U.S. States and Territories National Tsunami Hazard Assessment: Historical Record and Sources for Waves

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Executive Summary

The National Science and Technology Council (NSTC) is the principal means for the President to coordinate science and technology policy across the Federal government. In 2005, the NSTC released a joint report by the sub-committee on Disaster Reduction and the U.S. Group on Earth Observations entitled *Tsunami Risk Reduction for the United States: A Framework for Action*. The *Framework* outlines the President's strategy for reducing the United States tsunami risk. The first specific action called for in the *Framework* is to "Develop standardized and coordinated tsunami hazard and risk assessments for all coastal regions of the United States and its territories." The National Tsunami Hazard Mitigation Program (NTHMP), a partnership between Federal and State agencies, provides the organizational framework needed to execute the President's tsunami initiative. Since the National Oceanic and Atmospheric Administration (NOAA) is the lead agency for providing tsunami forecasts and warnings, the NTHMP requested that NOAA take the lead in conducting the first national tsunami hazard assessment.

The first step in a tsunami hazard assessment is to examine the past record since it provides clues to what might happen in the future. NOAA's National Geophysical Data Center (NGDC) catalogs information on global historical tsunamis. Earthquakes or earthquake-generated landslides caused more than 85 percent of the tsunamis listed in the NGDC tsunami database, with the remainder due to volcanic eruptions, non-earthquake generated landslides, and other sources. The United States Geological Survey (USGS) conducts research on earthquake hazards facing all of the United States and its territories. Therefore, NOAA/NGDC and USGS collaborated to conduct the first tsunami hazard assessment of the United States and its territories for the NTHMP.

The great diversity of coastal areas at risk—from metropolitan areas to beaches crowded with thousands of vacationers to quiet seaside towns—makes such a total risk assessment an essential, but daunting, task. A complete assessment as called for in the *Framework* consists of a hazard assessment, exposure, and vulnerability assessment of buildings and people, and loss assessment. In July 2006, a group of tsunami experts convened to review the current state of knowledge in areas essential to tsunami risk reduction. The results of this review, published as NOAA Technical Memorandum OAR PMEL-133, *National Tsunami Research Plan*, identified six high-priority tsunami research areas. The fifth high-priority area is understanding the impact of tsunamis at the coast. This includes measuring the tsunami current regime in harbors and at the coast, improving hydrodynamic modeling, developing credible fragility models of the interaction of tsunamis with the built and natural environment, and validating models through benchmarking. This research is essential for a full tsunami risk assessment. The goal of *U.S. States and Territories National Tsunami Hazard Assessment*, a first step toward satisfying the requirement in the *Framework*, and the fifth-priority of the *Plan*, is to provide a national qualitative assessment of the United States tsunami hazard at a regional level by examining the record of historical tsunamis and earthquakes, the predominant cause of tsunamis, at the State and territory level.

In this report, two different sources of information are compiled to assess the U.S. tsunami hazard. The first involves a careful examination of the NGDC historical tsunami database which resulted in a qualitative tsunami assessment based on the distribution of runup heights and the frequency of tsunami runups. We characterize the tsunami hazard by first determining the number of individual tsunamis reported in each State or territory and then binning the results into five categories of runup amplitudes—Undetermined runup height, 0.01 m to 0.5 m, 0.51 m to 1.0 m, 1.01 m to 3.0 m, and greater than 3.0 m. Based on the total spread of events, runup amplitudes, and earthquake potential, we assigned a subjective hazard from very low to very high. These assessments recognized that tsunami runups of a few tens of centimeters have a lower hazard than those with runups of a few to many meters.

Our database search reinforces the common understanding that the U.S. Atlantic coast and the Gulf Coast States have experienced very few tsunami runups in the last 200 years. In fact, Louisiana, Mississippi, Alabama, the Florida Gulf coast, Georgia, Virginia, North Carolina, Pennsylvania, and Delaware have no known historic tsunami runup records in the NGDC database. Further, only a total of six tsunamis have been recorded anywhere in the other Gulf and East Coast States. Three of these tsunamis were generated in the Caribbean, two were related to magnitude 7+ earthquakes along the Atlantic coastline, and one reported tsunami in the mid-Atlantic States may be related to an underwater explosion or landslide. There is only one documented runup on the Atlantic in the range 0.51 m to 1.0 m and none in the higher runup ranges.

In contrast, all U.S. coasts in the Pacific Basin as well as Puerto Rico and the U.S. Virgin Islands have a “moderate” to “very high” tsunami hazard based on both frequency and known runup amplitudes. The sheer number of runups and the large number greater than 3.0 m observed in Alaska and Hawaii justified assigning a “very high” hazard for these two States. The Pacific territories including Guam, American Samoa, and the Northern Marianas experience many tsunamis, but only one event had an amplitude greater than 3.0 m. Accordingly, we assigned a “moderate” hazard to the Pacific island territories. Both the frequency of tsunami runups and the amplitudes support a qualitative “high” hazard assessment for Washington, Oregon, California, Puerto Rico, and the Virgin Islands. The “high” value for Oregon, Washington, and northern California reflects the low frequency (~1 per 500 years) but the potential for very high runups from magnitude 9 earthquakes on the Cascadia subduction zone.

Although tsunami deaths are a measure of risk rather than hazard, we compared the known tsunami deaths found in our NGDC database search with our qualitative assessments based on frequency and amplitude. There are no known deaths from tsunamis along the U.S. Atlantic coast or Gulf coast and only one known death in the Pacific territories (on Guam). In contrast, both Alaska and Hawaii have unfortunately experienced several hundred deaths each from tsunamis. Tsunamis in Puerto Rico and the U.S. Virgin Islands have caused a total of 172 deaths. The U.S. west coast has had 25 tsunami deaths, but due to the lack of written records, there are no estimates of deaths caused by the great Cascadia earthquake in 1700. There is evidence from oral traditions and computer simulations that

this event must have severely impacted native populations.
The NGDC tsunami database contains *reported* tsunamis and is therefore limited to written records existing for an area. The hazard assessment used the USGS National Seismic Hazard Map (NSHM) databases to partially extend the time interval. These databases are primarily meant to assess earthquakes affecting U.S. possessions and do not include all possible seismogenic tsunami sources in the Pacific and Atlantic Basins. However, the databases make it possible to estimate the rate of occurrence of larger magnitude earthquakes that could generate a tsunami. The USGS NSHM databases are based on tectonic models, and paleoseismic and paleotsunami data. It is important to understand that the USGS NSHM databases are used to calculate earthquake, not tsunami, occurrence. Along the U.S. Pacific and the Caribbean coastlines, the rate of the largest magnitude local subduction zone earthquakes calculated by the USGS is essentially the same as the rate of near-shore tsunami generation, because great (>M7.5 to 8.0) subduction zone earthquakes are the most common cause of tsunamis along these coastlines. This is not the case along the Atlantic or Gulf coasts, where very limited experience suggests that the occurrence of a large earthquake does not necessarily mean a tsunami is generated.

One difference between most local earthquake sources along the U.S. Pacific and Caribbean coasts compared to the U.S. Atlantic coast is that, in the former areas, earthquake displacements directly displace huge volumes of water because of large earthquake source dimensions, whereas along the Atlantic and Gulf coasts they do not. The extremely limited experience with earthquake sources along the Atlantic coast suggests that the earthquake-triggering of underwater landslides is an important source for generating tsunamis. The seismic databases obviously do not account for earthquake sources removed from the American shorelines or non-earthquake related tsunami sources.

The table (next page) summarizes the results of the NGDC and USGS database searches.

In terms of our goal to provide a national tsunami hazard assessment, better understanding of possible sources in the Atlantic Basin and offshore southern California are high priorities. For the Atlantic Basin, a better understanding of the cause of the known magnitude 7 events along the margin is needed. This should be coupled with an analysis of the potential for these events to initiate underwater landslides capable of generating a tsunami similar to that observed after the 1929 Grand Banks (Newfoundland) earthquake. In addition, the possibility of non-earthquake triggered underwater landslides along the Atlantic Basin needs examination. Fortunately, the USGS has begun a one-year study of tsunami potential along the Atlantic coast.

An investigation of coastal marshes in search of any evidence of past Atlantic tsunamis should support these efforts. In the Caribbean, efforts should be made to better document the catalog of tsunamis. Modeling studies should be undertaken for all possible sources, in order to better understand earthquake recurrence, tsunami source generation, and propagation issues.

Table A. Qualitative tsunami hazard assessment based on NGDC and USGS databases.

Region	***Hazard based on runups***	***Hazard based on frequency***	***Hazard based on local earthquakes***	***Number of reported deaths***
U.S. Atlantic coast	Very low to low	Very low	Very low to low	None
U.S. Gulf coast	Very low	Very low	Very low	None
Puerto Rico and the Virgin Islands	**High**	**High**	**High**	**172**
U.S. west coast	**High**	**High**	**High**	**25**
Alaska	**Very high**	**Very high**	**High**	**222**
Hawaii	**Very high**	**Very high**	**High**	**326**
U.S. Pacific island territories	**Moderate**	**High**	**High**	**1**

The tsunami threat to southern California from local earthquakes and underwater landslides remains highly uncertain. The USGS has begun a two-year study of these sources that, when completed, will improve this initial national assessment.

Much uncertainty remains about the variability in size and patterns of deformation of Cascadia subduction zone earthquakes. Since this is one of the largest tsunami sources threatening the U.S. coast, improvement in our knowledge of this source should have a high national priority. Reducing these uncertainties could be accomplished by modeling studies and field investigations designed to improve our understanding of the possible ranges of earthquake size and deformation.

We stress that this report is an initial step towards a national tsunami risk assessment. Although this *National Tsunami Hazard Assessment* is focused on the qualitative, relative ranking of American coastlines to tsunami hazards, it is instructive to examine how detailed science and emergency management practices can greatly improve the country's ability to prepare for future tsunamis. Accordingly, a portion of a more rigorous probabilistic tsunami hazard assessment for Seaside, Oregon, is included in Appendix C as an example of products that may be useful in other selected communities as tsunami hazard assessment methods mature.

Section 1. Introduction

Tsunamis are infrequent high impact events that can cause a considerable number of fatalities, inflict major damage, and cause significant economic loss to large sections of the U.S. coastlines. Since the beginning of the 20th century, tsunami events have caused more than 700 deaths and over $200 million dollars in damage to the U.S. coastal States and territories. More than 50 percent of the U.S. population now live in coastal communities (Crosset et al., 2004) and may be at risk for impacts from a destructive tsunami. Had this large population been present in 1700 when the last magnitude 9 Cascadia earthquake struck, there would have been many times this number of deaths from the tsunami impact to the Pacific Northwest. As more people continue to move to the coasts, the risk of deaths and damage will continue to climb. Because of the large coastal area affected, it is imperative that the United States understand the tsunami threat to its States and territories, and to identify coastal areas that face the greatest tsunami risk.

The tsunami hazard assessment for the United States is presented in **Sections 2** and **3. Section 2** presents an initial qualitative assessment of the tsunami hazard based on the history of tsunamis in the United States. **Section 3** provides an extension of this assessment based on local earthquake source probabilities and their potential to generate tsunami waves that could impact the United States.

There are several areas where a better characterization of tsunami sources would lead to immediate improvement in this initial tsunami hazard assessment. Accordingly, **Section 4** highlights some of these key gaps in the current knowledge on tsunami sources. For a review of the current state of tsunami research, users are urged to read *National Tsunami Research Plan* (Bernard et al., 2007). This document includes state-of-the-science reports on tsunami hazard assessment, warning guidance, preparedness, response, and mitigation.

Because there are large parts of the coast with little, if any, familiarity with tsunamis, **Appendix A** provides a brief description of the causes, mechanics, and impacts of tsunamis.

An overview of the entire risk management process that includes modules for assessing the tsunami hazard, exposure and vulnerability, probable maximum losses to buildings, and mitigation is presented in **Appendix B**. A complete tsunami hazard assessment requires the following key elements: collection, analysis, and quality assurance of all data related to U.S. tsunami events; assessment of frequency, severity, and uncertainty of tsunami sources; acquisition, quality assurance, and archiving of bathymetric and near-shore topographic data; development of tsunami inundation forecast tools; and inundation mapping and modeling of all U.S. coastal areas. The next step will be to use these data as input for a complete tsunami hazard and risk assessment.

Finally, **Appendix C** concludes this report with an example of a more detailed probabilistic tsunami hazard assessment that was recently completed for Seaside, Oregon (Tsunami Pilot Study Working Group, 2006).

This report is intended to be an overview of the hazard down to the State level, not a detailed description of the tsunami hazard at a particular locality. This document will be updated periodically as new research improves our ability to assess the U.S. tsunami hazard.

1.1 References

Bernard, B., Dengler, L., and Yim, S. (editors), 2007, *National Tsunami Research Plan*: *Report of a Workshop Sponsored by NSF/NOAA*. NOAA Technical Memorandum OAR PMEL–133, 135 p. http://www.pmel.noaa.gov/pubs/PDF/bern3043/bern3043.pdf

Crosset, K.M., Culliton, T. J., Wiley, P.C., and Goodspeed, T.R., 2004, *Population Trends Along the Coastal United States: 1980-2008,* U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, 47 p.

Tsunami Pilot Study Working Group, 2006, *Seaside, Oregon Tsunami Pilot Study—Modernization of FEMA Flood Hazard Maps*, Joint NOAA/USGS/FEMA Special Report, 94 p., 7 appendices. http://pubs.usgs.gov/of/2006/1234/

Section 2. Known Historical Tsunami Record

NOAA's National Geophysical Data Center (NGDC) serves as the archive for many kinds of earth science information, including global observations of tsunami sources and tsunami runup records. Tsunami source information includes the date, location, and source type, plus a summary of measurements and effects. The runup database includes the date and location of the observation as well as details of the runup measurements and effects at the location. These two databases have been significantly improved over the last few years by careful checking of historical entries to flag either poorly identified possible tsunami runups or verify a meteorological origin for some entries.

Historical tsunami data are an important first step for assessing the tsunami hazard of a region. Therefore, the NGDC historical tsunami databases were examined to understand the scope of tsunami hazards facing U.S. States and territories. Although NGDC is preparing a tsunami deposits database that will extend the record into prehistoric times, this section focuses on the known historical tsunami record. It is important to note that if there were no people in an area to observe the phenomenon or to keep written records, it would not have been reported and included in the historical tsunami database. The largest deficit in this regard is the impact to native populations in Oregon, Washington, and northern California from the 1700 Cascadia tsunami.

2.1 Validity of Tsunami Data

A validity score is assigned to each tsunami source event ranging from 0 for erroneous entries to 4 for definite tsunamis. The validity of tsunami events and runups is based on several factors. For example, tsunamis recorded on tide gauges generated by earthquakes recorded on seismographs are assigned a high validity of 4 in the database.

Historical events that occurred before the invention of the seismograph or tide gauge must be evaluated differently. If the event caused significant effects such as deaths and damage, or was observed in many locations, it is also considered a high validity. For example, a tsunami generated by an earthquake in Chile that was observed in Hawaii and California would be assigned a high validity. The number of reliable and independent sources that list a historical event also affects the validity. Historical tsunami events generated by earthquakes are crosschecked with regional and local earthquake catalogs. If the tsunami was reported to have been generated by an earthquake, but there are no listings in the earthquake catalogs, the validity is lowered. For example, if a newspaper article reports a tsunami wave was generated by an earthquake, but there are no earthquakes that can be related, the tsunami event would be assigned a validity of 1. Tsunami events generated by volcanoes are crosschecked with volcano catalogs.

Whether the tsunami event occurred before or after the invention of seismographs and tide gauges, a high validity of 3 or 4 is considered a confirmed report of a tsunami event, whereas a validity of 0, 1, or 2 is considered an unconfirmed report.

2.2 NGDC Database Searches

2.2.1 Earliest Historical Accounts in the Pacific

The NGDC tsunami event database was queried to determine the earliest historical accounts of tsunamis impacting the U.S. States and territories. The first report was a Hawaiian chant composed in the 16th century describing a huge wave that came on the west coast of Molokai and killed the inhabitants. A Kamchatka earthquake in 1737 generated the first tsunami observed in Alaska. There were a few unconfirmed accounts of tsunamis as early as 1767 in the Pacific islands of Guam, American Samoa, and the Northern Mariana Islands; the first confirmed account was in 1837 in America Samoa. An earthquake off the coast of southern California in 1812 generated the first confirmed tsunami reports on the U.S. west coast and Hawaii. The confirmed report of a destructive tsunami striking the Japanese islands in 1700 has been shown by Satake et al. (2003) and Atwater et al. (2005) to be the last great Cascadia tsunami that devastated the U.S. west coast, but this event is not counted in this section in the present study, since there is no written record for the U.S. coast. Although the impact of a Cascadia tsunami is not considered in this section, the results of paleoseismic studies are used as input to the USGS earthquake hazard maps. Therefore, research on the Cascadia tsunami is included in the results discussed in Section 3.

2.2.2 Earliest Historical Accounts in the Atlantic

Caribbean tsunamis were reported as early as 1498 in Venezuela; the first confirmed observation in the U.S. territories was in 1690 in the Virgin Islands. On the east coast of North America there were unconfirmed tsunami reports as early as 1688; the first confirmed report on the Canadian east coast was from the 1755 Lisbon event. The first confirmed tsunami reports on the U.S. east coast were from the 1886 Charleston, South Carolina, tsunami that was observed in South Carolina and Florida. In 1918, a Puerto Rico earthquake generated a tsunami that was recorded on a Galveston, Texas, tide gauge with a small amplitude.

2.2.3 Runup Counts

To evaluate the impact of tsunamis on each State separately, the NGDC tsunami runup database was searched by State. Runups in each State were then divided into tsunami events using the tsunami source event date and time. Multiple runups over several hours from great subduction zone earthquakes, such as 1960 Chile or 1964 Alaska, observed at multiple sites within a particular State, were considered as one event per state. Tsunamis reported on inland waters were not counted, such as Lake Erie or Roosevelt Lake, Washington. Tsunamis in Puget Sound and all reported tsunamis in the bays of southeastern Alaska were included, including those with local landslide sources. A possible submarine landslide in 1964 that generated a tsunami that was recorded in Connecticut, New Jersey, Rhode Island, and New York was included in the count. All runups associated with tsunami events flagged as either known meteorological events or suspected of being a spurious or unconfirmed entry (low validity of 0, 1, or 2) were eliminated from the count.

The above procedure generated a count of tsunami events recorded in each State (Table 2-1, page 2-5). The reported runup heights were used to develop additional details of the tsunami runup distribution. For each individual tsunami event, the events were binned based on the maximum-recorded runup height in each State. Measured tsunami runup heights were subdivided into five groups:

- Undetermined runup heights
- 0.01 m to 0.5 m
- 0.51 m to 1.0 m
- 1.01 m to 3.0 m
- greater than 3.0 m

For example, if a tsunami was recorded in Oregon with two measured runups of 0.5 m and 1.4 m, the tsunami was binned into the 1.01 m to 3.0 m group. The same tsunami, if recorded in Washington with runups of 0.05 m, 0.15 m, and 0.6 m, would be binned into the 0.51 to 1.0 m group. Some tsunamis were observed, but there were no measurements of the runup heights. These events are counted as "events with undetermined runup heights." Finally, the total number of tsunami runups, all deaths, and damage in dollars reported as due to tsunamis were summed for each State and Territory.

2.3 Results

The results were organized into seven broad regions: U.S. Atlantic coast, U.S. Gulf coast, Puerto Rico and the Virgin Islands, U.S. west coast, Alaska, Hawaii, and U.S. Pacific island territories. Florida's coast is divided between the Atlantic and Gulf coast regions. The Pacific island territories include Guam, Northern Mariana Islands, and American Samoa. It is very clear from Table 2-1 that the American experience with tsunamis is greatest in the Pacific Basin based on the total number of runup events. Again, we emphasize that the numbers in Table 2-1 do not represent the total number of individual tsunamis, but the number of tsunamis per State with reported runups. For instance, the 1964 Alaska earthquake generated a tsunami that counts as a recorded tsunami event in many States (e.g., Washington, Oregon, Alaska, California, Hawaii, etc.). Thus, the numbers in columns three through seven (Table 2-1) are essentially State tsunami events with runups within the listed criteria. It is important to understand that although a tsunami source event (e.g., the 1964 Alaska tsunami) might be counted in several states, it is only counted once for each individual State.

The number of State tsunami events ranges from none in Pennsylvania, Delaware, Virginia, North Carolina, Georgia, Alabama, Mississippi, and Louisiana to 114 in Hawaii. The State tsunami events include both local sources of all types as well as runups resulting from a distant source. In terms of the tsunami events, about 10 percent are in the Atlantic Basin (Atlantic, Gulf, Puerto Rico, and the Virgin Islands) and 90 percent are in the Pacific (U.S. west coast, Alaska, Hawaii, and western Pacific). Again, one tsunami is often counted in several States.

Of the total 419 tsunami events, there are 376 (262+30+38+46) events with measured runups. The remaining events (43) were observed, but there were no runup measurements reported. The totals for each maximum runup category show the particular issue with tsunamis. The large total number of tsunami events (262) with runups between 0.01 m and 0.5 m is driven primarily by distant tsunamis. For example, American Samoa has 56 recorded tsunami events and 47 of these have measured runup amplitudes (40+4+3+0 in columns four through seven). Of the 47 tsunami events with measured runups in American Samoa, 40 are 0.01 to 0.5 m; 32 of these 40 events are from distant tsunami sources (≥1000 km).

As the measured runup height increases, the total number of tsunami events decreases quickly from 262 for runups up to 0.5 m, to 30 for runups between 0.51 m and 1.0 m, but increases to 38 between 1.01 m and 3.0 m, and increases again to 46 for tsunami events with runups more than 3.0 m. These numbers reflect the fact that in the subduction zones, local earthquakes generate severe tsunamis with amplitudes in excess of 3.0 m.

The Pacific Basin has 43 of the 46 State tsunami events with runup wave heights greater than 3.0 m. The number of events with runups greater than 3.0 m for Alaska (16) and Hawaii (18) points out the very severe nature of the tsunami threat in those States. The large number of local sources in Alaska along both the mainland and Aleutian arc contributes to the tsunami hazard facing Alaska. Both significant local tsunami sources and frequent devastating distant tsunamis strike Hawaii.

In the Atlantic Basin, there are three tsunami events with runups greater than 3.0 m for Puerto Rico and the Virgin islands, but there are no measured runups along the U.S. Atlantic coast greater than 3.0 m. For the U.S. Atlantic coastline, there is only one event with a measured tsunami runup exceeding 0.5 m. The 0.68 m runup is from the 1929 Grand Banks earthquake and was observed in New Jersey. This magnitude 7.3 earthquake caused an underwater landslide that generated the tsunami. This generation process is much different from that in subduction zones, where the vertical motion of a large area of seafloor generates the initial tsunami, although subsequent landslides can increase later wave heights.

The eighth column in Table 2-1 shows the total number of reported tsunami runups per State. The number of runups ranges from 0 to more than 400 in Hawaii for the devastating 1946 tsunami that struck Hilo and other cities. A total of 1,592 runup reports are available for Hawaii. There are 82 tsunami runup reports for the Atlantic Basin (U.S. east coast, Gulf coast, Puerto Rico, and the Virgin Islands), about 3 percent of the 2,661 total reported runups.

The database search resulted in 746 reported deaths (column 9, Table 2-1) and $207 million damage attributed to tsunamis (column 10, Table 2-1). There are no deaths or dollar damages reported for the eastern and Gulf coasts. The NGDC database shows that Hawaii, Alaska, Puerto Rico, and the Virgin Islands have suffered the largest number of fatalities from tsunamis; Hawaii, Alaska, and the U.S. west coast have suffered the largest amount of dollar damages. This is not a surprising result given the dangerous subduction zones along the Alaskan and Caribbean coasts and the central location of Hawaii—surrounded in the Pacific by many tsunami source regions in addition to local sources (Appendix A, Figure A-1). Since the last local Cascadia tsunami occurred in 1700, before significant

Table 2-1.
Tsunami events, total number of runups, deaths, and dollar damage by State and region from the NOAA/NGDC tsunami database. Dollars have not been adjusted for inflation. See Section 2.2.3 for an explanation of the counts. For more information on specific events, access the online database at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml.

	Location (and year of first confirmed report)	**Total number of tsunami events with any observed runup**	Events with undetermined runup heights	Events with runups 0.01 to 0.5 m	Events with runups 0.51 to 1.0 m	Events with runups 1.01 to 3.0 m	Events with runups > 3.0 m	**Total number of runups for all tsunami events**	**Reported deaths**	**Million dollars damage reported**
U.S. Atlantic Coast	Maine (1929)	1	1					3		
	New Hampshire (1929)	1	1					1		
	Massachusetts (1929)	1	1					2		
	Rhode Island (1929)	2	1	1				3		
	Connecticut (1964)	1	1					1		
	New York (1895)	2	1	1				7		
	New Jersey (1918)	6	3	2	1			8		
	Pennsylvania									
	Delaware									
	Maryland (1929)	1		1				1		
	Virginia									
	North Carolina									
	South Carolina (1886)	2	1	1				2		
	Georgia									
	Florida (1886)	4	3	1				5		
	Atlantic Coast Totals	**21**	**13**	**7**	**1**	**0**	**0**	**33**	**0**	**$0**
U.S. Gulf Coast	Florida									
	Alabama									
	Mississippi									
	Louisiana									
	Texas (1918)	1	1					1		
	Gulf Coast Totals	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**$0**
Puerto Rico and Virgin Islands	Puerto Rico (1867)	9	1	3	2	2	1	33	142	$4
	Virgin Islands (1690)	7	2	1	1	1	2	15	30	
	PR & VI Totals	**16**	**3**	**4**	**3**	**3**	**3**	**48**	**172**	**$4**
U.S. West Coast	Washington (1891)	21	2	13	1	4	1	64	1	$2
	Oregon (1854)	18	1	12	1	2	2	62	5	$1
	California (1812)	75	5	48	9	8	5	425	19	$19
	West Coast Totals	**113**	**8**	**73**	**11**	**13**	**8**	**550**	**24**	**$22**
U.S. Pacific Island Territories	Guam (1849)	15	2	10	1	1	1	23	1	
	Northern Mariana (1990)	1	1					1		
	American Samoa (1837)	56	9	40	4	3		60		
	Pacific Is. Totals	**72**	**12**	**50**	**5**	**4**	**1**	**84**	**1**	
	Alaska (1737) **Totals**	**81**	**6**	**49**	**4**	**6**	**16**	**352**	**222**	**$122**
	Hawaii (1812) **Totals**	**114**	**0**	**79**	**6**	**11**	**18**	**1592**	**326**	**$59**
	AMERICAN TOTALS	**419**	**43**	**262**	**30**	**38**	**46**	**2661**	**746**	**$207**

Figure 2-1. Map showing Cascadia subduction zone and tsunami deposit locations in the NOAA/NGDC tsunami deposit database.

populations lived on the coast and kept written records, there is no estimate of the effect of this tsunami on Native American populations. But there are clear references to this event in tribal oral traditions (Ludwin et al., 2005), and tsunami sediments have been found at many sites on the west coast of Canada and the United States (Figure 2-1). The results in Table 2-1 are summarized on the maps in Figure 2-2 for the Pacific and Figure 2-3 for the Atlantic.

In the Pacific Basin, tsunamis generated in one subduction zone are usually recorded at distant locations outside of the source region. Based on the NGDC database, that is not necessarily the case in the Atlantic. The Atlantic tsunami runups were tabulated by their source (Table 2-2). Known historical sources of tsunamis recorded on the U.S. Atlantic and Gulf coasts are few, consisting of:

- two major Atlantic earthquakes greater than magnitude 7: the 1886 Charleston, South Carolina, earthquake and the 1929 Grand Banks, Canada, earthquake
- three Caribbean earthquakes greater than magnitude 7: the 1918 Mona Passage earthquake and two Dominican Republic earthquakes in 1946
- one distant earthquake in Sumatra (2004)
- a possible mini-tsunami in 1964, possibly generated by an underwater landslide or explosion
- one local earthquake—the 1895 High Bridge, New Jersey earthquake—that is too small (estimated magnitude of 4.3) to directly generate a tsunami but has observations of wave effects

Figure 2-2. Map showing total number of tsunami events and total number of events causing runup heights from 0.01 m to greater than 3.0 m for U.S. States and territories in the Pacific Ocean. (Note: Histogram scales in Figures 2-2 and 2-3 are not the same.)

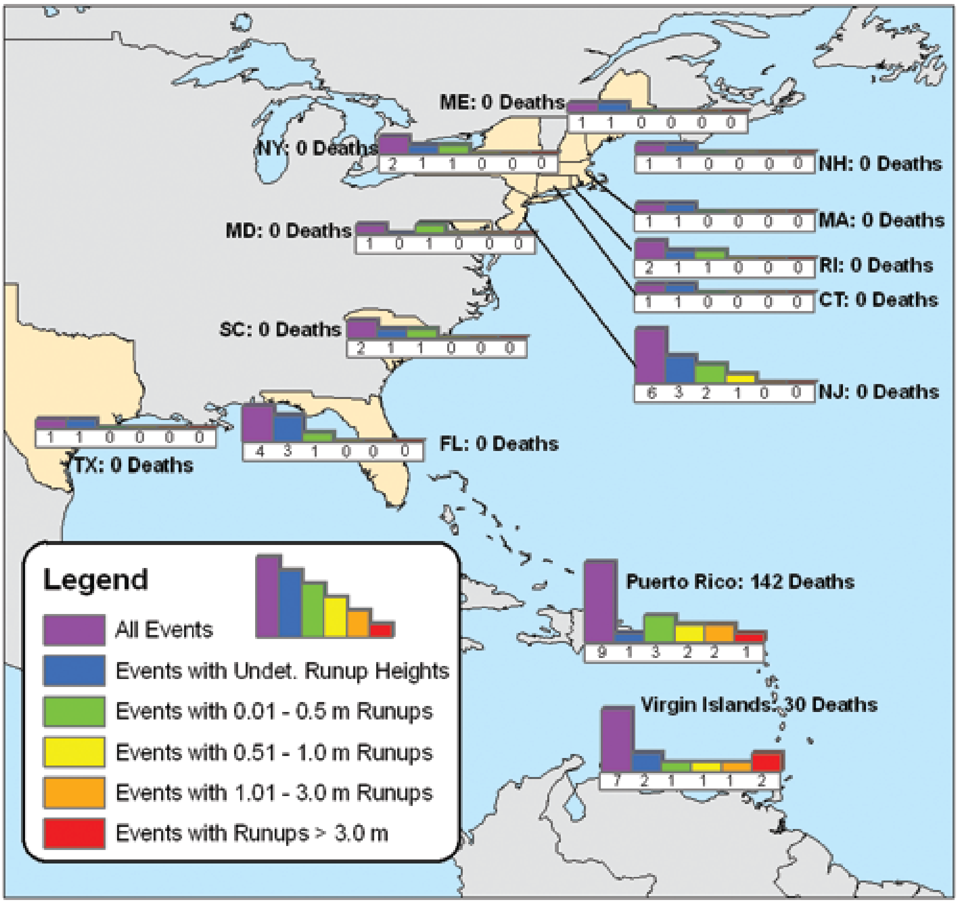

Figure 2-3. Map showing total number of tsunami events and total number of events causing runup heights from 0.01 m to greater than 3.0 m for U.S. States and territories in the Atlantic, Gulf Coast, Puerto Rico, and the Virgin Islands. (Note: Histogram scales in Figures 2-2 and 2-3 are not the same.)

consistent with those expected from a tsunami. The wave effects might reflect an unreported (unknown) local landslide or slump, or an unusual sloshing effect from the ground shaking.

The possible mini-tsunami occurred on May 18, 1964, and was recorded on tide gauges in four States—Rhode Island, Connecticut, New York, and New Jersey. The waves were characteristic of a small tsunami with maximum amplitude of 0.28 m. No seismic source is known for this event. Lander and Lockridge (1989) speculated that either an underwater landslide or an explosion caused the tsunami.

2.4 Discussion

It is clear from Table 2-1 that States and territories near subduction zones (or surrounded by subduction zones in the case of Hawaii) dominate the United States tsunami hazard with respect to the known historical record. There are four points to consider. First is the length of the historical record of tsunamis documented in the NGDC databases. It is reasonable to assume that most of the Atlantic coast tsunami events with runups of 1.0 m or more would likely have been noticed in populated places for the past 250 years; on the Gulf coast, for perhaps somewhat less, maybe 200 years. The records in Puerto Rico and the Virgin Islands are also likely complete for tsunami events with runups

Table 2-2. Source types for tsunami runups of any size observed on the U.S. Atlantic and Gulf coasts.

	Atlantic Coast Earthquake	Earthquake-triggered Landslide	Local Landslide	Caribbean Earthquake	Non-Atlantic Earthquake	Underwater Landslide?	Total
Maine		1					1
New Hampshire		1					1
Massachusetts		1					1
Rhode Island		1				1	2
Connecticut						1	1
New York	1					1	2
New Jersey		1		3	1	1	6
Pennsylvania							0
Delaware							0
Maryland		1					1
Virginia							0
North Carolina							0
South Carolina	1	1					2
Georgia							0
Florida	1			2	1		4
Alabama							0
Mississippi							0
Louisiana							0
Texas				1			1

of 1.0 m or more for at least 250 years and 200 or more years for much of California and all of Hawaii. The main gap in our knowledge of historic tsunamis is on the Pacific Northwest coast where the observational record is about 160 years. We know that a magnitude 9 earthquake and tsunami occurred there in 1700, but there is no written record of the local tsunami impact. Thus, aside from the Pacific Northwest, the available record throughout most of the United States is sufficient to assign an initial qualitative assessment of tsunami hazards.

Second, the tsunami data summarized in Tables 2-1 and 2-2 may still contain some suspicious events, such as the 1964 event mentioned above for the four Atlantic States or the 1895 Highbridge, New Jersey, earthquake. In the Pacific Basin and the Caribbean there may be a few suspicious events, but because of the large number of well-documented tsunamis those events have little overall effect on the hazard assessment. This is also not an issue on the Gulf coast, because there are no events reported, except for one distant tsunami from the Caribbean with a small amplitude recorded in Texas.

Third, there are striking differences in how tsunamis in the Pacific are recorded compared to tsunamis in the Atlantic Basin (Atlantic, Gulf, Puerto Rico, and the Virgin Islands). Although the observations in Table 2-1 were not divided into distant and local tsunami sources, the differences in the number of recorded tsunami runup events makes this clear. Only three of the Caribbean tsunami events are recorded at even a single station on the Atlantic and only one station in Texas on the Gulf coast. However, in the Pacific Basin tsunamis tend to get recorded at most States and territories within the Basin.

Fourth, this database does not consider explicitly the significant difference in hazard posed by distant versus local tsunamis. Local tsunamis arrive at the U.S. coast in minutes whereas distant events arrive hours after the causative earthquake. For Hawaii and the lower 48 States, the first arrival of distant tsunamis from subduction zones in the Pacific is at least four hours. For example, the level of hazard posed by rare magnitude 9 earthquakes in the Gulf of Alaska to the Alaska coast and Cascadia subduction zone earthquakes to the Pacific Northwest coast can be far greater than numerous small distant tsunamis to these same areas.

2.5 Qualitative Tsunami Hazard Assessment

Table 2-1 provides data for an initial qualitative assessment of tsunami hazards facing American States and possessions. The first criterion that can be used is the distribution of runup heights. It is clear that the record is sufficient to conclude that there are very few known historical tsunami runups on the Atlantic coast and almost none on the Gulf coast. Based solely on the known historical record, the qualitative tsunami hazard is labeled as very low to low on the Atlantic coast and very low on the Gulf coast.

It is also clear that Hawaii, Alaska, Puerto Rico, the U.S. Virgin Islands, and the U.S. west coast face a much higher tsunami hazard. Tsunami records in Hawaii go back about 200 years. A tsunami with a runup greater than 3.0 m, irrespective of source distance, hits Hawaii on average about once every ten years. Alaska faces about the same frequency of tsunamis with runups greater than 3.0 m. Compared to other U.S. States and territories, the tsunami hazard facing these States is very high. The U.S. west coast, Puerto Rico and the Virgin Islands clearly have a high tsunami hazard.

Tsunamis frequently strike American possessions in the Pacific, but proportionally many of the events record smaller runup heights than elsewhere in the Basin. Based only on the available data from NGDC, the qualitative tsunami hazard in American Samoa, Guam, and the Northern Mariana Islands is categorized as moderate. Table 2-3 shows the qualitative assessment of tsunami hazards based on a consideration of the distribution of recorded runup heights.

A second criterion for assessing tsunami hazard is based on the frequency of runups. The record is clear that on the Gulf and Atlantic coasts the frequency is very low. In contrast is the sheer number of events striking Alaska and Hawaii; thus, they are qualitatively rated as very high. The U.S. west coast and the Pacific island territories are rated high on the basis of frequency, once again showing that tsunamis in the Pacific Basin tend to be recorded widely around the rim. Puerto Rico and the Virgin Islands are also rated high on the basis of frequency.

Table 2-3. Qualitative tsunami assessment based on NGDC databases.

Region	***Hazard based on runups***	***Hazard based on frequency***	***Number of reported deaths***
U.S. Atlantic coast	Very low to low	Very low	None
U.S. Gulf coast	Very low	Very low	None
Puerto Rico and the Virgin Islands	**High**	**High**	**172**
U.S. west coast	**High**	**High**	**25***
Alaska	**Very high**	**Very high**	**222**
Hawaii	**Very high**	**Very high**	**326**
U.S. Pacific island territories	**Moderate**	**High**	**1**

*Does not include any deaths caused by the 1700 Cascadia tsunami on the U.S. west coast

The number of deaths reported in the NGDC database is corroborative evidence supporting our qualitative hazard assessments. Strictly speaking, tsunami deaths indicate risk as opposed to hazard, but it is worth noting that the number of deaths is consistent with the qualitative assessment. As shown in Table 2-1, the number of deaths in Hawaii, Alaska, Puerto Rico, and the Virgin Islands is much greater than in the other regions. Accordingly, these areas were assigned a high to very high hazard assessment based on the last 200 years of data. The U.S. west coast, with 25 deaths from tsunamis, is assessed a high hazard. It is likely that, if estimates of deaths from the 1700 Cascadia tsunami existed, the U.S. west coast would rate a very high assessment as well. Despite the large number of tsunamis in the western Pacific, few deaths have resulted. A moderate to high hazard was assigned here. Finally, with no reported deaths to date on the Gulf or Atlantic coasts, the hazard is labeled as very low to low.

2.6 References

Although several hundred references were used to compile the NGDC tsunami data for the U.S. States and territories, the following references were the major sources used. A complete list of reference citations for each tsunami event is available from the online database: http://www.ngdc.noaa.gov/hazard/tsu_db.shtml

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Section 3. USGS Earthquake Hazards Assessment

The USGS conducts research on earthquake hazards facing all U.S. States and territories. These hazard assessments rely on a combination of historical and modern earthquakes, geological information, and plate tectonic theories and models. (See Frankel et al., 1996, 2002). These inputs allow the earthquake hazard to be determined probabilistically. The USGS earthquake hazard maps specify the probability that ground shaking will exceed some level over a given number of years. Figure 3-1 is an example of a probabilistic map.

In this section, the results of USGS (NSHM) earthquake database searches are reported for possible earthquake sources near U.S. coastlines to extend the NOAA/NGDC tsunami databases. The USGS hazard calculations generally do not take into account either earthquake sources more than about 100 km offshore, or far-field earthquake sources. Ultimately, these sources will need to be considered in another matter, particularly for the Atlantic Basin.

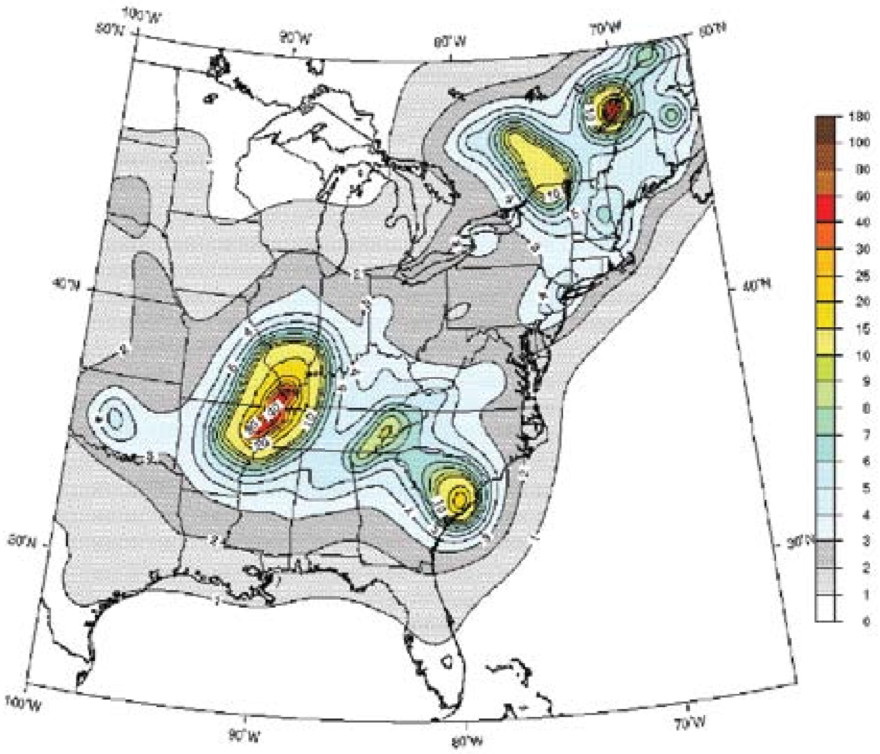

Figure 3-1. Probabilistic earthquake hazard map for the eastern United States within 100 km offshore. The map shows the peak ground acceleration with a 10 percent probability of being exceeded in 50 years. The Charleston, South Carolina, area stands out as the only section of coast where significant ground shaking of 10 percent of the acceleration of gravity or more is expected (Frankel et al., 2002).

A probabilistic representation for earthquake hazards has been adopted in most building code and engineering applications. Engineering and building code officials typically use USGS hazard maps that show either a 10 percent chance of exceeding mapped levels over 50 years, or a 2 percent chance of exceeding the mapped levels in 50 years. The map showing 10 percent in 50 years gives a 500-year window for expected ground shaking; the map showing 2 percent in 50 years corresponds to 2500 years.

Figure 3-1 (previous page) shows the probabilistic earthquake hazard for the eastern half of the United States for a 500-year window. The map shows that ground accelerations with a 10 percent probability of exceedance in 50 years vary considerably along the coast. Although ground shaking may occasionally be felt along the Gulf and U.S. Atlantic coasts (as occurred in 2006 and 2007), moderate to strong shaking is expected primarily near Charleston, South Carolina.

Extensive databases are used to produce the USGS earthquake probabilistic maps. These databases include both historical and instrumental seismicity, earthquake observations such as damage patterns, geodetic records, fault history, and fault details. The USGS databases are used to calculate earthquake, not tsunami, occurrence. In the Pacific, the rate of the largest subduction zone earthquakes calculated by the USGS along U.S. subduction zones is essentially the same as the rate of local tsunami generation. For local tsunamis, this is not the case along the U.S. Atlantic or Gulf coasts which are not bordered by subduction zones. Thus the occurrence of the largest expected earthquakes of magnitude 7 to 7.5 does not necessarily mean a tsunami is generated.

The critical importance of using the USGS NSHM databases together with the NGDC databases is clear in Cascadia. Here, the last great subduction earthquake occurred on January 26, 1700. Until the USGS launched extensive paleoseismic research in the late 1980s, this event was unknown.

At numerous coastal marshes along the Pacific Northwest coast, evidence of sudden influxes of both saltwater and sand sheets characteristic of tsunami deposits quickly led paleoseismologists to conclude that large vertical elevation changes of the marshes were caused by an earthquake. These were rapidly followed by inundation from a locally generated tsunami (Atwater, 1992). The only source for such an earthquake was the Cascadia subduction zone. Based on paleoseismology findings, researchers estimate that this earthquake broke the Cascadia fault along the entire Pacific Northwest coast, from northern California to central Vancouver Island (Atwater et al., 1995). The fault length, estimated from the distribution of elevation changes observed in coastal marshes, supports a magnitude 9+ event similar to the 2004 Sumatra earthquake.

In the middle of several coastal marshes, geologists found standing dead western red cedar trees still rooted in their original growth position. When the marsh elevation dropped suddenly during the last Cascadia earthquake, saltwater overtook the marsh, killing the trees. Using tree-ring dating techniques, paleoseismologists determined that these trees died during the winter of 1699–1700 (Yamaguchi et al., 1997). A damaging tsunami was well-recorded in Japan on January 27, 1700, but

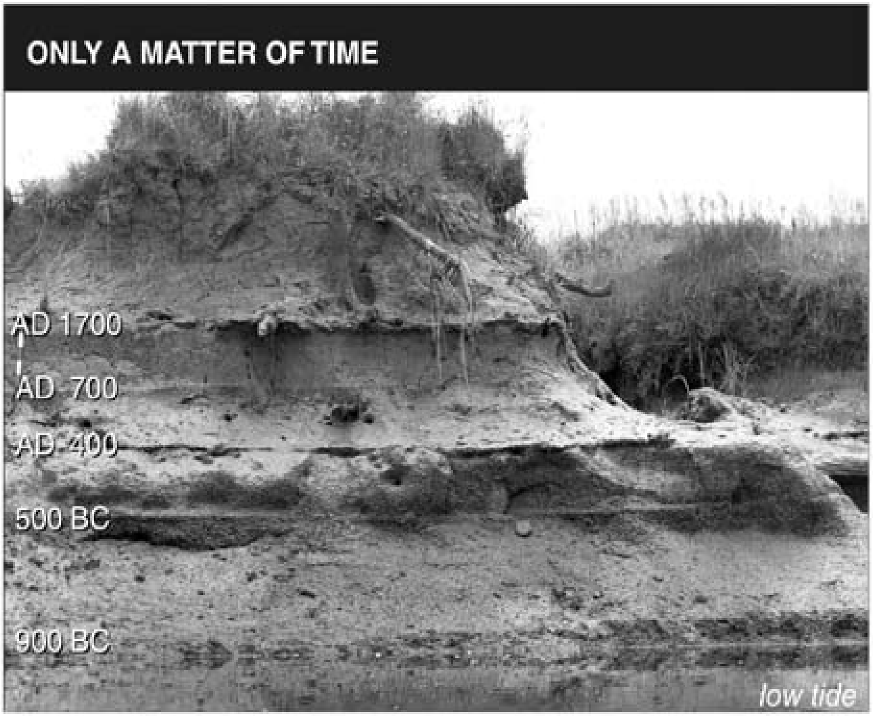

Figure 3-2. Paleoseismic and paleotsunami record at Willapa Bay, Washington. A stack of layers dating from 1700 A.D. back to 900 B.C. is very distinctive. Each layer represents the downdropping of the marsh during a Cascadia subduction zone earthquake and subsequent depositing of locally generated tsunami sands. Observations at many sites along Cascadia have led to the estimated recurrence of about 500 years for great subduction earthquakes. (USGS photo.)

its source was unknown. Researchers paired the coastal observations in the Pacific Northwest with written Japanese records, documenting the tsunami damage (Atwater et al., 2005). This detective work established the January 26, 1700, date as the last great Cascadia earthquake.

In addition to the historical Japanese records of the 1700 tsunami (seven runup locations), many tsunami deposits have been found along the coasts of California, Oregon, Washington, and British Columbia from this event (NGDC tsunami deposit database, Figure 2-1). Although the paleoseismic records have considerable variation in the time estimated between great earthquakes, the average recurrence time is currently estimated at 500 years for earthquakes of magnitude 9. These great earthquakes are recorded by the sudden vertical displacement of numerous coastal marshes, and nearly every displaced marsh shows evidence of tsunami deposits (Atwater and Hemphill-Haley, 1997). These paleoseismic studies underpin the USGS earthquake assessments.

In subduction zones where tectonic models link these studies to earthquake occurrence, the 200 years of runup observations represented by the NGDC database can effectively be extended backward in time, extending the historical database. Because the USGS earthquake assessments are cast in a probabilistic framework, they represent a proxy for local tsunami hazards in the Alaska, western Pacific, Pacific Northwest, and Caribbean subduction zones.

3.1 Atlantic and Pacific Basin Differences

A national comparison of tsunami hazards must account for the difference in tectonics between the Atlantic and Pacific Ocean Basins. As is well known, much of the Pacific consists of subduction zones (Appendix A, Figure A-1)—the Alaska, Cascadia, Kermadac-Tonga, and many others that are responsible for producing most of the world's great earthquakes and tsunamis (Table 2-1). The plethora of sources in the Pacific drives the number of tsunami events to the high levels seen in Hawaii. Not only are there large tsunami sources local to Hawaii, but the State is also in the crosshairs of tsunamis generated around the Pacific from South America to Alaska. To a lesser extent, other U.S. States and territories in the Pacific are subject to the dual threat posed by many distant sources and significant local sources.

The mid-Atlantic ridge, a spreading system, dominates the Atlantic Basin (Figure A-1). Unlike the subduction zone boundaries that dominate the Pacific and the Caribbean, the mid-Atlantic ridge is a passive boundary and tends to produce smaller magnitude earthquakes than those in subduction zones (Table 2-1). Generally, there is little probability of generating tsunamis along passive boundaries.

Lacking a tectonic plate boundary, the near-shore U.S. Atlantic and Gulf coasts are considered to be intraplate. This tectonic setting results in reduced expected earthquake maximum magnitudes (compared to the subduction zones in the Pacific) and greatly increased recurrence times. The USGS uses a maximum magnitude earthquake of 7.5 for all Gulf and Atlantic coastal areas (Frankel et al., 1996, 2002). Unlike the Pacific or the Caribbean where earthquakes rupture to the seafloor causing large vertical displacements, primary surface faulting and vertical displacement have a very low probability of occurrence along the Gulf and Atlantic coasts.

Complicating the assessment in the Atlantic is the uncertainty of the physics responsible for producing the largest events. The 1929 magnitude 7.3 Grand Banks, Newfoundland, earthquake is one of three known earthquakes with magnitudes of 7 or greater along the eastern coast of North America. More importantly, this event generated a tsunami that killed 29 people in Canada. Seismological studies show this was a complex earthquake with a largely horizontal slip at a depth of about 20 km (Bent, 1995). The seismological parameters rule out vertical displacement on the seafloor as the cause of the accompanying tsunami. Instead, an underwater landslide, triggered by the earthquake, caused the tsunami. In the NGDC database summarized in Table 2-1, the 1929 tsunami is the only runup listed for Maryland, Massachusetts, and New Hampshire, and is one of the two runups listed for South Carolina and Rhode Island.

The other two magnitude 7.0 or greater events along the Atlantic coast did not have destructive tsunamis. The first was the 1886 Charleston, South Carolina, earthquake. This event had an estimated magnitude of 7.3. Based on felt reports, the epicenter was estimated to be just onshore. A small, non-destructive tsunami was observed in both Florida and South Carolina. The second event occurred near Baffin Bay, Canada, in 1933. Also of magnitude 7.3, this event apparently did not cause an underwater landslide, and no tsunami was generated.

The Geological Survey of Canada has very qualitatively estimated that an earthquake in the magnitude range of 6.5 to 7.0 is the minimum required to initiate a significant underwater landslide in offshore Atlantic conditions (John Adams, Geological Survey of Canada, personal communication, 2006). Because events along and near the Atlantic coast are not expected to rupture faults to the surface and thus directly displace a volume of water, the simple occurrence of an event of this magnitude does not necessarily generate a tsunami. In areas along the Grand Banks where detailed bathymetric data exists, the number of observed underwater landslides is much less than the rate predicted from seismicity data. There is considerable uncertainty in relying on seismicity data alone.

The Geological Survey of Canada's estimate of magnitude 6.5 was used to assess the likelihood of an earthquake initiating underwater landsliding along the Gulf and Atlantic coasts. But it must be understood that as on the Canadian coast, the rate of underwater landsliding will be less than the earthquake rate. How many of those landslides may generate tsunamis is yet another unknown. Considerable research is needed on offshore earthquake rates and magnitudes, the stability of offshore sediments along the margin, shaking levels required to initiate underwater mass movement, and the likelihood of tsunami generation from such movement.

In subduction zones offshore U.S. States and territories, including the Caribbean, Cascadia, Alaska, American Samoa, and Guam/Northern Mariana, the rate of the largest magnitude earthquakes estimated in USGS hazard assessments is essentially the same as the generation of local tsunamis. The maximum magnitude and the recurrence time of subduction zone earthquakes differ from area to area, but the relation to tsunami generation remains more or less the same. In some subduction zones such as Cascadia, the great events that occur on the fault interface between the subducting and overriding plates give rise to the slip on the ocean floor that generates severe tsunamis. In others, such as the Caribbean, faults within the overriding plate (upper plate) generate severe local tsunamis.

Although the details of how earthquakes generate tsunamis are ultimately important for forecasting local wave behavior (whether these events occur on the long subducting plate interface or in the upper plate), these details are of lesser importance in the national overview. Accordingly, this report focuses on the recurrence of local earthquakes in subduction zones that exceed a local magnitude. A local magnitude of 7.5 is used for Puerto Rico and the Virgin Islands, and a local magnitude of 8.1 was used for Cascadia (Frankel et al., 2002).

3.2 Earthquake Probabilities determined from the USGS NSHM Databases

3.2.1 Non-Subduction Zones: Atlantic and Gulf Coasts

For the U.S. Atlantic and Gulf coasts, the USGS NSHM databases were searched for any known earthquakes with estimated magnitudes of 6.5 or greater located within 50 km of the shoreline. The probability of recurrence of earthquakes greater than magnitude 6.5 over 500 and 5000 years was then determined (Table 3-1, next page). Unlike the subduction zones where the largest earthquakes can be associated confidently with tsunami generation, along the U.S.Atlantic and Gulf coasts that is not possible. In some cases, such as the 1886 Charleston earthquake, the event is onshore, but serves

Table 3-1. Local earthquake sources—USGS probability of earthquake occurrence for non-subduction zones. (Table last updated in 2007.)

State/Territory	Earthquake with Magnitude > 6.5 in 500 years within 50 km of coast	Earthquake with Magnitude > 6.5 in 5000 years within 50 km of coast	Historical maximum magnitude observed near shore or offshore	Comment
U.S. Atlantic Coast				
Maine	<3%	<30%	<6	
New Hampshire	<3%	<30%	<6	
Massachusetts	<3%	<25%	<6	
Rhode Island	<2%	<15%	<6	
Connecticut	<2%	<30%	<6	
New York	<4%	<30%	<6	
New Jersey	<4%	<30%	<6	
Pennsylvania	<3%	<15%	<6	
Delaware	<3%	<15%	<6	
Maryland	<2%	<15%	<6	
Virginia	<1%	<4%	<6	
North Carolina	<1 to 5%	<5%	<6	
South Carolina	<35%	100%	7.3	1886 Charleston, non-destructive tsunami
Georgia	<1%	<10%	<6	
Florida	<1%	<3%	<6	
U.S. Gulf Coast				
Florida	<1%	<3%	<6	
Alabama	<1%	<4%	<6	
Mississippi	<1%	<5%	<6	
Louisiana	<1%	<5%	<6	
Texas	<1%	<4%	<6	

to drive the probability of an event greater than magnitude 6.5 along the South Carolina and Georgia coasts considerably higher than in other areas along the Atlantic.

In Figure 3-3 the return time for a magnitude 6.5 or greater earthquake provides an alternate view of how infrequently earthquakes of this magnitude occur along these coasts. Recurrence times are typically thousands of years everywhere except along the South Carolina coast. Additional research is needed to determine if the South Carolina area is unique in terms of the rate of magnitude 7 events along the U.S.Atlantic coast. If earthquake magnitudes closer to 7 are required to initiate underwater landslides, the mean recurrence times lengthen even more. Figure 3-3 also shows that the USGS earthquake hazard assessment is centered on estimating ground shaking as opposed to tsunami occurrence. The gray areas offshore in Figure 3-3 are outside of the areas considered in the earthquake assessment.

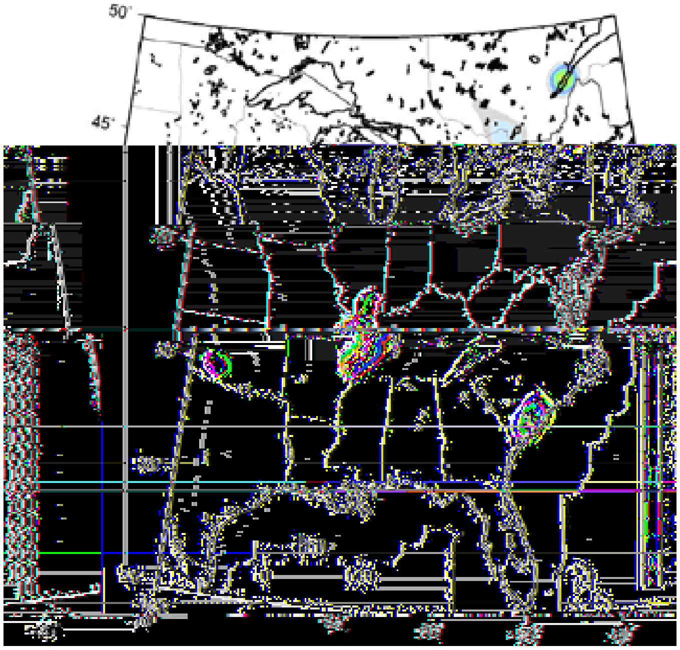

Figure 3-3. Return time for earthquakes with magnitude greater than 6.5 and within 50 km of a given location. (Figure courtesy of Steve Harmson, USGS.)

3.2.2 Subduction Zones: Pacific and Caribbean

The search results for subduction zones are summarized in Table 3-2 (next page). For comparison with the Atlantic and Gulf coasts, the probability of events greater than magnitude 6.5 over 500 years was included. This probability does not have the simple interpretation available for the Atlantic and Gulf coasts.

Subduction zones have three distinct earthquake source zones, and all three contribute to the earthquake hazard and two are sources for severe tsunamis. The interface between the Juan de Fuca and North American plates (Figure 3-4) is an example of a subduction zone. The long sloping interface between the downgoing plate (Juan de Fuca) and overriding plate (North American) is the subduction interface (fault). These types of plate boundaries are where most of the world's great earthquakes of magnitude 8 and larger occur. When the interface slips, sometimes tens of meters, the ocean floor moves as well. Since subduction zones have lengths of hundreds if not more than 1000 km and widths of 100 km or more, the slip between the plates is able to displace hundreds of km^3 of water.

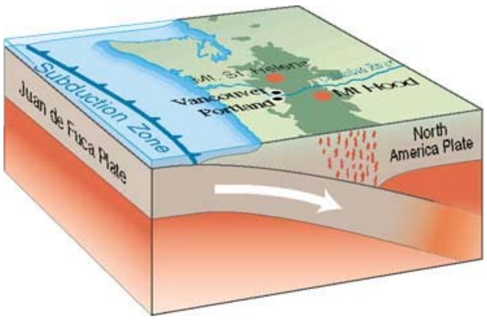

Figure 3-4. Diagram showing subduction zone. (USGS figure.)

The other two earthquake sources are in the downgoing and the upper plates. Earthquakes in the downgoing plate (Juan de Fuca), at depths of about 40 km and deeper and with magnitudes sometimes as large as 8 or greater, can

Table 3-2. Local earthquake sources—USGS probability of earthquake occurrence for subduction zones. The magnitude of a subduction zone earthquake is referred to as "msubduct."

State/Territory	Non-subduction earthquake with magnitude > 6.5 in 500 years within 50 km of coast	Subduction zone event with magnitude >msubduct in 500 years within 150 km of coast	Maximum magnitude observed or estimated for near shore or offshore	Comment
Puerto Rico and the Virgin Islands, msubduct = 7.5				
Puerto Rico	100%	~100%	7.5	1918 Mona Passage, severe tsunami**
Virgin Islands	100%	~100%	7.5	1867 Virgin Islands, severe tsunami
Pacific Coast--Cascadia, msubduct = 8.1				
Washington	30% to 90%	~100%	9+	1700 Cascadia, severe tsunami
Oregon	10% to 100%	~100%	9+	1700 Cascadia, severe tsunami
California	100%	~100%	9+	1700 Cascadia, severe tsunami
Pacific Coast--Alaska, msubduct = 7.5				
Alaska	100%*	~100%	9.2	1964 Alaska, severe tsunami
Pacific Island Territories, msubduct = 7.8				
Guam	N/A	~100%	7.8	1993 Guam, non-destructive tsunami
Northern Mariana	N/A	~100%	7.8	1993 Guam, non-destructive tsunami
American Samoa	N/A	~100%	8.5	1917 Northern Tonga trench, moderate tsunami

* Alaska calculation for magnitude >6.5 includes subduction interface events
** Events as large as magnitude ~8 are estimated in the Puerto Rico trench

cause significant ground shaking. Their depth limits their potential to directly generate tsunamis, as little, if any, surface displacement occurs on the ocean floor. However, the ground shaking from these events could cause underwater landslides that might generate tsunamis. Events in the upper plate (North American), again sometimes of magnitude 8, can cause strong ground shaking and generate severe tsunamis. The destructive 1918 Mona Passage earthquake and tsunami in Puerto Rico occurred on an upper plate fault within the Caribbean subduction zone system.

The search results for the subduction zones are considerably different than those for the Atlantic and Gulf coasts. First, for those subduction zones where data is available, the probability of an event greater than magnitude 6.5 over 500 years is extremely high everywhere. In the Caribbean and Cascadia, the probabilities do not include earthquakes on the subduction interface, whereas for Alaska the probability does. Generally, the events represented in the second column are not expected to generate tsunamis both because of their magnitude and the location of the causative faults. There are numerous earthquakes of magnitude 6.5+ off the California coast at depths of a few kilometers that did not generate either underwater landslides or significant tsunamis.

The third column of Table 3-2 shows the probability of a subduction zone event capable of generating a tsunami. In the Caribbean, the calculation includes expected upper plate fault sources, whereas in

Cascadia the calculation is only for a great interface event. Despite these differences, the conclusion is obvious—these coasts will almost certainly be hit by severe local tsunamis over 500 years.

3.2.3 Hawaii

Hawaii has a long history of damaging tsunamis (Table 2-1). Although not near a subduction zone, Hawaii's tsunami record includes numerous events resulting from large local earthquakes, as well as those tsunamis generated in the Pacific subduction zones. The most recent example of a local earthquake that generated a destructive tsunami is the 1975 Kalapana magnitude 7.5 event. This earthquake occurred on the south flank of Kilauea, moving the flank into the ocean and causing a tsunami that killed two people camped on the beach in Hawaii Volcanoes National Park.

The earthquake database search criteria were adjusted to meet Hawaii's tectonic setting. Table 3-3 shows that the probability of a magnitude 6.5 or greater earthquake and that of a magnitude 7.5 or greater event is about 100 percent over 500 years. The probability that these events will cause landslides is high, as there are examples in the recent historical and geological record.

3.2.4 Southern California

The offshore area of southern California has a series of crustal faults that have the potential to produce underwater earthquakes and generate local tsunamis. The 1927 Lompoc magnitude 7.1 earthquake produced a tsunami recorded at numerous sites in southern California, with the largest reported runup being 1.8 m in Surf, California. Earthquake fault parameters have been used to reproduce the tsunami runup pattern observed along the California coast (Satake and Sommerville, 1992). These suggest that primary faulting was responsible for generating the tsunami.

How frequently such events may generate tsunamis is uncertain, but the nearly 100 percent certainty of repeat events greater than magnitude 6.5 and 7.5 in offshore California indicates that this is an area of needed research. The likelihood that these events could generate underwater landslides and

Table 3-3. Local earthquake sources—USGS probability of earthquake occurrence for Hawaii, southern California, and the Arctic coast of Alaska.

State/area	Magnitude > 6.5 in 500 years within 50 km of coast	Magnitude > 7.5 in 500 years within 50 km of coast	Maximum magnitude observed or estimated for near shore or offshore	Comment
Hawaii and Southern California				
Hawaii	~100%	~100%	7.9	1868 Ka'u district, severe tsunami
Southern California	~100%	~100%	7.1	1927 Lompoc, moderate tsunami
Arctic Coast—Alaska				
Alaska	<1%	N/A	<6	Arctic coast rated no tsunami risk by Alaska

a tsunami requires study. The possibility of landslides generating tsunamis in southern California is also discussed in Section 4.

3.2.5 Alaska Arctic Coast

The Arctic coast of Alaska is part of the large intraplate area of the North American plate. As such, it has no near-shore tectonic plate boundary. The USGS estimates very low probabilities for earthquakes greater than magnitude 6.5. The State of Alaska considers a risk of a tsunami here to be none to very low.

3.3 Discussion

The USGS NSHM databases reinforce the conclusions from the NGDC historical tsunami runup database (Table 2-1). Because U.S. States and territories in the Pacific Basin and the Caribbean are located at plate boundaries with geologically short recurrence times, the tsunami hazard for these areas is much higher than along the non-plate boundary areas of the Gulf and Atlantic coasts. On the Gulf and Atlantic coasts, the probability of magnitude 6.5 and greater earthquakes is low almost everywhere with the notable exception of South Carolina.

The earthquake data was used to extend the initial assessment of tsunami hazards based on the NGDC database shown in Table 2-3. Because subduction zone events can also generate local tsunamis, a reliable estimate for tsunami recurrence in those zones is possible. In most Pacific U.S. States and territories, a local tsunami, often with severe runups, is expected at least once every 500 years. In Alaska, portions of the subduction zone have an even higher expected frequency of both earthquakes and tsunamis. This contrasts markedly with the assessment on the Gulf and Atlantic coasts, where the rate of even the minimum magnitude event thought necessary to generate a tsunami is very small over 500 years. And, as noted above, even the occurrence of a magnitude 6.5 or greater event carries no certainty that it will result in producing a landslide-driven tsunami.

Table 3-4 summarizes the qualitative tsunami hazard assessment based on the USGS NSHM databases.

Table 3-4. Qualitative assessment of tsunami hazards based on USGS NSHM databases.

Region	***Probability that an earthquake generates a local tsunami in 500 years by seafloor displacement***
U.S. Atlantic coast	Very low to low
U.S. Gulf coast	Very low
Puerto Rico and the Virgin Islands	**High**
U.S. west coast	**High**
Alaska	**High**
Hawaii	**High**
U.S. Pacific island territories	**High**

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Section 4. Gaps in Knowledge of Tsunami Sources

The NGDC tsunami database and the USGS NSHM databases characterize a significant part of the tsunami hazard facing the United States. Since the frequency of tsunamis generated by subduction zone earthquakes far exceeds the frequency of other sources, such as volcanic eruptions or underwater landsliding, further research on these subduction zone sources is critical for hazard assessments of nearby coastlines, but will have little effect on the national tsunami hazard assessment. However, non-earthquake sources, such as a volcano collapse in the mid-Atlantic and slope failure along the Atlantic coastal shelf, are possible tsunami sources that could affect the hazard assessment. Further, in the Atlantic Basin, the available databases may not fully characterize earthquake sources, particularly along the Azores–Gibraltar fracture zone. In this section, we highlight several key tsunami source studies that would narrow the uncertainty for a tsunami hazard assessment of U.S. coastlines.

4.1 Atlantic Basin

4.1.1 Earthquake Sources

Earthquakes along the eastern seaboard are poorly understood. It is clear that a better understanding of the generation of magnitude 7+ earthquakes similar to the 1929 Grand Banks earthquake is necessary. Unfortunately, such source studies are apt to be difficult, as there are very few available earthquakes that might provide some clues of the stresses responsible for generating these events. Again, the mere occurrence of such events does not guarantee a local tsunami.

Outside of the Caribbean, the Azores–Gibraltar fracture zone represents the clearest distant threat to the U.S Atlantic, Caribbean, and possibly Gulf coasts. It forms a portion of the plate boundary between the African and the Eurasian plates. The 1755 Lisbon earthquake generated a severe tsunami that devastated the City of Lisbon. Wave heights of 30 m were recorded along the European coast (Kozak and James, 1998). A highly stylized illustration, done 100 years after the actual event, shows how this earthquake and tsunami resonated in Europe (Figure 4-1).

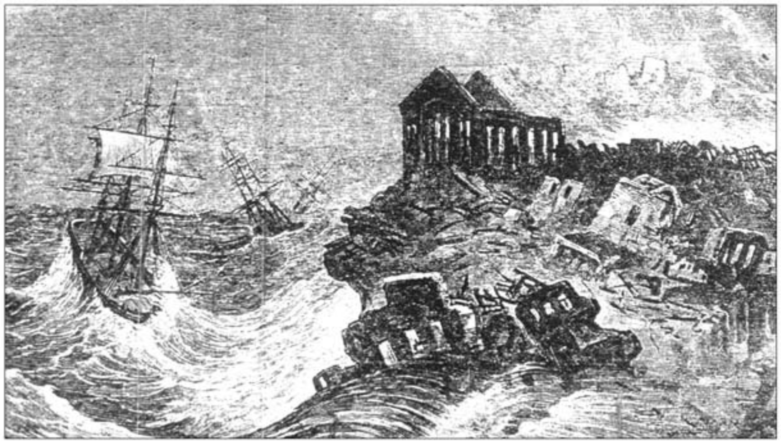

Figure 4-1. Published in the *Illustrated London News*, March 30, 1850, as part of a story on the Lisbon earthquake (Kozak and James, 1998).

The 1755 tsunami was reported in the West Indies, where an initial sea level rise of 1.0 m was followed by large waves (Kozak and James, 1998). There was a report in Cape Bonavista, Canada, of the harbor being drained then refilling and overflowing parts of the community. No observations on the U.S. Atlantic seaboard have been found for this event, although one numerical model suggests 2.0 m waves offshore with onshore runups of 3.0 m (Mader, 2001).

The plate boundary between the Eurasian and African plates is thought to be the source for the 1755 earthquake (Gràcia et al., 2003a; Thiebot and Gutscher, 2006). For much of its length eastward from the mid-Atlantic ridge, this boundary is either a passive spreading center or supports largely horizontal slip (small map insert, Figure 4-2). However, near the Iberian Peninsula, the plate boundary becomes complex. Sea floor bathymetry shows evidence of significant vertical motions (near Gorringe Bank) and there are large areas in deep water that could generate a major tsunami similar to the 1755 event.

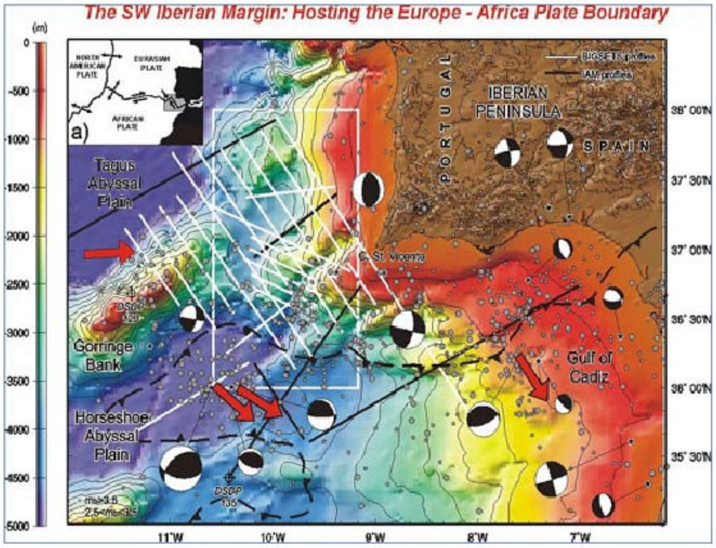

Figure 4-2. Map details of African-Eurasian plate boundary near the Iberian Peninsula. The plate boundary is complex here, with evidence of vertical motion indicated by earthquake focal mechanisms. (Figure courtesy of Dr. Eulalia Gràcia, Centre Mediterrani d'Investigacions Marines i Ambientals, Unidad de Tecnologia Marina (CSIC), Barcelona, Spain. Modified from Gràcia et al., 2003a.)

Three lines of research examining the 1755 event would be useful. First is developing a better understanding of earthquake occurrence and possible tsunami generation near the Iberian Peninsula. Fortunately, European researchers have an aggressive program underway to investigate both earthquake and tsunami generation (Gràcia et al., 2003a; Gràcia et al., 2003b; Gutscher et al., 2006). Second, possible evidence of the 1755 tsunami on the Caribbean and Atlantic coast should be pursued. Such a study needs to take a multi-disciplinary approach, from examining local newspapers to sifting through tidal marshes for possible tsunami deposits. Third, modeling efforts are needed to understand any propagation or source effects that might control the severity of the tsunami recorded in the Caribbean and North America for a source near the Iberian Peninsula.

A second source area, considerably less likely to generate a major tsunami, is the northern edge of the Caribbean plate west of Hispaniola (Figure 4-3). The northern boundary consists of a broad strike-slip zone that is dominated by horizontal motion, but features along the boundary indicate some vertical motion is accommodated over time. The installation of a Deep-ocean Assessment and Reporting of Tsunamis (DART™) station in the Gulf of Mexico (25.409° N, 86.800° W) is

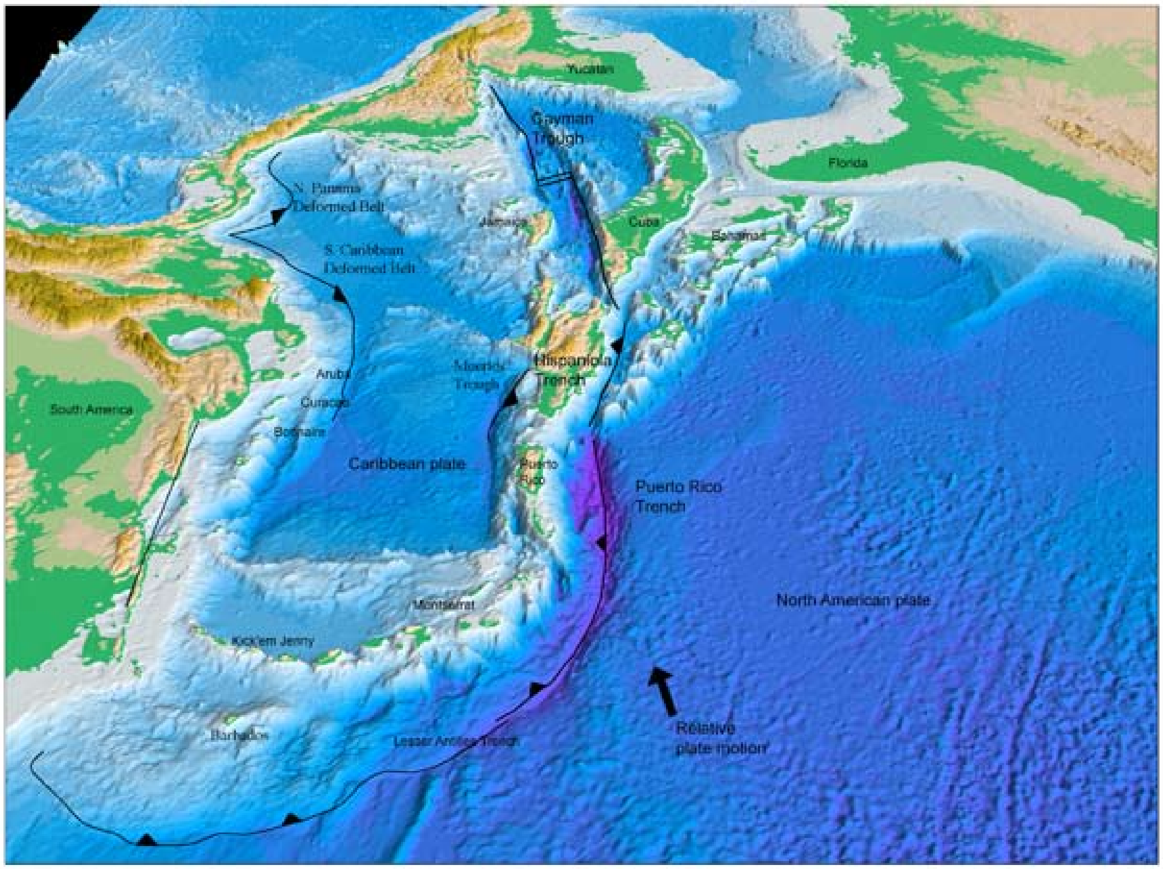

Figure 4-3. Caribbean plate boundaries. The area west of Hispaniola may have some potential to generate a tsunami, but this potential is poorly studied. (Figure courtesy of Uri ten Brink, USGS, Woods Hole, Massachusetts.)

geographically located in part to provide a warning from poorly studied sources such as this plate boundary.

4.1.2 Landslide and Volcano Sources

Because there are many fewer subduction zones in the Atlantic than the Pacific, there are fewer earthquake source regions to generate tsunamis. Underwater landslides are increasingly recognized as a potentially deadly tsunami source that need further study. Earthquakes (such as the 1929 Grand Banks event), volcanic activity, or gravity slumping could all generate underwater landsliding sufficient to cause tsunamis. The deadly Grand Banks tsunami, generated by an earthquake-induced underwater landslide, was recognized in 1952 as the first documented turbidity current (Lockridge et al., 2002). Recently, Tuttle et al. (2004) found sand layers deposited by the 1929 tsunami on Newfoundland (Figure 4-4). These researchers were able to distinguish the tsunami deposits from storm-related deposits, demonstrating that tsunami deposit studies can be successfully conducted on the Atlantic coast.

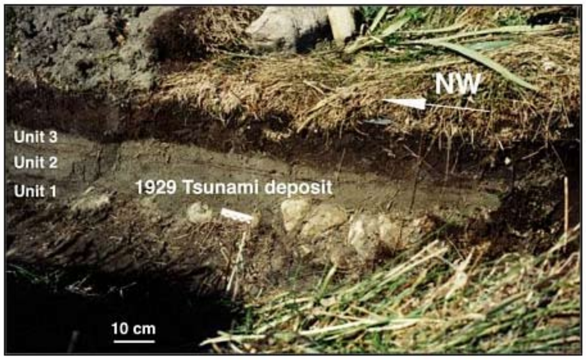

Figure 4-4. Tsunami deposits at Taylor's Bay on Newfoundland's southern coast from the 1929 Grand Banks earthquake and tsunami. The photograph shows three sandy units deposited by consecutive waves. (Tuttle et al., 2004.)

Since the Grand Banks tsunami, many underwater landslides have been found in the Atlantic Basin. Along the Atlantic coast, a number of underwater landslides are known in the deep canyons (Figure 4-5). Like landslides on land, underwater landslides show a distribution with many small slides incapable of generating a significant tsunami, to a few very large slides that could possibly generate catastrophic tsunamis.

The Albemarle–Currituck underwater landslide, offshore of the North Carolina–Virginia coast, is an example of the landslide problem for the Atlantic States. Driscoll et al. (2000) determined the age of the landslide as about 18,000 years and estimated the volume as about 140 km^3. Because of the large volume of displaced material, it is possible that this event generated a tsunami even though no record is known.

Side-scan sonar imagery of the landslide shows a series of three en-echelon (steplike) cracks to the north of the existing slide (Figure 4-6, next page). Driscoll et al. (2000) suggested that these cracks could be a prelude to a future landslide, with the potential to generate a tsunami. These authors estimated that such a tsunami might have runups of several meters. An improved assessment of tsunami hazards along the Atlantic coast requires

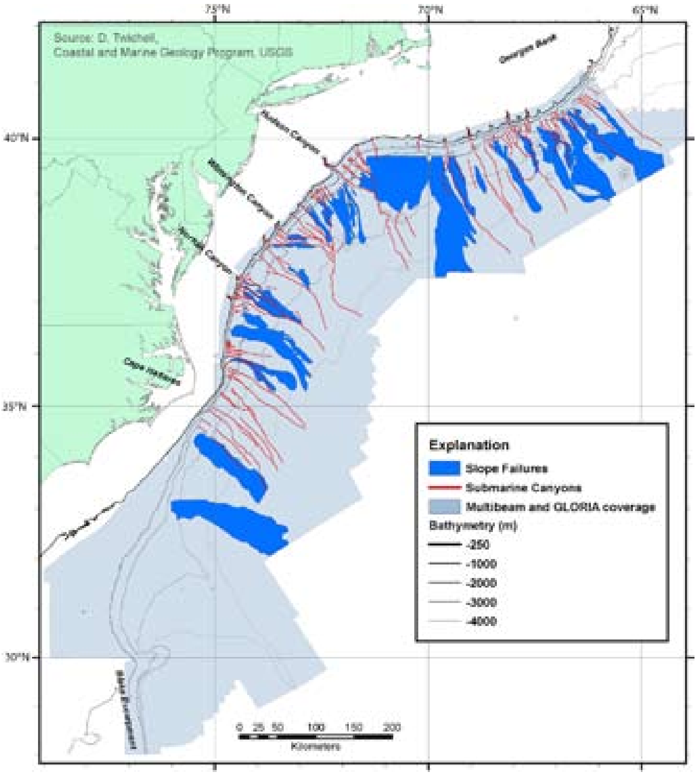

Figure 4-5. Slope failures and submarine canyons along a portion of the Atlantic coast. (Figure courtesy of Dr. David Twichell, Woods Hole Science Center, USGS.)

additional study of the underwater landslide record and tsunami deposit studies onshore. Fortunately, the USGS has begun a one-year investigation of tsunami sources along the Atlantic coast with funding from the Nuclear Regulatory Commission. This study has the advantage of looking at sources over 15,000 years that might affect nuclear facilities along the U.S. east coast. Those findings will be incorporated into a future version of this national assessment.

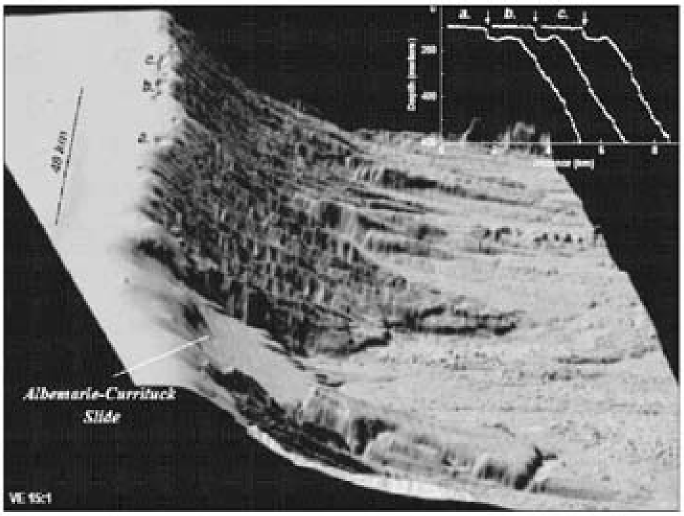

Figure 4-6. Side-scan sonar image of the Albemarle-Currituck landslide off the Virginia and North Carolina coasts. The scarps to the north of the slide are marked a, b, and c and are discussed in the text. (Driscoll et al., 2000.)

Failure of slopes on volcanic islands may also generate tsunamis. Soufriere Hills, Montserrat, in the Caribbean, erupted in 1997, 1999, and 2003. Each eruption resulted in a slope failure which generated a local tsunami. To date, no volcanic eruption in the Caribbean has generated a significant tsunami recorded along the Atlantic or Gulf coasts, but historically damaging tsunamis related to volcanic eruptions are responsible for much damage and loss of life in the Caribbean. More distant from the United States, the volcanic systems on the Canary Islands are viewed by some researchers as a potentially disastrous tsunami source. Ward and Day (2001) suggested that a massive volcanic eruption could trigger a massive landslide, with a block 15 to 20 km wide and 15 to 25 km long, dropping at high speeds into the deep Atlantic Ocean. According to their calculations, massive waves would result, and the United States coastline could see wave heights of as much as 10 to 25 m.

There is considerable controversy surrounding this estimate. Some researchers question whether such a catastrophic landslide is possible and suggest instead that an eruption would lead to a series of much smaller landslides (Wynn and Masson, 2003) and other researchers estimate far smaller waves reaching American shores, on the order of 3 m (Mader, 2001). Considerable research is needed to narrow the wide uncertainty surrounding such proposed catastrophic tsunamis in the Atlantic. It should be stressed that these very catastrophic sources are admitted, even by proponents, to be very rare compared with the 500 or so year recurrence time typical in Pacific and Caribbean subduction zones.

4.2 Pacific Basin

In principle, the Pacific could expect to see tsunamis generated by underwater landslides and volcanic activity causing sector collapses. However, given the recurrence time of 500 or less years in virtually all subduction zones, other sources will add relatively little to short-term hazard assessments. For example, Goldfinger et al. (2006) report that a number of exceptionally large, and many smaller, submarine landslides have been identified along the Cascadia margin that are thought to have repeat times on the order of 75,000 years for smaller slides, to 500,000 years for the largest slides. Goldfinger et al. (2006) estimate that the initial tsunami height of the largest of these slides may have been ~60 m, with a shallow water wave height of 10.0 m–20.0 m, and initial heights for the other largest slides were likely ~40 m (Figure 4-7). The smaller landslides most likely generated tsunamis with initial heights of ~1.0 m–5.0 m.

Similarly, upper plate faults connected to the slipping master subduction zone fault could play a significant role in generating very large tsunamis. The details of whether faults immediately off the northern California, Oregon, and Washington coasts might have significant vertical displacement during a Cascadia earthquake will have large repercussions for local tsunami hazard calculations. However, these details will do little to change the relative ranking of the very high and frequent hazard facing the Pacific States and territories, versus the very low and much less frequent hazard for Atlantic coastal States.

Improving the assessment of southern California is a high priority area. The Lompoc earthquake generated a tsunami with 1.8 m runups at several locations. Work is needed to assess the threat

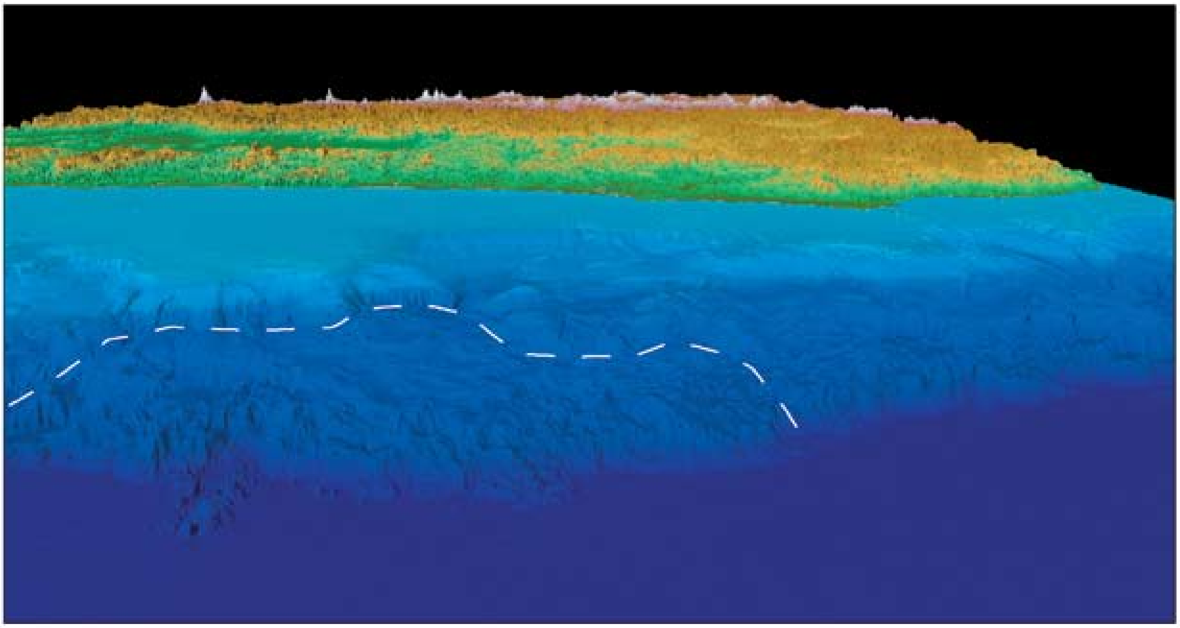

Figure 4-7. One of four megalandslides along the Cascadia subduction zone margin (Goldfinger et al., 2000). The Heceta Slide is ~80x50 km, and 2 km deep. The chaotic seafloor outlined by the dashed line marks the debris lobe of the slide, only about half of which is visible due to burial beneath the smooth abyssal plain in the foreground. Long-traveled buried debris indicates a catastrophic, not slow, failure. Numerous smaller slides ~10–15 km in width dot the continental slope. One young example is seen in the left foreground. Such slides are infrequent, but exceptionally large tsunami sources. The Oregon coast and Cascade Range is in the background.

of both earthquake-generated tsunamis by underwater surface displacement and to improve understanding of the potential for large underwater landslides that could generate tsunamis. In southern California, there is a very high rate of magnitude 7.0 and greater offshore earthquakes. A clearer understanding of possible locally-generated tsunamis would improve the national assessment.

Fortunately, the USGS has begun a two-year assessment of the tsunami potential of southern California as part of a new Federal Hazards Initiative. This assessment will look at both landslide and earthquake sources in southern California. As with the USGS east coast study, the results from southern California will significantly improve the overall national assessment and will be incorporated into future versions.

4.3 Discussion

The understanding of possible tsunami sources is clearly incomplete, as is the severity of tsunamis expected from underwater landslides or island sector collapse. It is clear that the lessons learned by Tuttle et al. (2004) for the 1929 tsunami need to be applied to marsh sites along the Atlantic, Gulf, and southern California coasts in an effort to begin to document the tsunami record. The 1755 event is a particularly attractive target for research, as the date and location of the event is well known. Ample evidence exists that the 1755 tsunami was observed in the West Indies, but determining whether runups occurred further north would help prioritize possible tsunami source region studies in the Atlantic—particularly the Azores–Gibraltar zone.

Also clear is the difficult nature of designing mitigation strategies for very rare, but possibly large, tsunamis from landslides or volcanic sector collapse in the Atlantic. From the view of warning, the deployment of DART™ stations in the Atlantic is designed to provide warning to American shores from distant sources like those noted here. Until the severity of waves possible on the Atlantic is better understood, the true nature of the tsunami hazard will remain uncertain.

It is also clear that lacking firm constraints on some tsunami sources, the Tsunami Warning Centers and other wave modeling researchers will have to continue to generate suites of theoretical waves that could affect American coastlines in the Atlantic. A successful research program on documenting tsunamis and understanding potential sources will allow updating and improving models used to provide warning guidance along the Atlantic and Gulf coasts.

4.4 National Tsunami Research Plan

The results of a review of the current state of tsunami research and a strategic plan for tsunami research in the United States are presented in the *National Tsunami Research Plan* (Bernard et al., 2007). This document includes state-of-the-science reports on hazard assessment, warning guidance, preparedness, response, and mitigation. Generally, the specific recommendations outlined here are reflected in this broader review of tsunami research needs.

4.5 References

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Section 5. Next Steps

This report is the first national tsunami hazard assessment of the United States and its territories. The core of the report consists of an evaluation of the NGDC historical tsunami databases and a consideration of probable local earthquake sources along U.S. coastlines capable of generating tsunamis. The results were summarized in tables that identified a qualitative tsunami hazard assessment of "very low" to "very high." These assessments recognized that tsunami runups of a few tens of centimeters have a lower hazard than those with runups of a few to many meters.

Hazard assessments are by their nature dynamic and new understanding of tsunami sources should trigger a review to ensure that the relative rankings of America's coastal tsunami threat reported here remain appropriate. As noted, two new studies of tsunami sources by the USGS, one off the U.S. east coast and one in southern California, when completed, will significantly improve the completeness of the national assessment presented here. The need to improve the characterization of tsunami sources was also one of six high-priority research areas identified in the *National Tsunami Research Plan* (Bernard et al., 2007). This plan was the result of a review in July 2006 by a group of tsunami experts on the current state of knowledge in areas essential to tsunami risk reduction. The six high-priority research areas are:

1. Enhance and sustain tsunami education
2. Improve tsunami warnings
3. Understand the impacts of tsunami at the coasts
4. Develop effective mitigation and recovery tools
5. Improve characterization of tsunami sources
6. Develop a tsunami data acquisition, archival, and retrieval system

The *Plan* also described the need to develop a probabilistic framework for characterizing tsunami sources that includes thousands of years of recurrence. Moving to a probabilistic framework, however, depends on high-resolution elevation models that currently do not exist for most coastal communities and the availability of resources for conducting numerous inundation and propagation simulations. A clear benefit of these inundation and propagation studies is the ability to provide estimates of currents in inundation areas. In some situations, relatively small runup amplitudes might have considerable currents that could cause significant damage in harbors and on beaches.

Recent examples of probabilistic tsunami hazard assessments illustrate the challenge of conducting this type of analysis. A probabilistic assessment of Western Australia (Burbridge et al., 2007) considers only tsunami sources from earthquakes along the Sunda Arc in the Indian Ocean. Offshore wave heights, not inundation or runup heights used in this report, form the basis of the tsunami hazard assessment. The goal of the report is noteworthy, however, as it represents an attempt to identify areas of Western Australia with the highest tsunami hazard from modeling studies and use these results to guide subsequent inundation modeling.

Two additional examples of probabilistic tsunami hazard assessments that include inundation modeling and runup height estimates are the Seaside, Oregon, study (Tsunami Pilot Study Working Group, 2006) described in Appendix C and a recent study of tsunami runup hazards in California at marine oil terminal sites (Borrero et al., 2006). The California study estimated tsunami runup heights for both 100– and 500–year return times. These runup heights for 100–year return times range from 1.0 m (3.3 ft) in the western Carquinez Strait in San Francisco Bay, to 3.3 m (11.0 ft) at Port Hueneme on the southern California coast. For a 500–year return period, the heights increase at these two locations to 1.2 m (4.0 ft) and 6.4 m (21.0 ft) respectively. A better understanding of inundation characteristics for the highly varied U.S. coastal environments is an obvious critical missing ingredient to a national hazard assessment.

As the tsunami assessment matures, the next step is to determine what is at risk from tsunamis. A complete tsunami hazard and risk assessment, called for in the NSTC *Framework* report, brings together the hazard assessment, the exposure of people and structures, and their combined vulnerability. The *National Tsunami Research Plan* (Bernard et al., 2007) identified another research area that is directly related to conducting this type of assessment. The *Plan* identified the need to understand the impacts of tsunamis at the coast, including measuring the tsunami current regime in harbors and at the coast, improving hydrodynamic modeling, developing credible fragility models of the interaction of tsunamis with the built and natural environment, and validating models through benchmarking. The complexity inherent in a tsunami risk assessment demands a full and collaborative partnership of the NTHMP.

5.1 References

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Section 6. Conclusion

The first action called for in the joint report by the sub-committee on Disaster Reduction and the U.S. Group on Earth Observations entitled *Tsunami Risk Reduction for the United States: A Framework for Action*, is to develop standardized and coordinated tsunami hazard and risk assessments for all coastal regions of the United States and its territories. In response to this report, at the request of the National Tsunami Hazard Mitigation Program (NTHMP), NOAA's National Geophysical Data Center (NGDC) and the United States Geological Survey (USGS) collaborated to conduct the first tsunami hazard assessment of the United States and its territories.

This report provides a national qualitative assessment of the United States tsunami hazard at a regional level by examining the record of historical tsunamis and earthquakes, the predominant cause of tsunamis, at the State and territory level. Two different sources of information were compiled to assess the United States tsunami hazard. The NGDC historical tsunami database was first examined and resulted in a qualitative tsunami hazard assessment based on the distribution of runup heights and the frequency of tsunami runups. The NGDC tsunami database contains reported tsunamis and is therefore limited to written records existing for an area. The hazard assessment also used the USGS National Seismic Hazard Map (NSHM) databases to partially extend the time interval. These databases made it possible to estimate the rate of occurrence of larger magnitude earthquakes that could generate a tsunami. Based on the total spread of events, runup amplitudes, and earthquake potential, we assigned a subjective hazard from very low to very high. These assessments recognize that tsunami runups of a few tens of centimeters have a lower hazard than those with runups of a few to many meters.

This hazard assessment reinforces the common understanding that the U.S. Atlantic coast and the Gulf Coast States have experienced very few tsunami runups. In contrast, all U.S. coasts in the Pacific Basin as well as Puerto Rico and the U.S. Virgin Islands have a "moderate" to "very high" tsunami hazard based on both frequency and known runup amplitudes. The total number and the large number of runups greater than 3.0 m observed in Alaska and Hawaii justified assigning a "very high" hazard for these two States. We assigned a "moderate" hazard to the Pacific island territories due to the rare occurrence of events with amplitudes greater than 3.0 m. Both the frequency and the amplitudes of tsunami runups support a qualitative "high" hazard assessment for Washington, Oregon, California, Puerto Rico, and the Virgin Islands. The "high" value for Oregon, Washington, and northern California reflects the low frequency (~1 per 500 years) but the potential for very high runups from magnitude 9 earthquakes on the Cascadia subduction zone. Although tsunami deaths are a measure of risk rather than hazard, we compared the known tsunami deaths found in our NGDC database search with our qualitative assessments based on frequency and amplitude.

The table (next page) summarizes the results of the NGDC and USGS database searches.

Table 6-1. Qualitative tsunami hazard assessment based on NGDC and USGS databases.

Region	***Hazard based on runups***	***Hazard based on frequency***	***Hazard based on local earthquakes***	***Number of reported deaths***
U.S. Atlantic coast	Very low to low	Very low	Very low to low	None
U.S. Gulf coast	Very low	Very low	Very low	None
Puerto Rico and the Virgin Islands	**High**	**High**	**High**	**172**
U.S. west coast	**High**	**High**	**High**	**25**
Alaska	**Very high**	**Very high**	**High**	**222**
Hawaii	**Very high**	**Very high**	**High**	**326**
U.S. Pacific island territories	**Moderate**	**High**	**High**	**1**

As our understanding of the tsunami hazard facing the United States improves, this document will be updated. Updates will be required as additional knowledge is obtained of possible sources in the Atlantic Basin and offshore southern California. Updates will also be required as knowledge increases of the Cascadia subduction zone earthquakes.

A complete tsunami hazard and risk assessment, called for in the *Framework* report, brings together the hazard assessment, the exposure of people and structures, and their combined vulnerability. The next step is to determine what is at risk from tsunamis. NGDC, in partnership with States and territories and other federal offices, plans to examine the exposure, vulnerability, and, finally, the risk of people and structures to tsunamis on the coasts of the United States.

Appendix A. What is a Tsunami?

adapted from the International Tsunami Information Center Web site
http://ioc3.unesco.org/itic/

The word tsunami is composed of the Japanese words “tsu” (which means harbor) and “nami” (which means “wave”). A tsunami is a series of large waves of extremely long wavelength and period. They are usually generated by a violent, impulsive undersea disturbance or activity near the coast or in the ocean. When a sudden displacement of a large volume of water occurs, or if the seafloor is suddenly raised or dropped by an earthquake, tsunami waves can be formed by forces of gravity. The waves travel out of the area of origin and can be extremely dangerous and damaging when they reach the shore.

The most destructive tsunamis are generated from large, shallow earthquakes with an epicenter or fault line near or on the ocean floor. These usually occur in regions of the earth characterized by tectonic subduction along tectonic plate boundaries (Figure A-1).

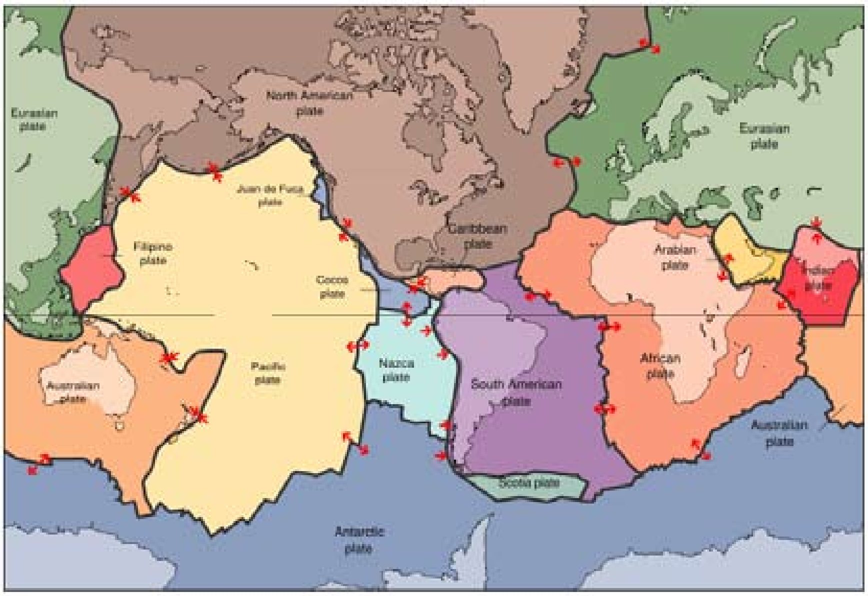

Figure A-1. The earth’s surface is broken into seven large and many small moving plates. Three types of movement are recognized at the plate boundaries: convergent, divergent, and transform-fault. At convergent boundaries, plates move toward each other and collide. Subduction occurs where an oceanic plate collides with a continental plate and the oceanic plate slides beneath the continental plate forming a deep ocean trench. This is the type responsible for most tsunamis (e.g., Gulf of Alaska Trench, Aleutian Trench, Chile Trench, Tonga Trench, and Puerto Rico Trench). At divergent boundaries, plates move away from each other (e.g., mid-Atlantic ridge). At transform-fault boundaries, plates move horizontally past each other (e.g., San Andreas fault, Cayman trough north of Puerto Rico).

When these plates collide or move past each other, they cause large earthquakes, which tilt, offset, or displace large areas of the ocean floor along a length of a few kilometers to as much as 1,000 km or more. The sudden vertical displacement of several meters over such large areas disturbs the ocean's surface, displaces water, and generates destructive tsunami waves. The waves can travel great distances from the source region, spreading destruction along their path. It should be noted that not all earthquakes generate tsunamis. Usually, it takes an earthquake with a Richter magnitude exceeding 7.5 to produce a destructive tsunami.

Although relatively infrequent, violent volcanic eruptions also represent impulsive disturbances that can displace a great volume of water and generate extremely destructive tsunami waves in the immediate source area. According to this mechanism, waves may be generated by the sudden displacement of water caused by a volcanic explosion, by a volcano's slope failure, or more likely by an explosion and collapse of the volcanic magmatic chambers.

Less frequently, tsunami waves can be generated from displacement of water resulting from rock falls, icefalls, and sudden submarine landslides or slumps. Such events may be caused impulsively from the instability and sudden failure of submarine slopes, which are sometimes triggered by the ground motions of a strong earthquake. Major earthquakes are suspected to cause many underwater landslides, which may contribute significantly to tsunami generation. In general, the energy of tsunami waves generated from landslides or rock falls is rapidly dissipated as they travel away from the source and across the ocean, or within an enclosed or semi-enclosed body of water—such as a lake or a fjord.

All oceanic regions of the world can experience tsunamis, but in the Pacific Ocean and its marginal seas, there is a much more frequent occurrence of large, destructive tsunamis because of the many large earthquakes along the margins of the Pacific Ocean.

Once a tsunami has been generated, its energy is distributed throughout the water column, regardless of the ocean's depth. The waves travel outward on the surface of the ocean in all directions away from the source area, much like the ripples caused by throwing a rock into a pond, except that the origin is not necessarily a point but can be along the entire length of ground disruption.

In the deep ocean, the height of the tsunami may be only a few centimeters to a meter or more. Tsunami waves in the deep ocean can travel at high speeds for long periods of time for distances of thousands of kilometers and lose very little energy in the process. The deeper the water, the greater the speed of the tsunami waves will be. At the deepest ocean depths, the speed of the tsunami wave will be as much as 800 km/h. Therefore, a tsunami generated in the Aleutian Islands may reach Hawaii in less than four and a half hours.

Several measurements are used to describe tsunamis. Inundation is the maximum horizontal distance inland that a tsunami penetrates. Runup is the maximum height above mean sea level the wave reaches at the maximum inundation. Water height is the average height of a tsunami measured from the trough to the crest after removing the tidal variation. Any tsunami runup over a meter is dangerous to people and property.

There are three direct factors of destruction from tsunamis: inundation, wave impact on structures, and erosion. Strong, tsunami-induced currents lead to the erosion of foundations and the collapse of bridges and seawalls. Flotation and drag forces move houses and overturn railroad cars. Considerable damage is caused by the resultant floating debris, including boats and cars that become dangerous projectiles that may crash into buildings, break power lines, and may start fires. Fires from damaged ships in ports, or from ruptured coastal oil storage tanks and refinery facilities, can cause damage greater than that inflicted directly by the tsunami. Of increasing concern is the potential effect of tsunami draw down, when receding waters uncover cooling water intakes of nuclear power plants.

Tsunami waves arrive at a coastline as a series of successive crests (high water levels) and troughs (low water levels). As they enter the shallow waters of the coastline, their speed decreases to about 50–60 km/h. For example, in 15 m of water the speed of a tsunami will be only 45 km/h. However, 100 km or more away, another tsunami wave travels in deep water towards the same shore at a much greater speed, and still behind it there is another wave, traveling at even greater speed. As the tsunami waves become compressed near the coast, the wavelength is shortened and the wave energy is directed upward—thus increasing their heights considerably.

Even if a tsunami wave may have been 1 m or less in the deep ocean, it may grow into a huge 30–35 m wave when it sweeps over the shore. Thus, tsunami waves may smash into the shore like a wall of water or move in as a fast-moving flood or tide—carrying everything in their path. If the tsunami waves arrive at high tide or during a storm, the effects will be cumulative and the inundation and destruction even greater. A locally-generated tsunami may reach a nearby shore in less than ten minutes. For people living near the coast, the shaking of the ground is a warning that a tsunami may be imminent. For tsunamis from more distant sources, however, accurate warnings of when a tsunami might arrive are possible because tsunamis travel at a known speed.

Tsunami warning systems have been established to protect life and property from the tsunami hazard by providing timely, accurate, reliable, and effective tsunami products to coastal populations and emergency management within the area-of-responsibility, as well as by advancing other aspects of tsunami hazard mitigation. The primary operational objectives of a tsunami warning system are to rapidly locate, size, and otherwise characterize major earthquakes, determine their tsunamigenic potential, predict tsunami arrival times, predict coastal runup when possible, and disseminate appropriate warning and informational products based on this information. The United States has established two tsunami warning centers: the Pacific Tsunami Warning Center (PTWC) in Honolulu, Hawaii, and the West Coast/Alaska Tsunami Warning Center (WC/ATWC) in Palmer, Alaska. PTWC serves as the operational headquarters for the Tsunami Warning System in the Pacific. PTWC works closely with other regional and national centers in monitoring seismological and sea level stations and instruments around the Pacific Ocean to evaluate potentially tsunamigenic earthquakes. The system disseminates tsunami information and warning messages to more than 100 points across the Pacific. Regional tsunami warning centers operated by the United States (WC/ATWC), France, and Japan provide regional warnings to the U.S. and Canadian coastlines, French Polynesia, and the northwest Pacific, respectively.

Appendix B. Risk Management Process

by Dale Dominey-Howes and Paula Dunbar

In this section the risk management process is discussed. This includes the identification and characterization of the hazard, identification of the vulnerability of people and assets that are exposed to the hazard, estimates of losses, and identification of appropriate mitigation strategies. This process is outlined in Figure B-1 (next page). The process is also described as it applies to tsunamis.

B.1 Hazard Assessment Module

A hazard assessment involves the process of identification and evaluation of a potentially-damaging phenomenon in a given area (Blanchard, 2006). In the hazard assessment module two activities are undertaken: (1) the identification and characterization of the hazard sources; and, (2) the calculation of the probability of occurrence. For hazards that occur frequently (e.g., floods), historical data give a reasonably accurate picture of the long-term hazard in terms of recurrence and the expected magnitude of events. For hazards that occur infrequently, such as earthquakes or tsunamis, historical data are insufficient to accurately assess the long-term hazard. Geologic data can be used to extend the record significantly for earthquakes and tsunamis (Atwater et al., 2005; Dominey-Howes, 2002).

Two approaches are often used to characterize infrequent hazards. The first approach, deterministic, uses discrete, single-valued events to arrive at a scenario-like description of the hazard. The second approach, probabilistic, allows the use of multi-valued or continuous events and models incorporating the magnitude and frequencies of all events that could impact a site. In other words, the inputs to a probabilistic analysis are the same as those used in a deterministic analysis, plus the assessment of the frequency of occurrence of the phenomenon.

Probabilistic tsunami hazard analysis (PTHA) was derived from probabilistic seismic hazard analysis (PSHA), developed by Cornell (1968). PSHA was modified to develop a PTHA that calculates wave heights and more recently to produce a probabilistic tsunami inundation map (Tsunami Pilot Study Working Group, 2006).

A probabilistic tsunami hazard analysis requires historical and prehistorical tsunami data, quantitative probabilistic models of local and far-field tsunami sources (earthquake, landslide, volcano), high-resolution digital elevation models (topography, bathymetry, tidal information), and numerous inundation and propagation simulations for the potential local and far-field tsunami sources. The result of this type of analysis, probabilistic tsunami inundation maps, was published in the *Seaside, Oregon Tsunami Pilot Study* (Tsunami Pilot Study Working Group, 2006), and described in Appendix C.

B.2 Exposure and Vulnerability Assessment Module

After the tsunami hazard has been characterized, the next step is to determine who and what is actually exposed to tsunami inundation and runup. This requires an assessment of the people, homes, commerce, industry, natural resources, etc., that are in the tsunami inundation zones for a given event. However, exposure does not equal vulnerability—the susceptibility to harm or damage during tsunami inundation. The vulnerability of a physical structure would be influenced by factors such as

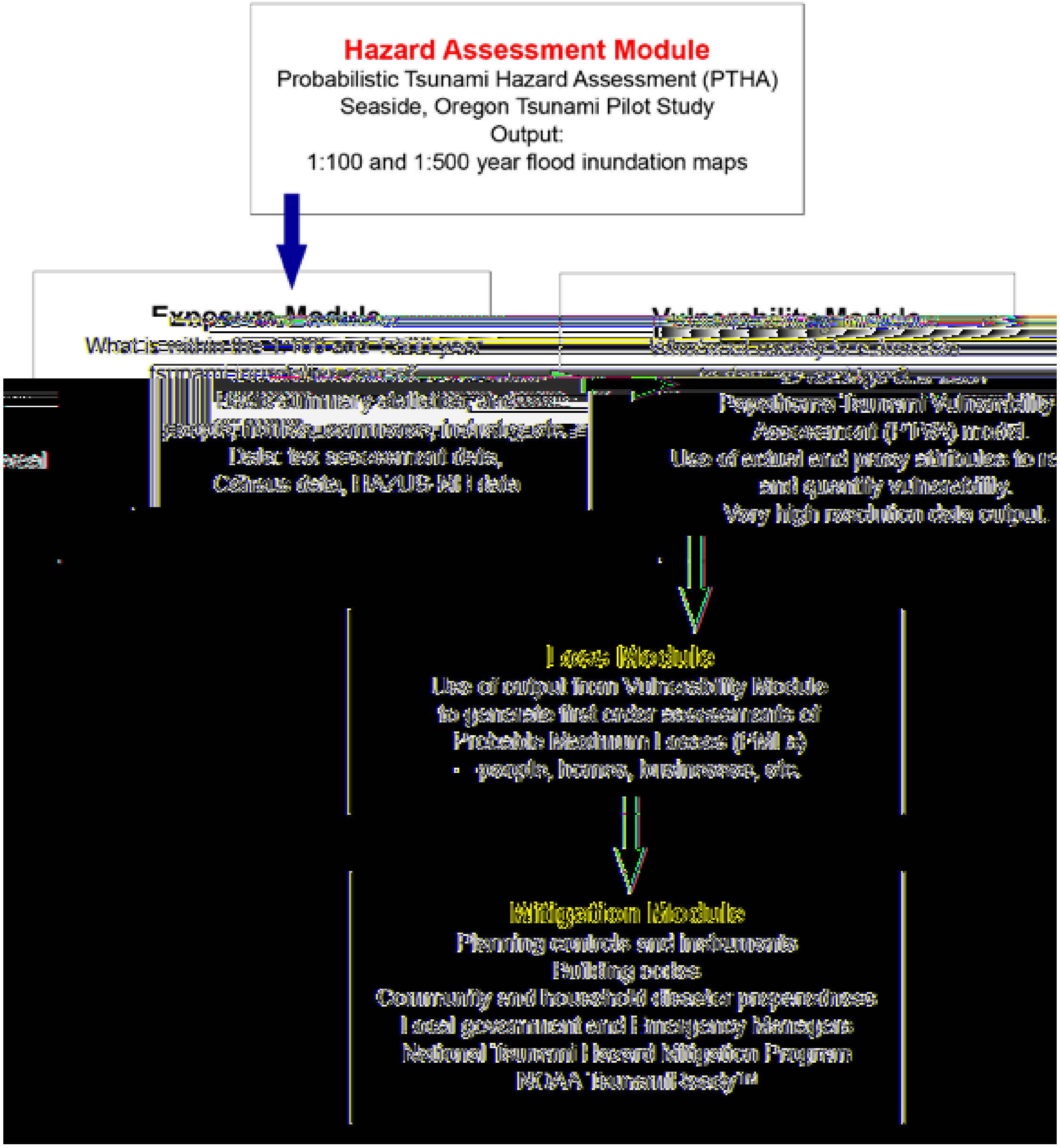

Figure B-1. Risk management process. HAZUS-MH is a Federal Emergency Management Agency software program that estimates potential losses from earthquakes, hurricane winds, and floods. HAZUS-MH includes national databases such as elevation, census tract, and building stock inventory data.

structural design, material, condition of structure, and distance from shoreline. The factors that would control the vulnerability of a person would include age, gender, education, mobility, and physical health. Therefore, the next step is to quantify the vulnerability of the people and structures exposed to tsunami inundation.

B.3 Loss Assessment Module

The next step is to combine the hazard, exposure, and vulnerability assessment modules, to calculate probable maximum losses (including number of casualties, direct economic losses, and indirect economic losses due to business interruption, etc.). From these probable maximum losses, it is possible to determine appropriate hazard mitigation strategies and disaster management plans. An examination of the literature indicates that the only validated tsunami vulnerability assessment and loss estimation methodology is that referred to as the Papathoma Tsunami Vulnerability Assessment (PTVA) model (Papathoma, 2003; Papathoma et al, 2003; Papathoma and Dominey-Howes, 2003; Dominey-Howes and Papathoma, 2006).

B.4 Mitigation Module

Once the probable maximum losses for tsunami have been determined, it is up to local government and emergency management agencies to develop appropriate mitigation and disaster management strategies. These would include such measures as land use zoning, building codes and regulations, outreach and awareness, etc. This completes the risk management process.

B.5 References

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Appendix C. Probabilistic Tsunami Hazard Assessment—Seaside, Oregon Tsunami Pilot Study—Modernization of FEMA Flood Hazard Maps

adapted from Seaside, Oregon Tsunami Pilot Study, Tsunami Pilot Study Working Group, 2006

A Tsunami Pilot Study was carried out for Seaside/Gearhart, Oregon, to develop an improved Probabilistic Tsunami Hazard Assessment (PTHA) methodology and to provide recommendations for improved tsunami hazard assessment guidelines. The study was part of FEMA's Map Modernization Program. It was an interagency effort by FEMA, the U.S. Geological Survey, and the National Oceanic and Atmospheric Administration, in collaboration with the University of Southern California, Middle East Technical University, Portland State University, Horning Geoscience, Northwest Hydraulics Consultants, and the Oregon Department of Geological and Mineral Industries.

The study consisted of a number of components including tsunami source specification; data acquisition of historical records, paleotsunami deposits and eyewitness reports; high-resolution digital elevation model development; tsunami propagation and inundation model development; probabilistic computations; and development of a GIS database.

C.1 Results

The final products of this study were two tsunami inundation maps. The first is a 100–year tsunami map, or maximum tsunami wave heights with a 1 percent annual probability of exceedance (Figure C-1, next page). The second is a 500–year tsunami map, or maximum tsunami wave heights with 0.2 percent annual probability of exceedance (Figure C-2). For a complete description of the process, it is suggested that readers obtain a copy of the complete report referenced below.

C.2 References

Tsunami Pilot Study Working Group, 2006, *Seaside, Oregon, Tsunami Pilot Study—Modernization of FEMA Flood Hazard Maps*, Joint NOAA/USGS/FEMA Special Report, 94 p., 7 appendices. http://pubs.usgs.gov/of/2006/1234/

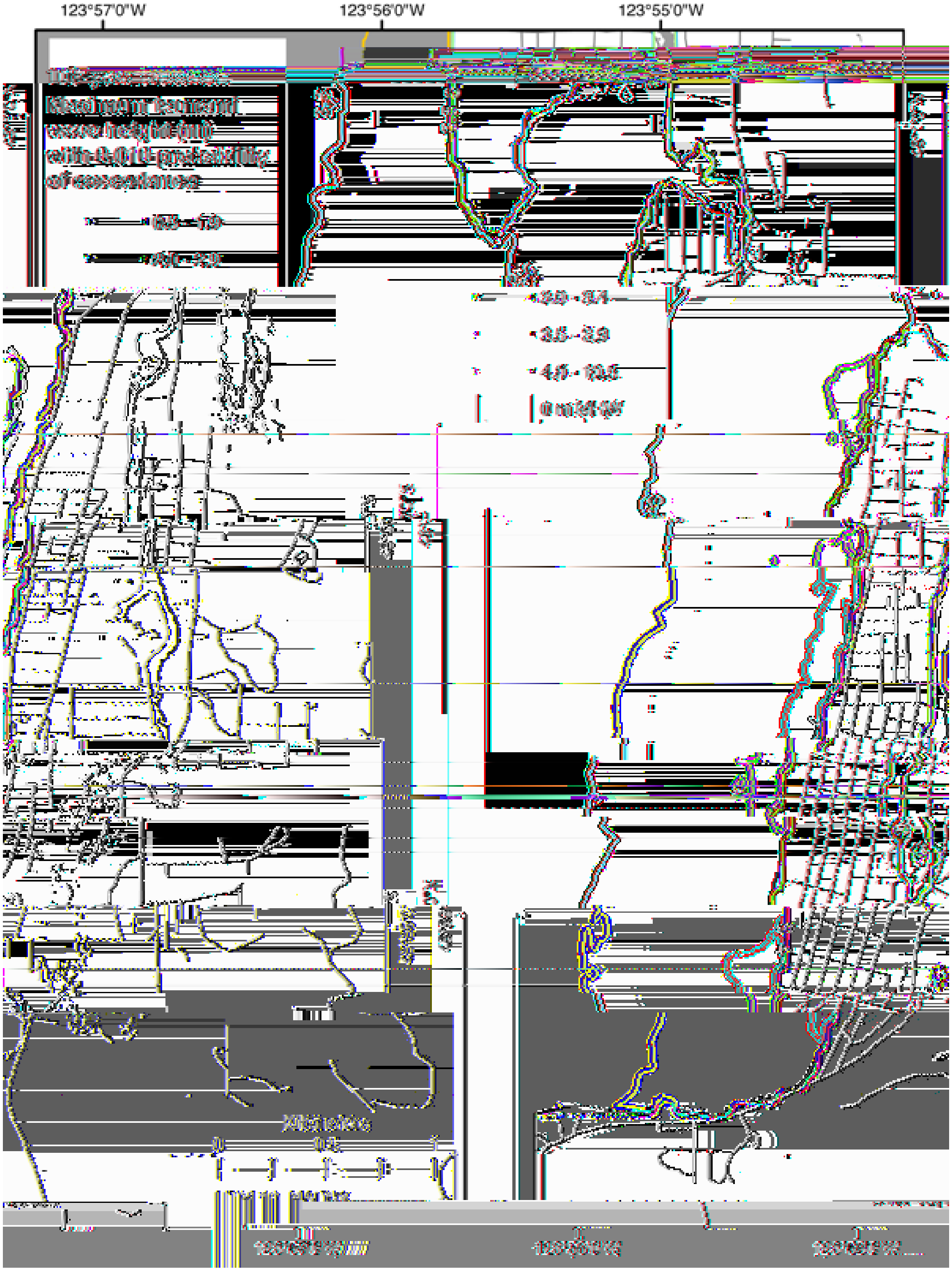

Figure C-1. Figure from the *Seaside Tsunami Pilot Study* (2006), showing a 100–year tsunami map for the Seaside-Gearhart, Oregon, area.

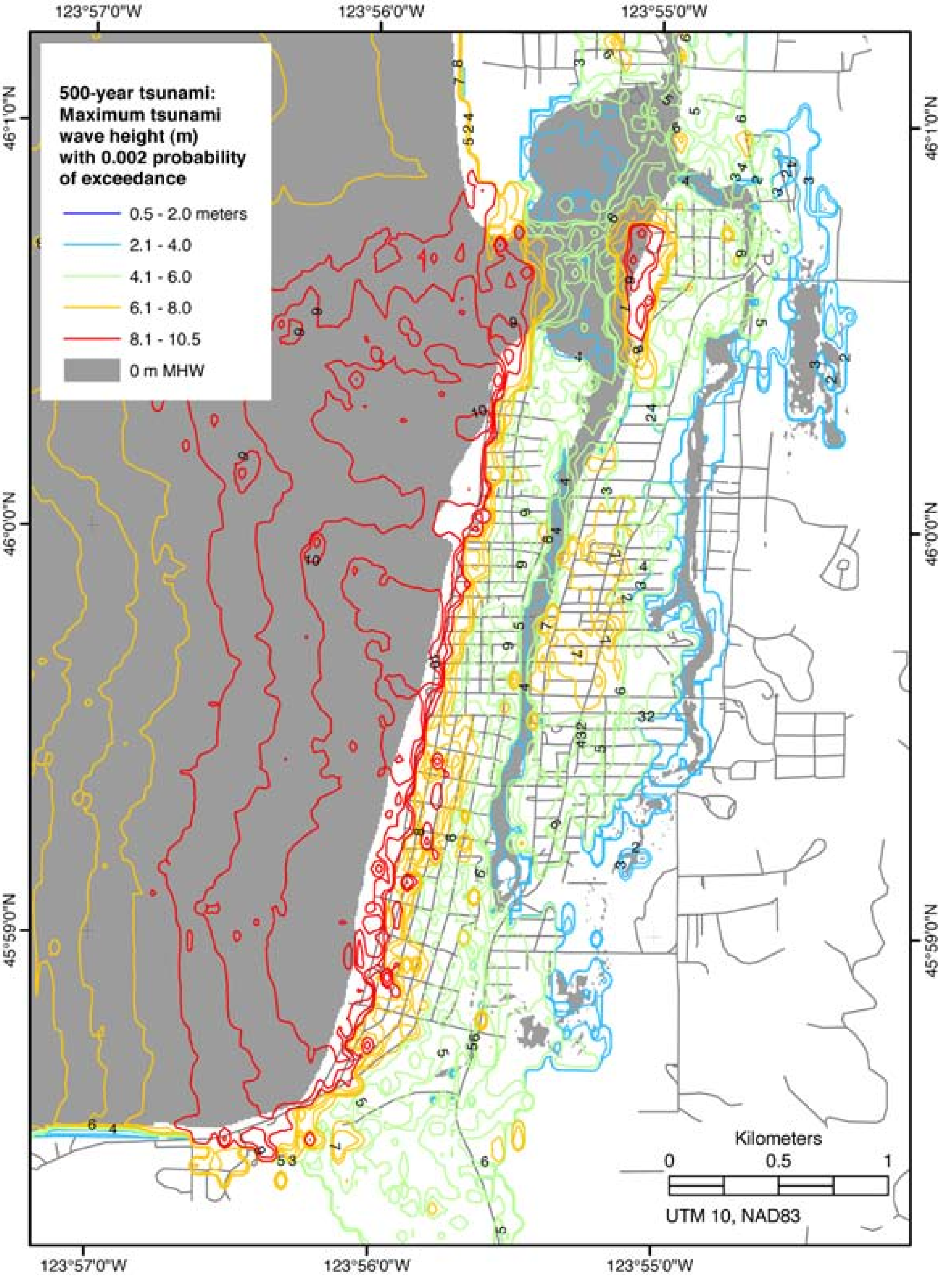

Figure C-2. Figure from the *Seaside Tsunami Pilot Study* (2006), showing a 500–year tsunami map for the Seaside-Gearhart, Oregon, area.