable damage. This was also a year of a reported major earthquake. He also reported similar movements for the 1809 and 1825 events where some ships experienced violent shocks near Guam. The 1837 event caused four of the Caroline Islands to disappear and only parts of two to remain above water level. Survivors emigrated to Guam and settled on Saipan. Surprisingly, Guam has a history of directly and clearly observing only a few tsunamis, including those local tsunamis in 1849, 1892, 1990 and 1993 and teletsunamis from the 1952 Kamchatka earthquake and the 1960 Chile earthquake. Only minor damage has resulted from these tsunamis with the 1849 event being the largest event. There is a report of a possibly observed local tsunami in 1903 but this given a low validity event.

Storm surges are also an urgent problem in Guam, reaching several meters in height, often coming unexpectedly, and occasionally causing extensive damage. For example, Soloviev and Go (1984) cite Dumolin (1940) that in October of 1837, just 12 years before the tsunamigenic earthquake of 1849, a strong storm surge did considerable damage on Guam and caused four low-lying islands in the Caroline group to be submerged. Two islands later reappeared and the other two became banks. The earthquakes of 1849 and 1993 produced similar intensities, although it is difficult to make direct comparisons due to different construction practices over time. The main reference for the 1849 event is Professor Marjorie G. Driver's translation of Governor Perez's report of the earthquake and tsunami effects to his superiors in the Philippines. The main reference for tsunami effects for the 1993 event is report of interviews by Judy Flores for a University of Guam class project in 1993. The resulting tsunamis affected the eastern and southern coast, with the 1849 event being the larger. This event caused Guam's only reported tsunami fatality. There are reports of the 1849 event strongly affecting the Caroline Islands of Satawal and Lamotrek that were completely overrun by large waves resulting in many casualties. There is also a report that the earthquake was felt aboard a ship 1000 kilometers from Guam. As the 1993 Mw 8.1 event was not reportedly observed in the Caroline Islands, the effects reported from the Caroline Islands in 1849 may be a separate tsunami or storm surge. The report of a remote earthquake felt on shipboard may also have been a separate event. The 1892 tsunami report mentions only a drop in water level in Agana Harbor and flooding of the San Antonio quarter that probably was caused by a submarine landslide inside the harbor.

The limited reports of the 1990 and 1993 events raises a question of the completeness of the history, but it is unlikely that an unreported destructive tsunami could have happened on Guam since the Spanish era beginning with contact in 1565 and settlement in 1668. The United States took over the administration of Guam in 1897. The marigraph was first installed in Apra Harbor in 1950. The Mw 8.3 earthquake at Hokkaido, Japan, in 1952, produced a tsunami which was recorded in Agana with an amplitude of 10 cm. Waves of 1.5 m were reported observed in Ylig Bay. All other recorded tsunamis had heights of 10 cm or less except the great 1960 Chile tsunami which had a height of 20 cm. The 1960 event was not reported observed on the eastern coast but this may reflect the frequent under reporting of tsunami observations at Guam. The lower heights may reflect that Agana is a sheltered harbor on the western coast and that instrumental measurements are usually significantly lower than the actual waves amplitudes. The 1993 event produced waves observed all along the eastern and southern coasts with a maximum height of about 2 meters and it was recorded in Agana and Apra with heights of only 10 and 15 cm respectively. However, the earthquake damage (more than $267 million per Hattori, 1995) was so severe that tsunami effects were largely unreported in the scientific community until a year later. Much of the damage occurred in structures damaged by the earthquake and then soaked by 1.9" of rain from Typhoon Steve that passed near Guam on the date of the 1993 earthquake.

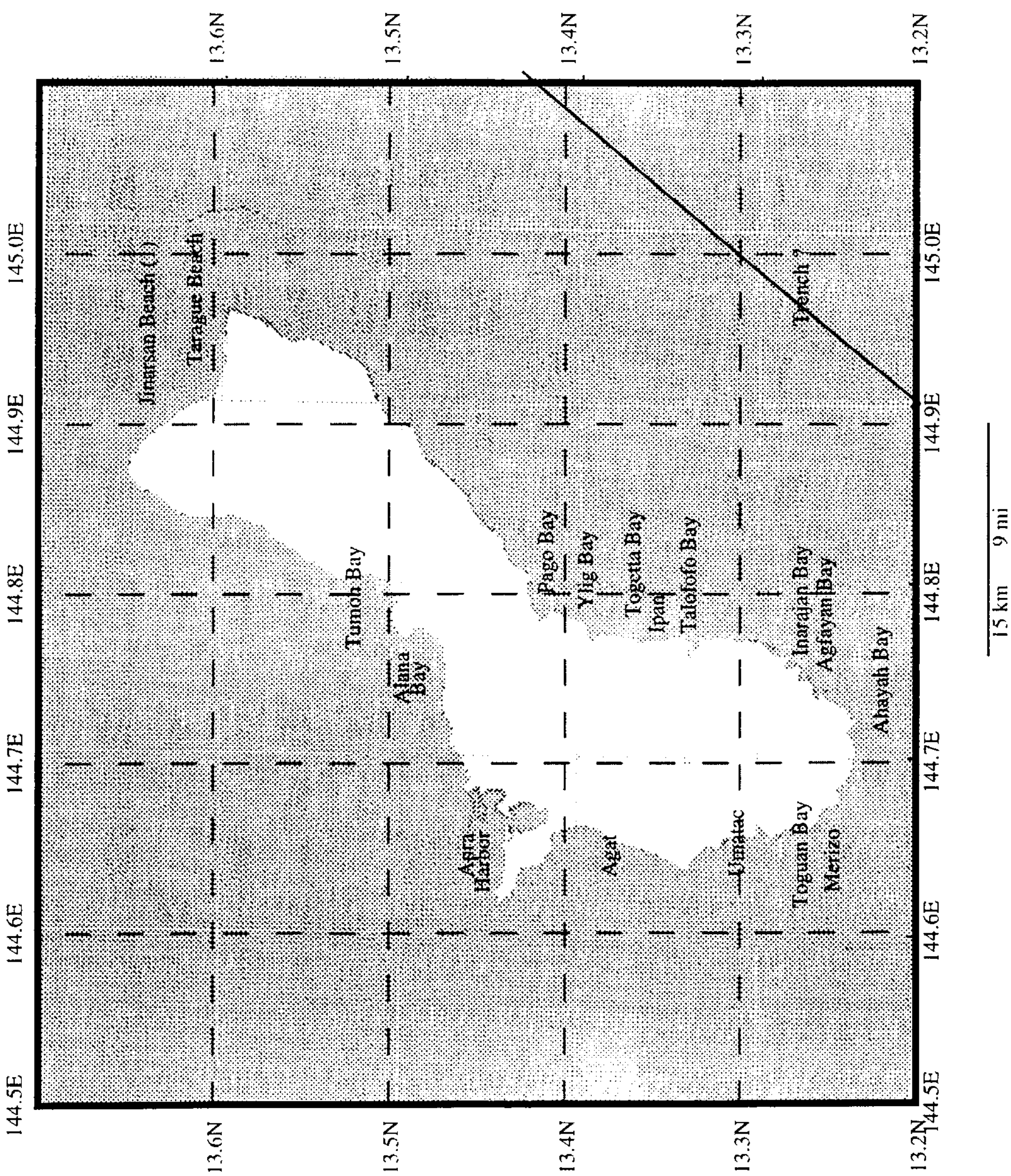

Figure 1. A simplified map of Guam, showing major bays.

TSUNAMI HAZARD FOR GUAM

To understand the potential hazard to the Island of Guam from tsunamis of local origin, it is necessary to understand the tectonics and seismic history of the region. Unfortunately, seismic history is available only from the early portion of the 19th Century, and is probably considerably under-reported until the advent of the WWSSN system and usable teleseismic catalog in the mid-1960s. The known tsunamis that have been observed and their effects on Guam are tabulated in the Appendix.

The Island of Guam (Figure 1) is located at the southern portion of the Mariana Islands arc. The Pacific plate is subducting beneath the Philippine plate with the Marianas Trench marking the boundary between these plates. This boundary is located about 50 km to the east of Guam. The Pacific plate in this region is among the oldest subducting plates in the world (age of about 200 million years). Because of it's age, it is thicker, denser, cooler and more brittle than most subducting material. Its high density with respect to the upper mantle causes the material to sink rapidly into the mantle once subduction has begun. This, in turn leads to a steep angle of subduction (>50 degrees) and the great depth of the Marianas Trench (Wortel, 1980). Because the Pacific plate is so dense, and therefore sinking rapidly with respect to the Philippine plate, the Mariana Islands arc is generally regarded as the archetype of a seismically decoupled subduction zone (Ruff and Kanamori, 1983). Furthermore, Ruff and Kanamori (1980) have demonstrated that in decoupled seismic zones, large (Mw>=7) earthquakes are rare and that great earthquakes (Mw>=8) should not occur. For most of the Mariana Islands arc this has been the case. While earthquakes in the magnitude range 5-6 occur at a rate of 5 to 8 per year within 400 km of Guam, earthquakes in the magnitude range 6-7 occur only on average once in ten years and quakes greater than 7 occur about once in 100 years. Figure 2 shows that when the dip of a subduction zone is between 45 and 90 degrees, the chance of tsunami generation is small. We define the efficiency of producing tsunamis defined by (1):

(1) $Et = Nt*100/N7$

where Et is the efficiency of producing tsunamis, Nt is the number of observed tsunamis and N7 is the number of regional events with Mw>=7.0. Et is quite low in the Mariana Islands region. In other words, decoupled subduction zones (with high dip and relatively low subduction velocity) are unlikely to produce significant tsunamis. We have used the regionalization of Wortel (1980) and his numerical dip, and age data for plates and subduction zones, the Preliminary Determination of Epicenters (USGS, 1993) for magnitudes and locations of earthquakes and the listing of historical tsunamis (Lockridge, 1996) from the NGDC database found on the Seismicity CD-ROM (Whiteside et al. 1996) to produce Figure 2.

However, in the region of Guam, the tectonic situation is slightly different from that in the rest of the Marianas arc. Figure 3a shows the historical seismicity (Whiteside et al. 1996) for the region of Guam. Several patterns can be seen in this figure. To the east of Guam and running on a line SW-NE there is a pattern of shallow seismicity extending from the trench toward Guam for about 50 km. Between this shallow seismicity band and a second band of seismicity to the north of Guam is a region about 50 km wide of little or no seismic activity. This is followed by a third band of seismicity, extending for about 50 additional km. This seismicity is composed of deep or intermediate focus earthquakes. An additional region of seismic quiescence can be seen between 12.2N 144E and 13N 144.6E (approximately the location of the August 1993 event).

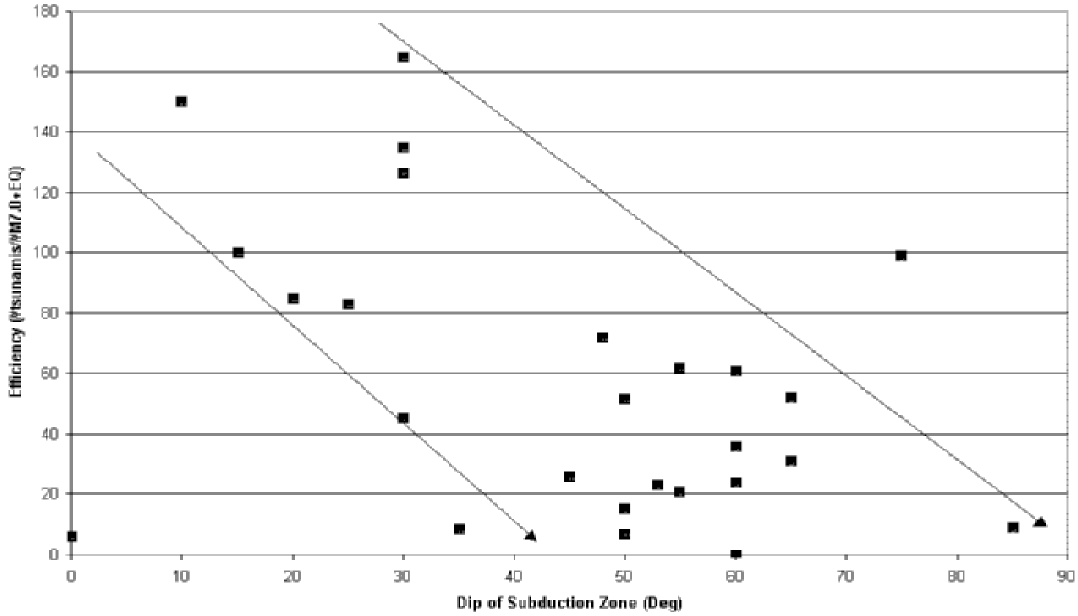

Figure 2. Subduction Zone Dip compared with calculated tsunami efficiency for tsunamigenic earthquake of Mw>=7. Tsunami efficiency is defined as the number of occurring tsunamis divided by the number of earthquakes of Mw>7 times 100.

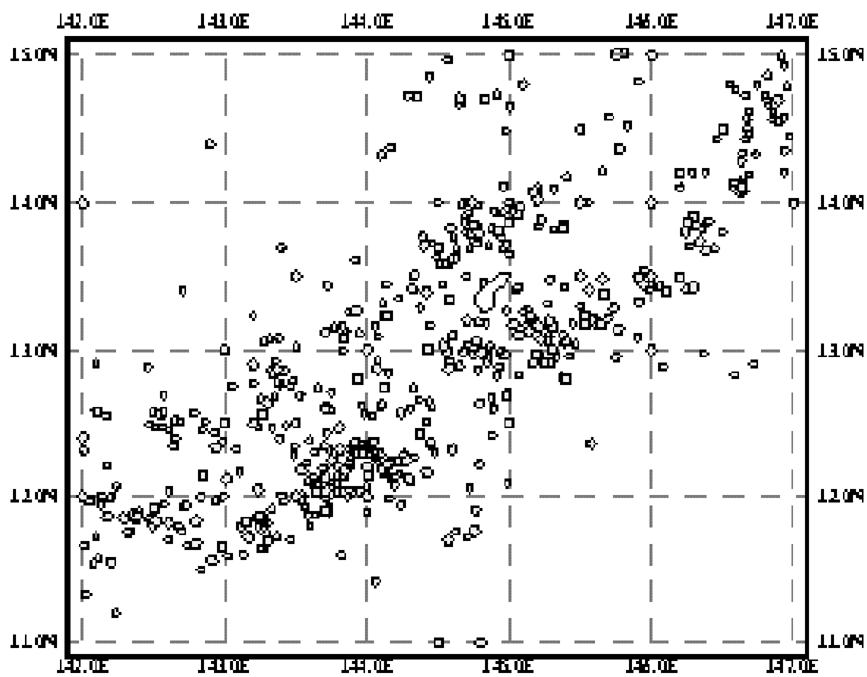

Figure 3a. Historical seismicity for the region of Guam, 1900-2001.

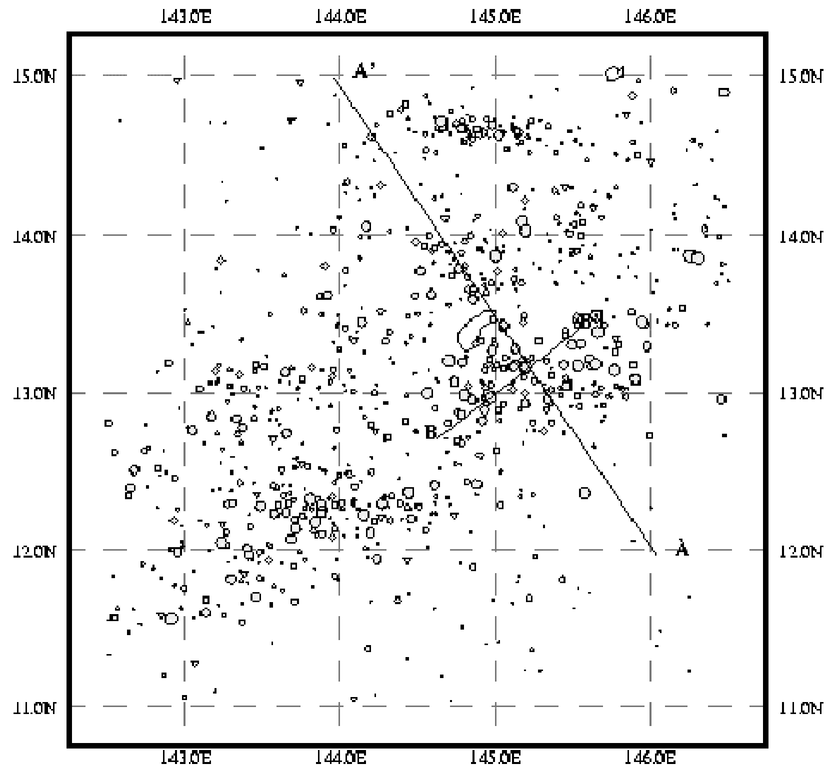

Figure 3b. Aftershocks and other seismicity near Guam following the earthquake of August 8, 1993 (1993-2001).

The 1993 event appears to have begun at 12.9N 144.8E and ruptured northeast with two subsequent events about 15 km to the NE and about 100 km to the NE (Campos et al. 1996). Li and Nabelek (1996) found that the CMT mechanism showed a time delay of 24 seconds with long period Rayleigh wave arrivals from the PDE epicenter. This is consistent with a rupture propagating at 3 km/sec to the CMT solution location about 70 km distant. Aftershocks of the 1993 event are shown in Figure 3b. The complex nature of this earthquake is confirmed by the observations of damage at the Seismological Observatory in Guam (Hattori, 1995) who noted that the pattern of breakage and fallen objects was consistent with "'two different mechanisms' … two different events close together, one from the SSE and the other from the SSW."

The 1993 earthquake hence appears to have filled a portion of a seismic gap between 13N and 14N and 145E and 146E. The seismically quiet section between 12 and 13N and 144 and 145E, however remains unruptured and may represent a significant threat of a tsunamigenic earthquake in the future.

Figure 4a shows a cross-section of seismicity within 150 km of either side of cross-section line AA'. The seismicity seen as bands on Figure 3a is shown as a change in subduction style in Figure 4a. The Pacific plate moving at about 3 cm/year encounters the Philippine plate about 50 km east of Guam (from direction A, Figure 4a). For about 50 km the subduction is shallow and with a low angle thrust. Near Guam, the direction of subduction changes dramatically. This change occurs in the region underlying the aseismic band on Figure 3a. To the west of this, the plate subducts at an angle between 60 and 80 degrees. Because of the aseismic nature of the bend, it is possible that the plate is broken at this section with two portions to the west and east of Guam detached from each other. If this is the case, large earthquakes directly under Guam are highly unlikely and this breakage in the plate may be the conduit for volcanic materials to rise through, creating the Island arc, including Guam. Figure 4b examines the eastern portion of the subduction more closely. The 1993 mainshock is marked by a triangular symbol. The approximate extent of the Pacific plate is outlined by arrows.

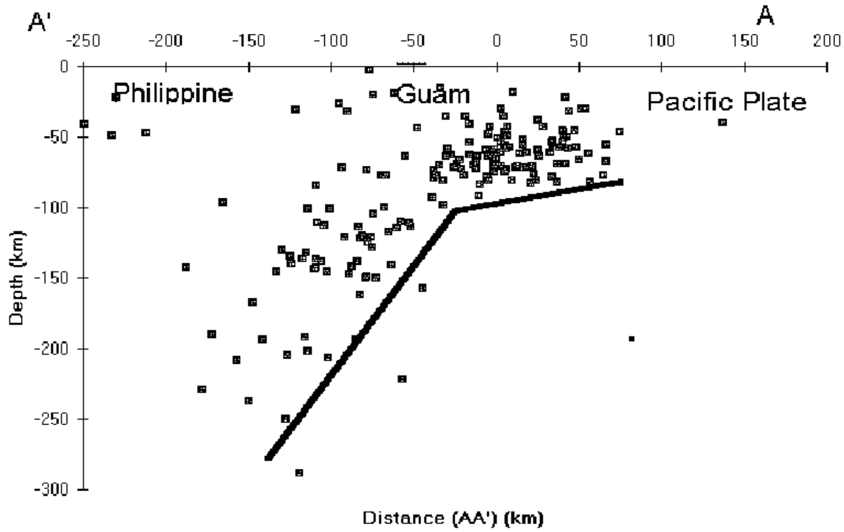

Figure 4a. Cross section of seismicity along line AA' from Figure 3b.

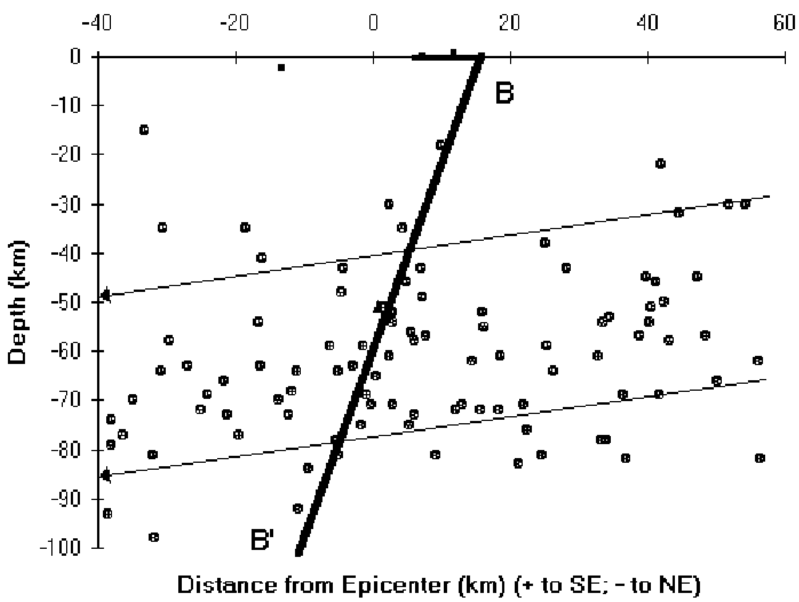

Figure 4b. Cross section of seimicity along line BB' from Figure 3b.

We find that the empirical dip of this plate in this region is about 13 to 15 degrees to the northwest. This observation confirms the modeling of Campos et al. (1993) who find that the dip of the fault plane was 13.77 degrees dipping to the NW. However, it is in sharp contrast with work of Tanioka et al. (1995) who modeled tsunami waveforms and proposed a steeply dipping fault plane cutting through the subducting slab. There is, however, some evidence in Figure 4b for an auxiliary fault plane similar to that modeled by Tanioka et al. at an angle of about 70 degrees with the vertical and passing through the hypocenter of the mainshock.

In general, the Campos et al. model provides the better match with the GPS data from Beaven (1994) that showed a 25 cm horizontal movement while the Tanioka et al. model reproduces the tsunami more accurately. Both are based to some extent on the Beaven GPS data. We, however, feel that since the Island of Guam (where the GPS data was obtained) may not be directly connected to either the westerly deeply subducting slab nor the easterly shallow subduction, the data may not describe the actual motion that is required to understand the earthquake or tsunami mechanism.

Most models of the mainshock of August 8, 1993 have determined a relatively deep hypocentral depth for the event. Depths range from Harvard CMT (59.3 km); USGS (68.0 km); Caltech (57.0 km) and Campos et al. (41.0 km). Depths around 60 km seem unlikely to be capable of producing a sizable tsunami, especially if they do not break through to the trench. To produce a tsunami, some differential motion of the ocean bottom must occur either directly from the event or from landslides secondary to the earthquake. A number of landslide and liquefaction events did occur in the coraline soils surrounding and on Guam (Mejia and Yeung, 1995), so the possibility exists that the tsunami was induced by mass motion of materials in the trench. The depths may also be in error. Both BJI (Beijing, China) and PDE report an earthquake on August 3 of Mb 5.1 - 5.3 whose epicenter is less than 2 km from the mainshock on August 8.

On the other hand, the epicenter of this moderate foreshock is listed as having a depth of 46 km by PDE and 37 km by BJI. These are in the depth range where a tsunami might be expected. If the mainshock nucleated at the epicenter of the foreshock, as might be expected, then it's depth would be shallower than that commonly modeled. The models are probably in error because they find the depth as a function of the average hypocenter given all first arrivals from the initial and sub-events of the mainshock or they locate the centroid not the hypocenter. If the initial rupture occurred at the top of the deeply dipping plane along line BB' on Figure 4b, then the average depth in the slab would be around 60 km as the models suggest. Nevertheless, earthquakes on the deeply dipping plane (BB') can be seen as shallow as 15 km +/-10 km. In this case motion at the surface could easily have triggered a tsunami. This mechanism is further supported by the difficulty of triggering a tsunami by horizontal motion of the ocean floor (Tanioka and Satake, 1996). While tsunamis can be generated by horizontal motion they are about ten times smaller than an equivalent tsunami generated by vertical motion. The nearly vertical fault plane hitting the surface at about 15 km to the SE of the mainshock would be an ideal candidate to trigger the observed tsunami.

We propose that both the Beavan and the Campos models are correct. The GPS data at Guam reflects the fact that the motion of Guam is mostly influenced by the dominant motion of the shallow slab pushing during the earthquake towards Guam. During the earthquake, however, a secondary fault ruptured (this is line BB' on Figure 4b). The tsunami was caused by this deeply dipping fault. This could be checked by examining the arrival times at various locations in Guam of the tsunami (if accurate times were available).

It appears that local tsunamis are not likely to be damaging to Guam because they will be generated to the east, while most of the settlement on Guam is on the western side of the island and because any generated tsunami is likely to be small because of the tectonics of the regions. The only likely area to produce a tsunami in the near future is in the seismically quiet region to the south of Guam.

THE TYPHOON CONNECTION

The earthquake of August 8, 1993 in Guam was closely associated with Typhoon Steve which dropped 1.89 inches of rain on Guam on the same date. Winds from Typhoon Steve measured more than 40 m/sec (Joint Typhoon Warning Center, 1994). Dunbar and Whiteside (1994) have proposed that the winds and microseisms from hurricanes can trigger nearby earthquakes when stresses are appropriately high in the earthquake region. An alternative hypothesis suggests that pressure changes associated with the extreme low pressures associated with typhoons and hurricanes causes the land to rise under a reduced load. This is a reasonable hypothesis when the earthquake occurs under land, but over the ocean, a change in pressure in the atmosphere is generally compensated for by an increased elevation of the water level, but the total column of air plus water retains a relatively constant mass because both the air and water are fluids. The resulting pressure on the sea floor and the subduction zone would remain unchanged. While the study by Dunbar and Whiteside examined hurricanes off the west coast of Mexico and the central Atlantic Ocean, the mechanisms are equally appropriate for typhoons in the region of Guam. The eye of Typhoon Steve passed about 80 km to the north of Guam on the 8th of August. Winds were pushing on Guam (and the Marianas arc) from the southeast. The resulting stresses would have pushed Guam and the Philippine plate to the northwest and reduced the normal stress between subducting Pacific and the overriding Philippine plates. This reduction in normal stress results in a loss of friction, which can trigger an earthquake.

We have examined the history of the association of typhoons and earthquakes in the region of Guam. Figure 5 shows the number of earthquakes of Mb>=5 in the region as a function of the time delay between the earthquake occurrence and the closest approach of a typhoon which ultimately passes within 500 km of the island of Guam. The delay time is the difference in time between the date of the closest approach of the typhoon and date and time of the earthquake. Numbers of earthquakes are summed over one-day intervals. Figure 5 shows that far more earthquakes occur within one day of the arrival of typhoons than on any other day in the 20-day interval shown (10 days before and 10 days after the closest approach of the typhoon). Data are from the annual "Typhoons of the Western Pacific Ocean" tabulations and typhoon paths (Joint Typhoon Warning Center, 1959-1994) for the time period 1959-1993 (data from 1960-1962 are missing). Earthquake data is from the Seismicity Catalog CD-ROM (Whiteside et al. 1996).

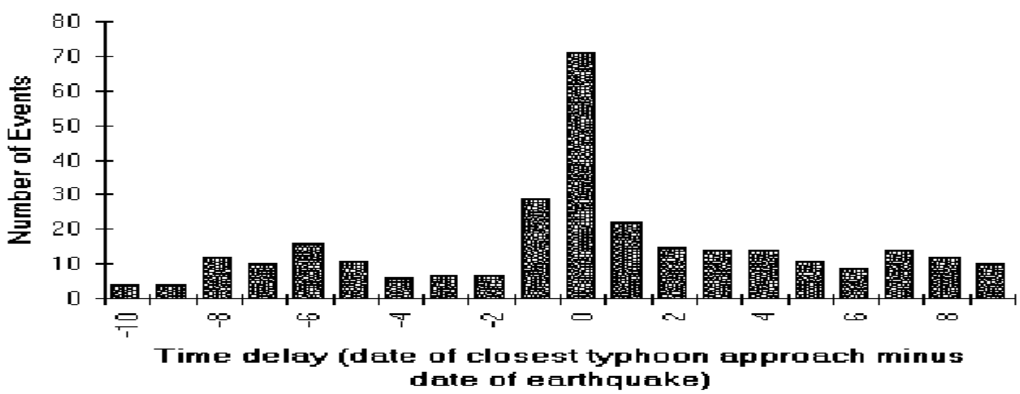

Figure 5. Comparison of number of earthquakes (M>=5) occurring at delay times of closest approach of typhoons to Guam.

The strong peak at zero time difference corresponding to coincidence between magnitude 5+ earthquakes and closest approach of typhoons to Guam is somewhat overstated on Figure 5 because when aftershocks of M 5+ occur they are included in the count. Therefore, when there are a number of aftershocks on a particular day, the count for that day may be more than one. This can be corrected by counting the total number of typhoons that are associated with an earthquake within a day of their closest passage to Guam. There were 107 coincidences between typhoons and earthquakes during the period 1959 to 1993. During this same time interval there were 582 earthquakes of M>=5.0 recorded in the area and a total of 185 +/- 10 typhoons passed within 500 km of Guam of which 109 were associated with an earthquake near Guam which occurred within 1 day of the closest passage of the typhoon.

The statistical analysis of the coincidence between earthquakes and typhoons in Guam is summarized in Table 1. Statistics are based on 34 years of earthquake and typhoon data (1959-1993) (12418 days), M>=5 in the area defined by Figure 1. Due to missing data and errors in both the earthquake and the typhoon catalog statistics are approximate only.

Table 1. Coincidental statistics for typhoons triggering earthquakes in the Guam region.

Total number of earthquakes vs. total number of typhoons:

	# Observed	Interevent Time	Daily Probabilities	Coincidences/Tsunami/Earthquake	
Q	582	21.3	0.015/0 .045	Expected # /34 years	Observed #
T	185	67.1	0.047/0.140		
				81.8	123

Total number of Earthquake Days vs. total number of typhoon days:

	# Observed	Interevent Time	Daily Probabilities	Coincidences/Tsunami/Earthquake	
Q	477	26.0	0.038/.115	Expected #/34 years	Observed #
T	185	67.1	0.015/.045		
				54.9	109

Q: Number of quakes or in the second instance the number of days on which quakes were observed in the time period
T: Number of typhoons observed to come within 500 km of Guam during the time period.
Interevent time: Average number of days between quakes or quake days or typhoons.
Daily probabilities: Probability that a quake or quake day or typhoon will occur on a given day or after the slash during a given 3-day interval (+/- 1 day)
Expected #: Number of coincidences between typhoons and earthquakes expected during the 34 year period.
Observed #: Number of observed coincidences between typhoons and earthquakes expected during the 34 year period.

From Table 1 we see that 1.5 times as many quakes are coincident with typhoons as are expected and that 2.0 times as many days on which quakes occur are coincident with typhoons as expected. This means that of the 123 observed coincidences about 41 are probably triggered by stresses induced by the typhoon, and that of the 109 days on which both typhoons and earthquake occur, in about 54 there is probably a causative relationship between the typhoon and the earthquake. It should be noted that since 1985, some of the best coincidences are the result of earthquakes reported by NAO (the NORSAR array) but by no other teleseismic network. It is possible that NAO is misidentifying arrivals from the microseismic activity due to the typhoon as earthquakes. This would reduce the significance of the above results, but there are too few of these events (10) to reduce results to insignificance. The results would still require 31 triggered earthquakes and 44 excess earthquake days.

CONCLUSION:

Guam is located near the Marianas Trench, a subduction zone of high seismic activity. While several M>=8.0 earthquakes have occurred near Guam in recorded history, none have produced the devastating tsunamis often associated with great earthquakes in other subduction zones, such as Chile or the Kuril Islands. We have shown that this is probably due to the age of the subducting Pacific plate and slowness of the subduction. This decouples the plates to the extent that large earthquakes in the deeply dipping subduction zone are unlikely. The large tsunamigenic earthquakes of 1849 and 1993 occurred to the east of Guam in the shallow dipping region of the subduction. Because the extreme depth of the trench, large tsunamis do not occur between the epicenters of these quakes and the island itself, even when they occur.

In addition to the protection offered by the location of Guam the harbor at Apra is a natural barrier to large tsunamis. The tsunami of 1993 was probably caused by a triggered earthquake on a secondary fault at a steep angle to the horizontal which ruptured towards the surface during the mainshock as proposed by Tanioka et al. (1996) and may have been related to the close passing of Typhoon Steve on the same day. The mainshock occurred at the upper

Pacific/Philippine plate interface in the shallow portion of the Pacific plate subducting at about 13 degrees dip under the Philippine plate (Beaven et al. 1994).

Nevertheless, Guam needs protection from the sea, as storm surges from typhoons and other tropical storms can cause major damage. In the past 35 years nearly 200 typhoons have brushed Guam. For example in 1990, Typhoon Hattie caused $1.7 million in damage to Guam. In 1991, Typhoon Yuri, the largest in 33 years, inflicted losses of $33 million to Guam. In 1992, Typhoon Omar devastated Guam with losses estimated at $457 million. We have found that not only do typhoons directly damage the island, but probably also trigger earthquakes which cause indirect damage, as was apparently the case in the earthquake of August 8, 1993, with total losses to Guam of $267 million.

APPENDIX: TSUNAMIS REPORTED AT GUAM

Reported Observed and Recorded Local Tsunamis

Date	Description
late 1700's	Unconfirmed report 1767, 1769, 1779 or 1799. A tsunami probably occurred.
1809	A violent earthquake occurred. Ships at sea experienced shocks near Guam. **Validity 1.**
1825, April	Terrible earthquakes caused great damage. (Repetti, 1939) **Validity 2**.
1837, Oct.	Extraordinary movement was experienced at sea. A type of tempest disturbed it and caused flooding, landslides and damage. Four islands in the Caroline Islands were over-washed and only parts of two remained above the water level. Survivors migrated to Guam and settled on Saipan. Degraz (1838). Terrible earthquakes caused great damage. (Repetti, 1939) **Validity 2**
1849, Jan 25 5:10 UT	Major earthquake damage and tsunami effects reported by the governor including the only fatality due to tsunamis in Guam's history. Villages flooded, homes destroyed, bridges washed away. Runup of at least 6.1 m at Agat and inundation of at least 402 m at Umatac Bay. Evidence of submarine landslide in Apra Harbor. **Validity 4**
1892, May 16 11:31 UT	A strong earthquake caused the sea to recede in Agana Harbor. Only in San Antonio did the sea return and cause flooding. (Maso, 1910) **Validity 4.**
1903 Feb.	Earthquakes in Guam and a 15 cm rise of the sea. Location not given nor was the rise identified as water or land level. **Validity 2.**
1909 Dec. 10	Destructive earthquake. Several fissures opened in the ground. A large flow of water came from one of the fissures. A passing wave could be seen as it crossed the plaza, and the station ship in the harbor felt the shock. (Maso, 1910) **Validity 1.**
1990 Apr. 5	A magnitude 7.5 earthquake near Saipan caused 3 to 4 m waves at Saipan and Tinian and a 1.5 to 1.8 m wave at the Talofofo River going up the river to a settlement. This was just recently reported because eyewitnesses were found. Since there were no initially reported runup data, no survey of effects was conducted for this tsunami that probably affected Guam's northern and eastern coasts. **Validity 4.**
1993 Aug. 8	A magnitude 8.1 earthquake caused $200 million in damage. The tsunami was recorded at 15 cm at Apra, and 10 cm at Agana Harbors. Waves about 1.8 m high washed cars into the ocean on the east coast where an initial withdrawal was reported. A wave 2.4 m high went up the Talofofo River carrying debris 400 m upstream. A wave reported in Tumon Bay would have been due to a local slump**. Validity 4.**

DESCRIPTION OF LOCAL EVENTS

1810. Events similar to the 1837 event were reported by Degraz (1838). A violent earthquake occurred. Ships at sea experienced violent shocks near Guam. These were probably were sea quakes. **Validity 1.**

1825, April. An event similar to the 1837 event occurred (Degraz, 1838). Terrible earthquakes were experienced causing great damage. (Repetti, 1939) **Validity 2.**

1837, October. Extraordinary movement was experienced at sea. A type of tempest disturbed it and caused flooding, landslides and damage. Four islands in the Caroline Islands were over-washed and only parts of two remained above the water level. Survivors migrated to Guam and settled on Saipan. Degraz (1838). Terrible earthquakes were experienced causing great damage. (Repetti, 1939) **Validity 2.**

1849, January 25, 5:10, UT. At 2:49 P.M. local time as reported by the Governor to his superiors (Driver, 1993), a great earthquake occurred which lasted one and a half minutes and caused great damage. Aftershocks continued every four to eight minutes until 11 o'clock that night. They began again at 2:30 A.M. local time and continued for weeks. About 150 felt earthquakes were noted by March 11. The population was fearful that they were on a volcano and the island might explode or sink. Sand boils discharging sea water opened up cavities which had measured depths of one to six yards. Twelve to seventeen of the cavities were in a line parallel to the river by Santa Cruz just south of Agana. The only reported loss of life was to Josefa Lujan, a woman caught by one of the three reported tsunami waves, near the Talofofo River. She was from Agana and going to Inarajan. She is the only reported fatality due to a tsunami in Guam's history. Her two year old niece received bruises on her face and was carried 40 yards and deposited among some rocks (Driver, 1993). The Governor's report placed the woman at her ranch near the beach.

Tsunami observations for the 1849 event:

At Agana and the north coast the sea was seen to recede but did not rise or return quickly. This may suggest uplift of the island. At old Agat which was situated about 1 1/4 miles north of the present Agat centered north and south of the Pelagi Islets along the Ayuga River. The sea swept through the streets which were 1,000 varas (917 yards as a vara is about 33 inches) (839 meters) inland from the high tide mark at an elevation of about 20 feet.

At Umatac three waves came into the bay. The Captains of two whaling frigates reported that they were anchored in 96 feet of water that receded and left them high and dry for 5 minutes. They lost their anchor chain on the third wave. The ships probably had a draft of 15 feet. The water came up the Laelae River for about a league (3 miles, or colloquially, just a long way) nearly to the location of the settlement with buildings at a minimum of 12 feet above sea level and destroyed many plantings. The 1819 chart shows the La Paz anchorage point in 42 feet of water. The rivers did not empty into the bay but into coastal ponds. The chart shows them to be only 2.08 miles long and with a slope of 10%. The 20-foot contour is about 2,500 feet upstream. These numbers for the reported depths, and inundation are probably exaggerated.

On the following day casks and barrels that the frigates were using to collect water were found at a great distance in the jungle. Two bridges were destroyed. Pendleton (1865) reported "I had a boat on shore at the time, and the inflood of the water was so great that it took her into the tops of the trees near the ocean, and swept water casts and such things a fourth of a mile or more into the country. When the water receded, it left them with hundreds of fishes high and dry and the land at the watering place sank about 12 feet. When the water receded it took my ship back with such force that it parted my chain, and I lost an anchor. Several ships in Apra Harbor lost anchors by being covered up on the bottom of the harbor, and they had to cut their chains. I think six were lost. The motion of the water was east to west." Submarine landslides in the harbor may have caused this.

At Inarajan the ocean entered along the Laolao River and swept three homes away depositing them 400 varas (366 yards) distant. It flooded the town (elevation of only five feet). About 15 plots of rice and seven of sweet potatoes were lost and the soil washed away. It washed away three bridges, two adjacent to the town and one over the Acfallan River. It also washed away the raft used to cross the Talofofo River. (Driver, 1993)

At Pago the sea rose as far as the church patio and flooded the entire village (located about 2,000 varas (1833 yards) from the beach on a sloping rise). The water receded leaving the streets covered with fish (Driver, 1993). The river level is only 10 feet at a distance of 3,000 feet upstream.

On April 14, a sea-going canoe with eight Carolinians from the Island of Satawal arrived at Agana. They claimed to have survived great earthquake and the ensuing flood by climbing trees. They had remained on the island as they lacked boats to leave. Many perished on the Island of Satawal and some were left behind. The survivors reported that the earthquake had occurred two and one-half moons ago and at about 3 P.M., about the same time as the Guam earthquake. Satawal is 450 nautical miles S.S.E. of Guam. The next day two more canoes arrived from a neighboring Caroline Island, Lamotrek Island, with 41 men and women survivors. They were also granted asylum (Stafford, 1933, p. 115). Both Satawal and Lamotrek Islands are very low with heights of about 8 feet. **Validity 4.**

1892, May 16, 11:31 UT. At 9:10 P.M. local time when clocks stopped, a strong earthquake that lasted a minute caused tiles to fall from roofs. The sea receded to the reefs in Agana Harbor but due to its slow return it did not pass its ordinary line except in the San Antonio quarter where it invaded the area. A larger wave would have destroyed the village of San Antonio. This wave was probably due to a submarine landslide in the bay given the local effect at San Antonio. (Repetti, 1939) **Validity 4**.

1903, February 10, 2:28 UT. There was a series of earthquakes and the (level of the sea?) rose 0.15 meters. Montessus de ballore, 1903 cited by Soloviev et al. 1984. Probably a 15 cm tsunami would not have been observed or reported so the change would have been due to a rise or drop of the land. **Validity 1.**

1990, April 5, 21:12 UT. A MW 7.5 earthquake in the Marianas Trench near Saipan produced an observable tsunami at the Tinian dock but no damage. The Civil Defense survey did not find evidence of a tsunami at Saipan, and considered news reports of three to four meter waves at Saipan and Tinian to be greatly exaggerated (*ITIC Tsunami Newsletter*, Vol. 23, No. 1, p. 35-37). However, crewmen of the *Jungle Boat* on the Talofofo River, Ted, Andy and Lauren Fairfield told Paul Hattori that they were at the loading area at about 8:00 A.M. when they saw a rush of foamy sea water coming under the bridge to the loading raft going up the river. The raft rose 5 to 6 feet. The water receded to the bay after 15 minutes or longer and took the form of a strong rip current. As in 1993, debris was carried up the river for a distance of two miles. Talofofo bay is shaped to focus the water to the river mouth at the head of the bay giving a higher water level there. However, there must have been observable waves elsewhere on the northern and western coasts but this area is lightly developed and no known surveys were taken. The tsunami was not reported as having been recorded in Guam and the marigrams have not yet been located. It was recorded in Japan with heights of 26 cm at Hachi, 24 cm at Murotomisaki, 23 cm at Chichijima, 22 cm at Tosashimizu, 19 cm at Yaene, 16 cm at Mera, 15 cm at Kushimoto, 10 cm at Aburatsu, 7 cm at Owase, 6 cm at Choshi, and 4 cm at Uchiura and Naha, in Hawaii with a height of 24 cm at Kailua-Kona, at Midway Island with a height of 6 cm, at Wake Island with a height of 4cm, and at Truk Island with a height of 3 cm. (*ITIC Tsunami Newsletter*). **Validity 4.**

1993, August 8, 08:34 UT. A magnitude 8.1 (Mw) earthquake in the Marianas Trench caused over $200 million dollars in damage and generated a minor tsunami. Low tide was recorded at 1 foot at 06:10 UT. The tsunami was recorded with amplitudes of 15cm at Apra Harbor, and 10 cm at Agana Harbor. 15 cm was reported at Kwajalein Atoll. At Hawaii: Honokohau, 5 cm, Nawilili, 6 cm; Haleiwa, 10-14 cm; Kahului, 12 cm; Lanai, 15 cm; Port Allen, 15-19 cm. (*ITIC Tsunami Newsletter,* December 1993, and other sources). At Japan: Muroto-misaki. Shikoku, 98 cm; Chichi-shima, Bonin Islands, 68 cm; Tosashimazu, Shikoku, 58 cm; Abratsu, Kyushu, 56 cm; Mera and Owase, Honsu, 34 cm; Ayukawahama, Honshu, 44 cm; Omae-zaki, Honshu, 42 cm; Hanasaki and Kushimoto, Honshu, 34 cm; Hirara, Ryukyu Islands, 34 cm; Ofunato, Honshu, 28 cm; Hachinoe, Honshu, 12 cm.

A personal account in the *Pacific Sunday News* by a fisherman, Tony Guerrero, fishing in Pago Bay reported that after the earthquake he started walking toward his truck parked 125 yards away and 15 yards beyond the water line. It took him about 10 minutes to reach his truck and the water was calm. As he reached the truck a wave came up to his legs. As he drove along the shore, a second wave swept him and his truck, which was parked on the beach, into the bay about 30 feet from shore. Water rose over the windshield. He could not open the door due to the water pressure but, as the waters receded, he escaped by rolling down a window and climbing into the truck bed. He waded ashore in chest deep water (*Pacific Sunday News*, Sept 5, 1993). The truck was destroyed. He was lucky to survive since he would have been in grave danger if the bay had been deeper, or if a third wave had come in while he was wading ashore.

Several graduate students told their instructor that they were snorkeling or boogie boarding behind the University of Guam Marine Laboratory on Pago Bay. They reported that the sea receded, and they left the water. The water withdrew and left the reef dry. The sea returned but the students didn't give an estimate of the run-up height. A family was at a week-end picnic at Tarague Beach on the north shore when the water was seen bubbling and the sand swirling. As the family began to drive away after the earthquake, they saw water come over the reef. It was three feet high as it passed their truck. The tide was at low stage.

Although the mayor of Inarajan did not see any unusual activity of the sea, afterwards he had to clear debris from the roads which was brought in by the sea waves about two feet above the high water level. At the Jungle River Tour Boat dock on the Talofofo River about half a mile above the bridge the river was estimated to have risen about 7 feet nearly topping the bridge at 8 feet above the river. Tree debris was evident 1/4 mile further up the river from a river bore.

Mr. Joaquin Anderson was in his yard overlooking the Pago river just above the bridge and reported seeing the river first recede and then rise flooding family land and carrying off chunks of soil. Later he saw many fish lying on the ground well beyond the river. About 150 fresh water fish were found floating dead in the Pago River, possibly the result of a surge of salt water into the river (Petrovsky, 1993). The fish may have been killed by the earthquake by the shock waves or from silting. This has also been observed in Alaska many times.

Another man reported having his truck inundated in the parking lot below the bridge at Ylig Bay. The water overflowed the bridge that was about six feet above the river level (Hattori, report of August 22, 1993 citing information from Prof. B. Lorenz.)

Maria Rosario and Fabiana San Nicholas were stopped at the Talofofo bridge which had a gap between it and the road due to the earthquake As they were turning around at the lowest point the area was suddenly flooded.. There was little current but the water rose to the windows of the car, a level of over three feet and was chest deep. the water returned to normal level shortly. The water level at Inarajan bay subsided immediately after the earthquake and the bottom of the bay was visible for some distance. (*Man, Land and Sea, News of Guam and Her Ocean Environment*, Vol. VII, Bureau of Planning/Guam Coastal Management Program, No. 3, p. 2).

The International Coordinating Group for the Tsunami Warning System in the Pacific was completing its meeting when the earthquake struck. The great damage by the earthquake and the smaller tsunami effects on the less populated eastern coast caused the tsunami effects to not be widely published. The EERI Special Earthquake Report, October 1993, mentions only that "The Guam quake caused no significant tsunami although wave heights of 98 cm at Japan and 19 cm at Hawaii were recorded" and that was almost the only mention of the tsunami internationally even though the earthquake was examined by teams of seismologists (*ITIC Tsunami Newsletter*, vol. 25, No. 1, p. 1-2).

Teletsunamis Observed at Guam

Date	Source Area	Height (m)	Period (min)	Validity
1952, Mar. 4 01:23 UT	Hokkaido, Japan	0.1	21	4
1952, Mar 19 10:57 UT	Mindanao, Philippine Islands	<0.1		
	Recorded at Apra Harbor and Tarague (Murphy and Cloud, 1954, p 50)			
1952, Nov. 5 16:58 UT	Kamchatka	<0.1		
	An 8.25 (Mw) magnitude quake in east Kamchatka caused considerable damage and some loss of life locally. At Ylig Bay, it was observed to have an amplitude (height?) of 5 feet (1.5 m) and a period of 8 minutes, the natural period of the bay and hence may have been a seiche (Tracey et al.1960) *The Guam Daily* News (Nov. 6, 1952, p. 1) reported three waves were recorded at Ylig with the first arriving at 9:45 A.M. as two or three foot swells and the second arriving a little later and about the same height. The third wave was five and a half feet and arrived at 10:45 a.m.			
1957, Mar. 09 14:22 UT	Andreanoff Islands	3.5	54	
	Caused some damage and local waves of 15 meters at Scotch Cap, Unimak, Islands, Alaska. Travel time 6.7 hours.			
1960, May 22 19:11 UT	Chile	0.2		
	The great Chilean earthquake and tsunami caused more than 2,000 fatalities and $550 million in damage in Chile, 61 fatalities and $75 million in damage in Hawaii, 138 deaths and $50 million in damage in Japan, 32 fatalities and missing people in the Philippines and two fatalities and $500 thousand in damage to the U.S. West Coast. Travel time: 21. 5 hours.			
1963, Oct. 13 05:17 UT	Kuril Islands, Russia	<0.1		
	Travel time about 5.8 hours			
1964, Mar. 28 03:36 UT	Alaska	<0.1		
	Caused 106 fatalities and $84 million damage in Alaska, 16 fatalities and $20 million in damage on the U.S. West Coast. Travel time 8.2 hours.			
1966, Oct. 17 21:42 UT	Peru	<0.1		
1968, May 16 00:49 UT	Honshu, Japan	<0.1		
1968, Aug. 1 21:19 UT	Luzon, Philippines	<0.1		
1971, Dec. 15 08:30 UT	Kamchatka	<0.1		
1971, Dec. 2 00:20 UT	Mindanao, Philippines	<0.1		

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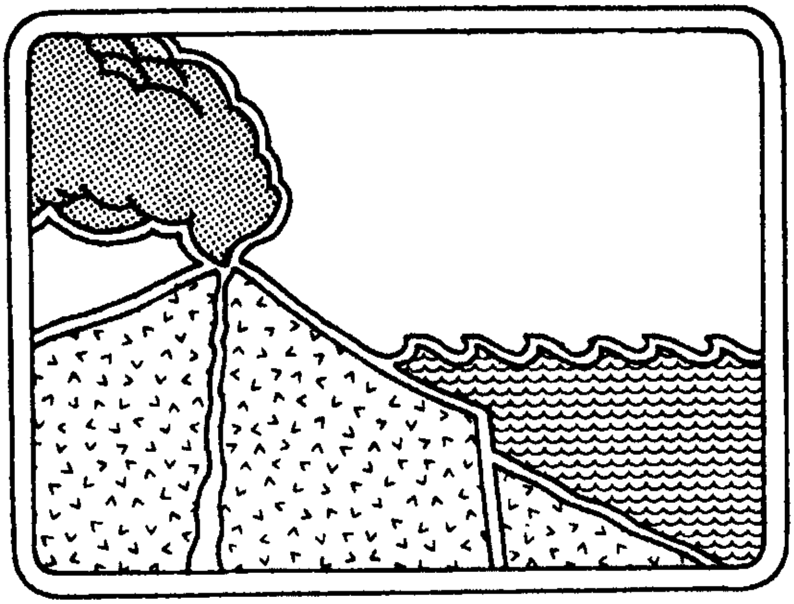

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