9

Risk and avoidance

INTRODUCTION

(Bak, 1997)

There are three problems in assessing the risk of modern tsunami to any coastline. All three suffer from popular *misconceptions*: The first problem involves the construction of probability of exceedence curves for the occurrence of tsunami based upon historical records. Such an approach is flawed logically and scientifically. It runs into a problem at the extreme end because many coastlines are devoid of credibly documented events. Second, it is often assumed that a coastline is immune from the threat of large tsunami if it has not recorded any. Any study attempting to show otherwise is assumed fundamentally wrong. This concept treats the occurrence of tsunami as being some stochastic or random process mainly generated by earthquakes (Figure 9.1). Because the sea is flat, so is the seabed. Any idea of submarine landslides is discarded. So too is any consideration of volcanoes as a cause of tsunami unless the smoke can be seen on the horizon. The idea that asteroids could cause tsunami is considered erroneous because no such phenomenon has been observed in the European-based historical record. Third, legends about tsunami, for whatever reason, are dismissed as myths, and, if any legend in a tsunamigenic region describes a tsunami as bigger than the historic record, it is dismissed as hyperbole by a primitive culture. Such attitudes are naive and ignore the fact that nature is critically self-organized. The laws for tsunami cannot be understood just by documenting tsunami that have occurred in the historical record. They must be set within the context of such events over hundreds of millions of years. Large catastrophic tsunami tend to occur because of the same processes that produce small ordinary tsunami. Conversely, if catastrophic phenomena such as asteroids have generated large tsunami, then they can be implicated in some of the smaller, more frequent events. Finally, tsunami events of all sizes tend to be clustered in time. The latter concept incorporates the notion of coherent catastrophism involving asteroid impacts.

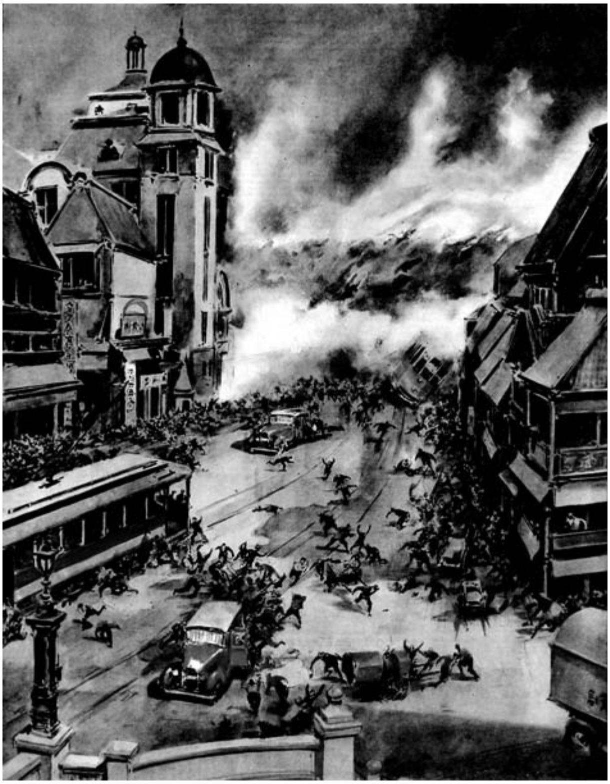


Figure 9.1. Drawing of a tsunami breaking on the Japanese coast. The drawing probably represents the September 1, 1923 tsunami, which affected Sagami Bay following the Great Tokyo Earthquake. While this earthquake is noted for its subsequent fires and appalling death toll, it generated a tsunami 11 m in height around the bay. See color section. The drawing is by Walter Molino and appeared in *La Domenica del Corriere,* January 5, 1947. *Source:* Mary Evans Picture Library Image No. 10040181/04.

Much of the world's coastline has never experienced a large tsunami in its historical record, be it European or otherwise. This is clearly illustrated in Figure 9.2, which shows that portion of the world's coastline subject to historical observation in 1500 and 1750. The boundaries in Figure 9.2 are liberally defined. Outside of eastern Asia, they reflect the presence of Europeans rather than any other society. In Chapter 8, the period around 1500 was identified as a possible time when a major asteroid struck the southwest Pacific. No one who could put pen to paper was there to observe any such event. A second event may have occurred in the Australian region in the early part of the 18th century. Again, the event would have gone unrecorded except by the odd Dutch merchant ship or ship of adventure.

There are various methods for assessing the vulnerability of coastal populations to the threat of tsunami. One of the simplest is to map population densities. Such population density maps are readily available over the Internet and indicate that the

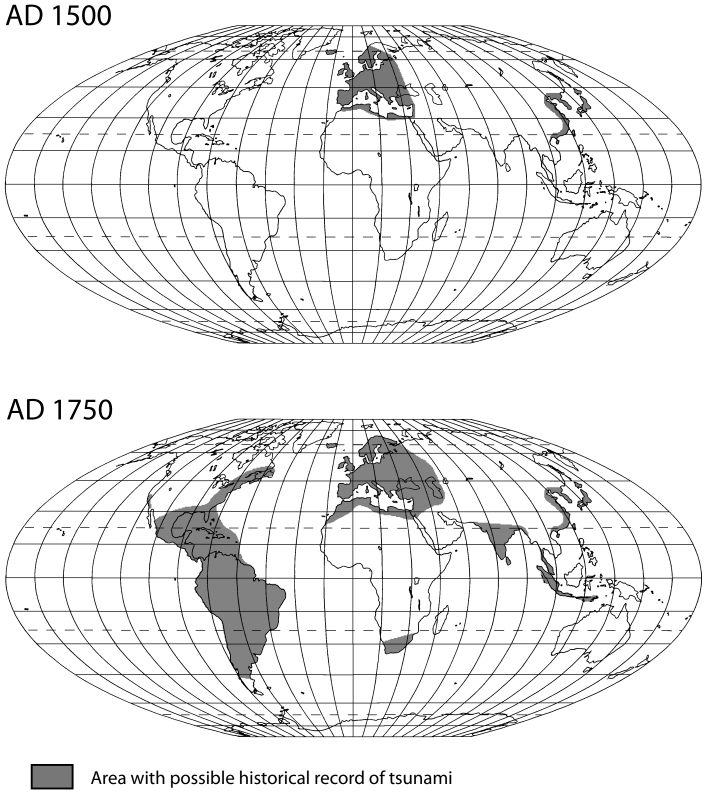
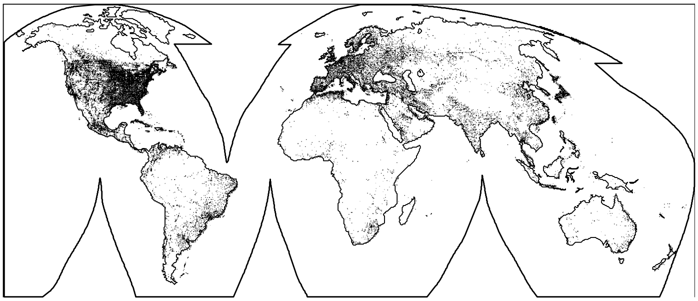
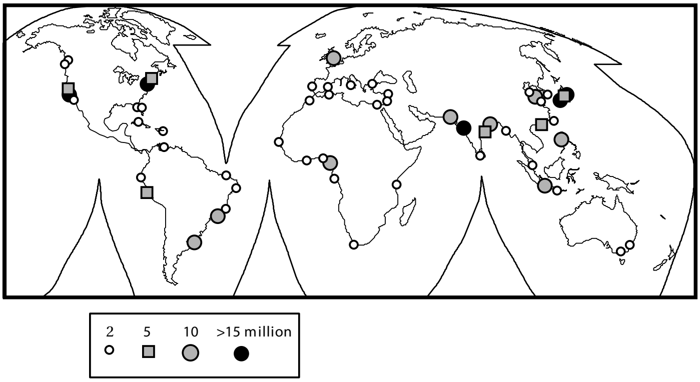


Figure 9.2. The world's coastlines having historical records of tsunami in 1500 and 1750.

most vulnerable regions of the world are the coastlines of China, India, Indonesia, Japan, the Philippines, the eastern United States, the Ivory Coast of Africa, and Europe. This approach ignores the economic impact of tsunami. Without belittling the death tolls due to tsunami that have occurred along isolated coastlines such as the Aitape coast of Papua New Guinea or the Burin Peninsula of Newfoundland, tsunami will have their greatest impact along densely populated coasts of developed countries or where large cities are located. For example, the next earthquake to strike Tokyo would have a worldwide economic impact. Here, any associated tsunami would destroy the shipping infrastructure so vital to that city's economy. It is possible to evaluate similar vulnerable coastlines in two ways. First, densely populated, economically developed coastlines can be detected by the amount of light they emit at night. The United States Air Force operates the Defense Meteorological Satellite Program (DMSP) that has a sensitive Operational Linescan System (OLS) that can detect visible and near-infrared light sources of $9\,\mathrm{W\,cm^{-2}}$–$10\,\mathrm{W\,cm^{-2}}$. Maps of stable light sources, with a nominal spatial resolution of 2.8 km, are readily available. These maps exclude transient fires. One such global map current to 1997 is presented in Figure 9.3a. It clearly shows that the developed coastlines of the world lie in western



A) Night lights of urban centers



B) Major coastal cities

Figure 9.3. Indicators of coastline where tsunami will impact the most. (A) Night lights from major economically developed urban centers. Data based on satellite measurements using the United States Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS). *Source: http://www.ngdc.noaa.gov/dmsp/download.html* The darker the shading, the greater the concentration of people. (B) Large coastal cities with over 2 million inhabitants. Data are current to the year 2000. *Source: http://www.citypopulation.de/World_j.html?E*

Europe, Japan, and the eastern United States. Tsunami would have the greatest economic impact along these coastlines.

Second, the largest coastal cities in the world require the greatest response irrespective of their role in the global economy. These cities are plotted in Figure 9.3b. Their populations are current to the year 2000. There are five coastal conurbations with populations of over 15 million people: Tokyo, New York, Osaka, Mumbai (Bombay), and Los Angeles. Were a major tsunami to strike any of these coasts, the impact would be severe. There are nine cities with populations of 10 to 15 million people. The majority of these are situated in poorly developed countries. Thirty-eight cities have populations of 2 to 5 million inhabitants. Over 60% of these are situated in Third World countries. It is only a matter of time before one of our world's major cities is crippled by a major tsunami.

WHAT LOCATIONS ALONG A COAST ARE AT RISK FROM TSUNAMI?

(National Oceanic and Atmospheric Administration, 1998;
International Tsunami Information Center, 2005)

A perusal of the chapters in this book will show that some locations along a coast are more susceptible to tsunami run-up, flooding, and inundation than others. Nine types of topography or coastal settings are particularly prone to tsunami. First and most obvious are exposed ocean beaches. Figure 7.1, which is an artist's impression of the tsunami generated by the eruption of Krakatau in 1883 hitting the coast of Anjer Lor, shows this clearly. If you live by the seaside, you are at risk from tsunami. This fact is clearly recognized for earthquakes by the United States National Oceanic and Atmospheric Administration (NOAA). In its publication *Tsunami! The Great Waves*, it states, "If you are at the beach or near the ocean and you feel the earth shake, move immediately to higher ground. DO NOT wait for a tsunami warning to be announced". Sometimes a tsunami causes the water near the shore to recede, exposing the ocean floor. Anyone who frequents the ocean should be aware that a rapid withdrawal of water from the shore is overwhelmingly a clear signature of the impending arrival of a tsunami wave crest. The time until arrival may be less than a minute or, in the case of the coast near Concepción, Chile, following the Great Chilean Earthquake of May 22, 1960, up to 50 minutes later.

Second, tsunami travel best across cleared land because frictional dissipation is lowest. This is shown mathematically by Equation (2.14) where the distance of inland penetration is controlled by the value of Manning's n, which is lower for smooth topography such as pastured floodplains, paved urban landscapes dominated by parking lots, and wide roads. The residents of Hilo, Hawaii, were dramatically made aware of this fact following the Alaskan earthquake of April 1, 1946 (Figure 9.4) and the Chilean earthquake of May 22, 1960 (Figure 5.11). On many flat coastlines that have been cleared for agriculture or development, authorities are now planting stands of trees to minimize the landward penetration of tsunami. The effect is clearly shown in Figure 9.5 at Riang-Kroko, on the island of Flores, following the December 12, 1992 Indonesian tsunami. The tsunami bore had sufficient energy to move large coral boulders; but these were deposited once the wave penetrated the forest and rapidly lost its energy through dissipation. If you like to live on the coast and are worried about tsunami, become green. Don't chop down the trees for the view, and be gracious to the neighbors that build in front of you, especially if they have an architecturally designed house with lots of corners and rough textured walls.

Third, tsunami flood across river deltas especially those that are cleared and where the offshore bathymetry is steep. On these coasts—and they are numerous (e.g., the east coast of Japan and the southeast coast of Australia—tsunami waves approach shore rapidly and with most of their energy intact. Delta surfaces lying only a few meters above sea level can allow tsunami to penetrate long distances inland, because once the wave gets onto the surface it propagates as if it was still traveling across shallow bathymetry. There are records of tsunami in small seas traveling 10 km inland across a delta for this reason.

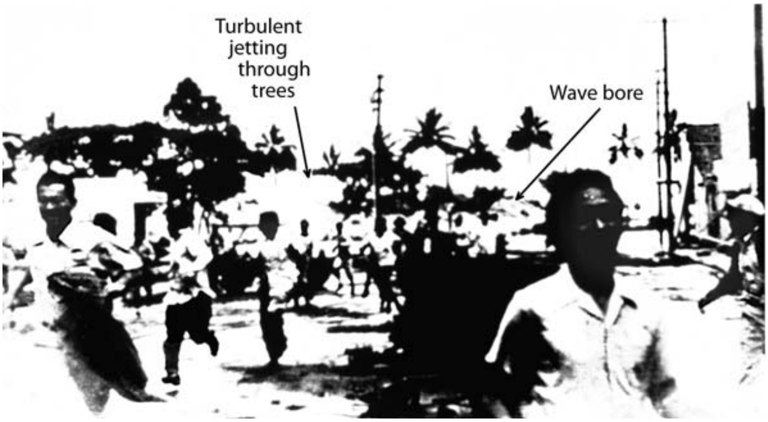


Figure 9.4. People fleeing the third and highest tsunami wave that flooded the seaside commercial area of Hilo, Hawaii, following the Alaskan earthquake of April 1, 1946. Photograph courtesy of the U.S. Geological Survey. *Source:* Catalogue of Disasters #B46D01-352.

Figure 9.5. Coral boulders deposited in the forest at Riang-Kroko, Flores, Indonesia following the tsunami of December 12, 1992. Note the person circled for scale and the abrupt termination of debris upslope. Photo credit: Harry Yeh, University of Washington. *Source:* NOAA National Geophysical Data Center.

Fourth, because of their long wavelengths, tsunami become trapped in harbors and undergo resonant amplification along steep harbor foreshores. As pointed out in Chapter 1, *tsunami* is a Japanese word meaning, "harbor wave", and when they get into harbors, especially ones where the width of the entrance is small compared with the length of the harbor's foreshores, they become trapped and can't escape back out to sea easily. Inside a harbor or bay, long waves such as tsunami tend to travel back and forth for hours dissipating their energy, not across the deeper portions but against the infrastructure built on the shoreline. Rapid changes in sea level and dangerous currents can be generated. Ria coastlines, such as those along the coast of Japan or southeastern Australia are ideal environments in which these effects can develop. Boats in harbors are particularly vulnerable and should put out to sea and deeper water following any tsunami warning.

Fifth, treat rivers exactly like long harbors. When a tsunami gets into a tidal river or estuary where water depths can still be tens of meters deep, the wave can travel easily up the river to the tidal limits or beyond. Along some coasts, tide limits may be tens of kilometers upriver, and residents living along the riverbanks may be very unaware that a threat from tsunami exists. If the river is deep and allows the penetration of the wave upstream, the height of a long wave can rapidly amplify where depth shoals or the river narrows. At these locations, water can spill over levees and banks, flooding any low-lying topography. In its publication *Tsunami! The Great Waves*, NOAA likewise warns, "Stay away from rivers and streams that lead to the ocean as you would stay away from the beach and ocean if there is a tsunami."

Sixth, tsunami have an affinity for headlands that stick out into the ocean, mainly because wave energy is concentrated here by wave refraction. Storm waves can increase in amplitude on headlands two- or threefold relative to an adjacent embayed beach. Tsunami are no different.

Seventh, if headlands concentrate tsunami energy because of refraction, then gullies do the same because of funneling. The highest run-up measured during the Hokkaido Nansei–Oki tsunami of July 12, 1993 was 31.7 m in a narrow gully. On the adjacent coastline the wave did not reach more than 10 m above sea level. It is safer to climb as far as you can up a steep slope rather than flee from a tsunami by running up a gully—even one that appears sheltered because it is hidden from the ocean.

Eighth, tsunami are not blocked by cliffs. Compared with the long wavelengths of a tsunami, which can still have a wavelength of 12 km at the base of a cliff dropping 20 m into deep water, the height of a cliff is minuscule. Steep slopes are similar to cliffs. Tsunami waves 1 m–2 m in height have historically surged up cliffs or steep slopes to heights of 30 m or more above sea level. If one has any doubt of this then turn to Figure 3.6 and look at the limit of run-up in the background of the photograph. This photograph was taken at Riang-Kroko following the December 12, 1992 tsunami. While the wave had a height of only a couple of meters approaching the coast and was stopped on gentle slopes by forest, it ran up to a height of 26.2 m above sea level on steeper slopes and bulldozed slopes clear of vegetation. The view from cliffs is great, but anyone standing there during a tsunami may have a unique life experience. Never do what 10,000 people did at San Francisco following the Great

Alaskan Earthquake of 1964. When they heard that a tsunami was coming, they raced down to vantage points on cliffs to watch it come in. Fortunately, the tsunami was a fizzler along this part of the Californian coast. However, it killed 11 people at Crescent City to the north.

Finally, tsunami are enhanced in the lee of circular-shaped islands. Not only do they travel faster here, but the height of their run-up can also be greater, especially if the initial wave is large. Two examples of this effect were presented in this text in Chapter 2. The December 12, 1992 tsunami along the north coast of Flores Island, Indonesia, devastated two villages in the lee of Babi, a small coastal island lying 5 km offshore of the main island. Wave heights actually increased from 2 m to 7 m around the island. Similarly, the July 12, 1993 tsunami in the Sea of Japan destroyed the town of Hamatsumae lying on a sheltered part of Okusihir Island. The tsunami ran up 30 m above sea level—more than three times the elevation recorded at some communities fronting the wave on the more exposed coast. Over 800 people were killed in the first instance and 300 people in the latter. Lee sides of islands are particularly vulnerable to tsunami because long waves wrap around these small obstructions as solitary waves, becoming trapped and increasing in amplitude.

WARNING SYSTEMS

The Pacific Tsunami Warning Center

(International Tsunami Information Center, 2005; Bryant, 2005)

As shown in Chapter 5, the most devastating ocean-wide tsunami of the past two centuries have occurred in the Pacific Ocean. For that reason, tsunami warning is best developed in this region. Surprisingly, a coherent Pacific-wide warning system was only introduced following the Chilean tsunami of 1960. To date that system still has flaws. These flaws will be discussed later. The lead time for warnings in the Pacific is the best of any ocean, anywhere up to 24 hours depending upon the location of sites relative to an earthquake epicenter.

Following the Alaskan tsunami of 1946, the U.S. government established tsunami warning in the Pacific Ocean under the auspices of the Seismic Sea Wave Warning System. In 1948, this system evolved into the Pacific Tsunami Warning Center (PTWC). Warnings were initially issued for the United States and Hawaiian areas, but following the 1960 Chilean earthquake, the scheme was extended to all countries bordering the Pacific Ocean. Japan up until 1960 had its own warning network, believing at the time that all tsunami affecting Japan originated locally. The 1960 Chilean tsunami proved that any submarine earthquake in the Pacific Ocean region could spread ocean-wide. The Pacific Warning System was significantly tested following the Alaskan earthquake of 1964. Within 46 minutes of that earthquake, a Pacific-wide tsunami warning was issued. This earthquake also precipitated the need for an International Tsunami Warning System (ITWS) for the Pacific that was established by the Intergovernmental Oceanographic Commission (IOC) of UNESCO at Ewa Beach, Oahu, Hawaii, in 1968. At the same time, other UNESCO/IOC member countries integrated their existing facilities and communications into the system. The United States National Weather Service currently maintains the Center. Before the Indian Ocean tsunami of 2004, 25 countries cooperated in the Pacific Tsunami Warning System: Canada, the United States and its dependencies, Mexico, Guatemala, Nicaragua, Colombia, Ecuador, Peru, Chile, Tahiti, Cook Island, Western Samoa, Fiji, New Caledonia, New Zealand, Australia, Indonesia, Philippines, Hong Kong, People's Republic of China, Taiwan, Democratic People's Republic of Korea, Republic of Korea, Japan, and the Russian Federation. An additional ten countries or dependencies received PTWC warnings. Many of these countries also operated national tsunami warning centers, providing warning services for their local area. After 2004, the Pacific Tsunami Warning Center took on additional responsibilities for the Indian Ocean, South China Sea, and Caribbean. As of June 2007, no separate warning center has been established for the Indian Ocean, although individual countries such as Thailand and Australia have substantially upgraded their detection and warning capabilities.

The objective of the International Tsunami Warning System is to detect, locate, and determine the magnitude of potentially tsunamigenic earthquakes occurring anywhere in the world. The warning system operates 24 hours per day, each day of the year. It relies on the detection of any earthquake with a surface wave magnitude of 6.5 or greater registering on 1 of 31 seismographs outside the shadow zones of any P or S waves originating in the Pacific region (Figure 9.6). These seismographs automatically relay information to the United States National Earthquake Information Center in Denver where computers analyze short-period waves for potentially tsunamigenic earthquakes. This detection process occurs within a few minutes. Once a suspect earthquake has been detected, information is relayed to Honolulu where a warning is issued. Anyone can receive these tsunami warnings direct via e-mail by subscribing to the International Tsunami Information Center (ITIC) website at *http://ioc3.unesco.org/itic/contents.php?id=142* With the warning, a request is issued to member countries for observations of anomalous sea level on tide gauges at 60 tide gauges scattered throughout the Pacific. These gauges can be polled in real time. Once a significant tsunami has been detected, its path is then monitored to obtain information on wave periods and heights. These data are then used to define travel paths using refraction–diffraction diagrams calculated beforehand for any possible tsunami originating in any part of the Pacific region. If no tsunami of significance is detected at tide gauges closest to the epicenter, the PTWC issues a cancellation.

The warnings are distributed to local, state, national, and international centers for any earthquake with a surface wave magnitude, M_s, of 7 or larger. At present, about three or four warnings per year are issued for the Pacific Ocean region for these sized earthquakes. A watch may also be initiated for regional tsunami earthquakes with a magnitude, M_s, of less than 7.5. Administrators, in turn, disseminate this information to the public, generally over commercial radio and television channels. The National Oceanic and Atmospheric Administration (NOAA) Weather Radio system provides direct broadcast of tsunami information to the public via VHF transmission. The U.S. Coast Guard also broadcasts urgent marine warnings on medium frequency (MF) and very high frequency (VHF) marine radios. Local

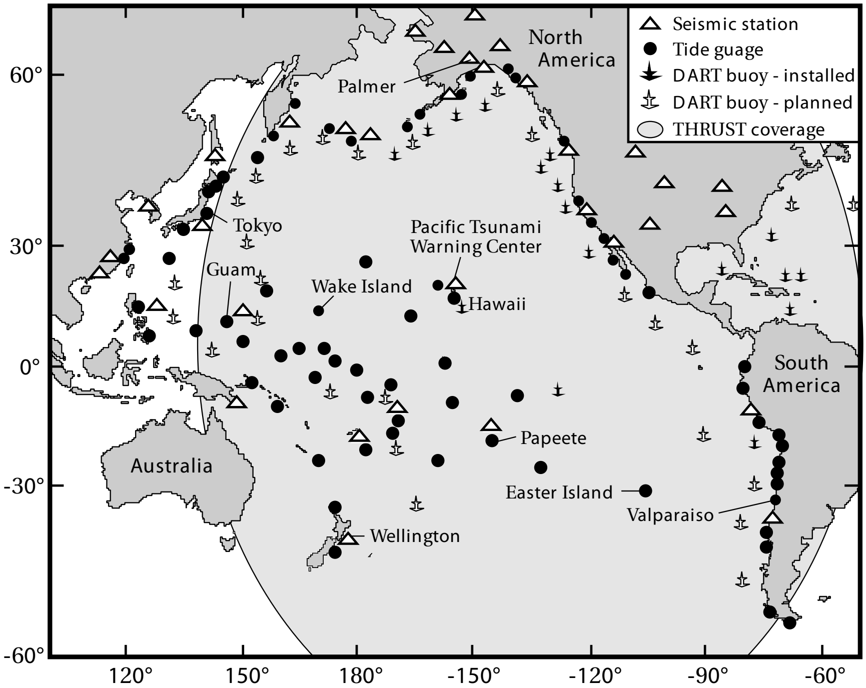


Figure 9.6. Location of seismic stations and tide gauges making up the Pacific Tsunami Warning System; buoys forming NOAA's DART network, installed before, and planned after, 2006; and area of possible coverage of the THRUST satellite warning system. *Sources:* Bernard (1991), and González (1999); *http://nctr.pmel.noaa.gov/Dart/Jpg/dartmapb-aug07.jpg*.

authorities and emergency managers are responsible for formulating and executing evacuation plans for areas affected by a tsunami warning (Figure 9.7).

Improvements have also been made in detecting teleseismic tsunami in the North Pacific. Seabed transducers have been installed and linked to surface buoys using acoustic telemetry (Figure 9.8). The transducers operate under the principle that long-wave motion can be sensed on the deepest seafloor. They can detect tsunami heights of only 1 cm in water depths of 6,000 m. The buoys have a GPS sensor and communicate their data to satellites for rapid communication. This networking can be used to forewarn of local tsunami, overcoming the necessity for long cable connections to shore that the Japanese experimented with unsatisfactorily in the early 1980s. NOAA deployed six of these deep ocean buoys before 2004 in a project known as Deep-Ocean Assessment and Reporting of Tsunami (DART). The 2004 Indian Ocean tsunami changed dramatically the deployment of DART buoys. The United States realized immediately that six buoys in the Pacific Ocean gave insufficient coverage to provide adequate tsunami warnings from all source regions in the Pacific. In addition, the United States realized that its eastern and southeastern coastlines were as vulnerable to tsunami as Sri Lanka and Thailand were to the Sumatran event of 2004. An upgraded buoy, DART II, was built linking tsunami

(A) (B)

Figure 9.7. Logos used to warn the public of the threat of tsunami in the United States. (A) International Tsunami Information Center. *Source: http://ioc3.unesco.org/itic/images/upload/tsunami_safety_sticker_big.gif* (B) NOAA National Weather Service. *Source: http://www.tsunamiready.noaa.gov/*

wave detection in the open ocean to land-based stations via Iridium satellites. Seven buoys were deployed in the Atlantic Ocean (Figure 9.6) and integrated into NOAA's Weather Radio All Hazards system and the Emergency Alert System to provide tsunami warnings to the entire US Atlantic coast, Gulf of Mexico, Puerto Rico, the US Virgin Islands, and eastern Canada. In addition, the number of buoys in the Pacific Ocean was increased to 37, scattered around the *Ring-of-Fire* earthquake source region. All buoys in the Atlantic and Pacific Oceans will be operational by 2008.

The International Tsunami Information Center also gathers and disseminates general information about tsunami, provides technical advice on the equipment required for an effective warning system, checks existing systems to ensure that they are up to standard, aids the establishment of national warning systems, fosters tsunami research, and conducts post-disaster surveys for the purpose of documentation and understanding of tsunami disasters. As part of its research mandate, the ITIC maintains a complete library of publications and a database related to tsunami. Research also involves the construction of mathematical models of tsunami travel times, height information, and extent of expected inundation for any coast. Planners and policy makers use results from these models to assess risk and to establish criteria for evacuation. The ITIC trains scientists of member states who, upon returning to their respective countries, train and educate others on tsunami programs and procedures, thus ensuring the continuity and success of the program. The Center also organizes and conducts scientific workshops and educational seminars aimed towards tsunami disaster education and preparedness. In recent years, emphasis has been placed on the preparation of educational materials such as textbooks for children, instruction manuals for teachers, and videos for the lay public. Finally, the ITIC publishes an information and education newsletter on a regular basis. This newsletter is distributed to interested individuals, scientists, and institutions in approximately 70 countries.

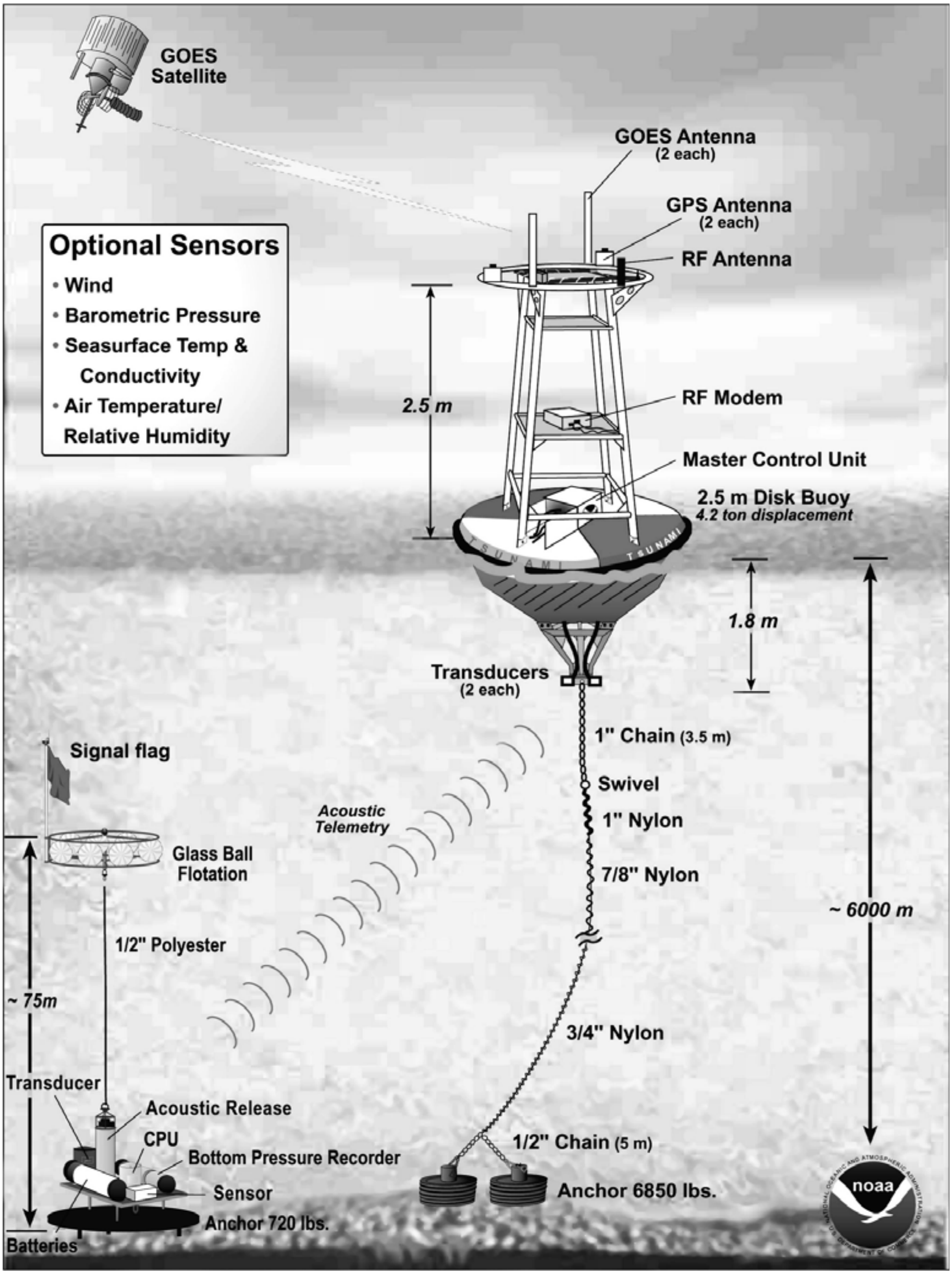


Figure 9.8. Schema of DART I buoy system. The upgraded DART II buoy is similar except it sends signals back to NOAA's Tsunami Warning Centers via an Iridium satellite. *Source: http://nctr.pmel.noaa.gov/Dart/Pdf/dart_buoy.pdf*

Flaws in regional warning systems

(Walker, 1995; González, 1999; Bryant, 2005)

The Pacific Warning Tsunami System is not flawless. The risk still exists in Japan and other island archipelagos along the western rim of the Pacific for local earthquakes to generate tsunami too close to shore to permit advance warning. Almost 99% of the deaths from tsunami over the past century have occurred in areas where the tsunami reached shore within 30 minutes of being generated. For example, the 7.8 magnitude earthquake that struck in the Moro Gulf on the southwest part of the island of Mindanao, the Philippines, on August 17, 1976, generated a 3.0 m to 4.5 m high local tsunami. The event was virtually unpredictable because the earthquake occurred within 20 km of a populated coastline. The Papua New Guinea tsunami of July 17, 1978 and the Indian Ocean tsunami of December 26, 2004 at Banda Aceh also arrived at shore within 30 minutes of the earthquake.

The accuracy of any warning system does not rely upon the number of tsunami predicted, but upon the number that are significant. False alarms weaken the credibility of any warning system. Although tide gauges can detect tsunami close to shore, they cannot predict run-up heights accurately. Consequently, 75% of tsunami warnings since 1950 have resulted in erroneous alarms. For example, on May 7, 1986, following an earthquake in the Aleutian Islands, and again in 1994 after an earthquake north of Japan, Pacific-wide tsunami warnings were issued for tsunami that never eventuated. Both events cost 30 million dollars in lost salaries and business revenues in Hawaii, where evacuations were ordered. The people who distribute such warnings are only human. Each time a false warning is issued, it weakens their confidence in predicting future tsunami, especially if the tsunami have originated from less well-known source regions. Worse than a false alarm is one that is realistic, but where the time has been underestimated. Tsunami travel charts have been constructed for tsunami originating in many locations around the Pacific Ocean. Many of these charts are inaccurate, with tsunami traveling faster than predicted. Before 1988, about 70% of the Pacific Ocean did not have publicly accessible bathymetry to permit accurate tsunami travel time forecasting. Fortunately, since the end of the Cold War, these data have become more available.

Earthquakes do not cause all tsunami. A relatively small earthquake can trigger a submarine landslide that then generates a much bigger tsunami. Nor is the size of an earthquake necessarily a good indicator of the size of the resulting tsunami. The July 17, 1998 tsunami along the Aitape coast of Papua New Guinea illustrates this fact. The earthquake that generated this event only registered a surface wave magnitude of 7.1, yet the resulting tsunami at shore was up to 15 m high. As described in Chapter 5, such tsunami earthquakes are common. For example, the April 1, 1946 Alaskan earthquake had a surface wave magnitude of 7.2, but it generated run-ups of 16.7 m as far away as Hawaii (Figure 2.10). On June 15. 1896, an earthquake that was scarcely felt along the coast of Japan generated the Sanriku tsunami that produced run-ups of 38.2 m above sea level and killed 27,132 people.

Finally, our knowledge of tsunami is rudimentary for many countries and regions, not just in the Pacific Ocean, but also other oceans. The Indian Ocean tsunami of December 26, 2004 dramatically illustrated this fact. While travel time maps have been drawn up for source regions in the Pacific Ocean historically generating tsunami—for example, the coasts of South America, Alaska, and the Kamchatka Peninsula—not all of the coastline around the Pacific Rim has been studied. This was made apparent on March 25, 1998 when an earthquake with a magnitude, M_s, of 8.8 occurred in the Balleny Islands region of the Antarctic directly south of Tasmania, Australia. Because of the size of the earthquake, a tsunami warning was issued, but no one knew what the consequences would be. The closest tide gauges were located on the south coast of New Zealand and Australia. Forecasters at the PTWC in Hawaii had to fly by the seat of their pants and wait to see if any of these gauges reported a tsunami before they issued warnings farther afield. While that may have helped residents in the United States or Japan, it certainly was little comfort to residents living along coastlines facing the Antarctic in the Antipodes. In cities such as Adelaide, Melbourne, Hobart, and Sydney, emergency hazard personnel knew they were the "mine canaries" in the warning system. Fortunately, the Antarctic earthquake was not conducive to tsunami, and no major wave propagated into the Pacific Ocean.

Localized tsunami warning systems

(Bernard, 1991; Okal, Talandier, and Reymond, 1991; Shuto, Goto, and Imamura, 1991; Reymond, Hyvernaud, and Talandier, 1993; Schindelé *et al.*, 1995; Furumoto, Tatehata, and Morioka, 1999; González, 1999; Sokolowski, 1999b)

A tsunami originates in, or near, the area of the earthquake that creates it. It propagates outwards in all directions at a speed that depends upon ocean depth. In the deep ocean, this speed may exceed $600\ \text{km s}^{-1}$. In these circumstances, the need for rapid data handling and communication becomes obvious if warnings are to be issued in sufficient time for local evacuation. Because of the time spent in collecting seismic and tidal data, the warnings issued by the PTWC cannot protect areas against local tsunami in the first hour after generation. For this purpose, regional warning systems have been established. Local systems generally have data from a number of seismic and tidal stations telemetered to a central headquarters. Nearby earthquakes have to be detected within 15 minutes or less, and a warning issued soon afterwards to be of any benefit to the nearby population. Because warnings are based solely upon a seismic signature, false warnings are common. At present, warning systems tend to err on the side of caution to the detriment of human life.

One of the first local warning systems was established for the northeast Pacific Ocean. The tsunami that followed the Alaskan earthquake of March 27, 1964 were of three types: localized, landslide induced, and ocean-wide. The Pacific Tsunami Warning System was only equipped to handle ocean-wide phenomena. Not only did warnings from Honolulu reach Alaska after the arrival of all three types of tsunami, they also went through a process that delayed dissemination to the public along the west coast of the United States. The West Coast/Alaska Tsunami Warning Center (WC/ATWC) was established in Palmer, Alaska, in 1967 to provide timely and effective tsunami warnings and information for the coastal areas of Alaska. In

1982, the Center's mandate was extended to include the coasts of California, Oregon, Washington, and British Columbia. Finally, in 1996, the Center's responsibility was expanded to include all Pacific-wide tsunamigenic sources that could affect these coasts.

The objectives of the West Coast and Alaska Tsunami Warning Center are to provide immediate warning of earthquakes in the region to government agencies, the media, and the public; and to accelerate the broadcast of warnings to the wider community along the west coasts of Alaska, Canada, and the United States. Because tsunamigenic earthquakes can occur anytime, the Center operates continuously 24 hours a day throughout the year. To achieve this objective and to reduce labor costs, the Center has been automated with state-of-the-art computers and earthquake-detecting software. Alarms are triggered by any sustained, large earthquake monitored at eight seismometers positioned along the west coast of North America and 23 short- and long-period seismometers in Alaska. Warnings are issued whenever any earthquake in the Pacific basin exceeds a predetermined magnitude. Tsunamigenic earthquakes can be identified immediately from seismic data using an algorithm that detects P waves. The algorithm then automatically determines the initial magnitude and location of the earthquake using all seismic stations in the network. Once a tsunamigenic earthquake's parameters have been determined, a warning can be issued automatically within 15 minutes of the event together with the estimated arrival time of the tsunami at 24 sites along the west coast of North America. Messages are disseminated by satellite, teletype, e-mail, the internet, and phone to a number of crucial people locally. Once a warning has been issued, over 90 tide gauges are monitored to confirm the existence of a tsunami, and its degree of severity. The Center also conducts community preparedness programs to educate the public on how to avoid tsunami if they are caught in the middle of a violent earthquake. Follow-up visits are made to the communities that have experienced a false alarm. The purpose of these visits is to explain why a warning was issued and to stress the continued need to respond to emergency tsunami warnings.

Other tsunamigenic source areas in the Pacific Ocean have developed localized warning systems. Separate warning systems also exist for Hawaii, Russia, French Polynesia, Japan, and Chile. The Russian warning system was developed for the Kuril–Kamchatka region of northeastern Russia following the devastating Kamchatka tsunami of 1952. This system operates from three centers at Petropavlovsk-Kamchatskiy, Kurilskiye, and Sakhalinsk. It is geared towards the rapid detection of the epicenter of coastal tsunamigenic earthquakes because some tsunami here take only 20–30 minutes to reach shore. In French Polynesia, an automated system was developed in 1987, for both near- and far-field tsunami, by the Polynesian Tsunami Warning Center at Papeete, Tahiti. The system uses the automated algorithm TREMORS (Tsunami Risk Evaluation through seismic MOment in a Real time System) to analyze in real time seismic data for any earthquake in the Pacific Ocean. Rather than using P and S waves to calculate earthquake magnitude, TREMORS uses the magnitude of seismic waves traveling through the mantle. This mantle magnitude, M_m, is calculated from Rayleigh or Love waves having periods between 30 s and 300 s. These long-wave periods are virtually

Figure 9.9. Ryoishi, a typical town along the Sanriku coast of Japan protected against tsunami by 4.5 m high walls. These walls are now common around the Japanese coast; however, they do not offer protection against tsunami having historical run-ups. *Source:* Fukuchi and Mitsuhashi (1983).

independent of the focal geometry and depth of any earthquake. Surprisingly good forecasts of tsunami wave heights have been achieved for 17 tsunami that reached Papeete between 1958 and 1986, including the Chilean tsunami of 1960. Because the TREMORS system is not site specific and the underlying equipment is inexpensive, there is no reason the system could not be installed in any country bordering the Pacific Ocean.

In Japan, a number of systems are used for local tsunami prediction. Tsunami warning began in Japan in 1941 under the auspices of the Japan Meteorological Agency. Originally, coverage was only for the northeast Pacific Ocean coast, but this was extended nationwide in 1952. The Japan Meteorological Agency has a national office in Tokyo and six regional observatories—at Sapporo, Sendai, Tokyo, Osaka, Fukuoka, and Naha, with each responsible for local tsunami warnings. Following the Chilean tsunami of 1960, communities threatened by tsunami in Japan were identified and protective seawalls built (Figure 9.9). However, large tsunami still require evacuation. Near-field tsunami are a threat in Japan, especially along the Sanriku coastline of northeastern Honshu, where only 25–30 minutes of lapse time exists between the beginning of an earthquake and the arrival at shore of the resulting tsunami. If it is assumed that most people can be evacuated within 15 minutes of a warning, then tsunamigenic earthquakes here must be detected within the first 10 minutes. The *P* wave for any local earthquake can be detected within seconds using an extensive network of high-frequency and low-magnification seismometers. The Japanese Warning System also utilizes satellite dissemination in case the ground base network is destroyed in a tsunamigenic earthquake. Algorithms have been written to estimate the seismic moment of an earthquake using as little as five minutes of record. Within the next 2 minutes the height of the tsunami along the adjacent coastline can be predicted using graphic forecasting models based upon the size of prior earthquakes and the distance to their epicenters.

Based upon this forecast a tsunami bulletin is issued as a warning, watch, or "no danger" advisory. Warnings are passed through central government offices, which include the Maritime Safety Agency, which transmits warnings to harbor authorities, fishing fleets, and fishermen, and the Nippon Broadcasting Corporation, which broadcasts warnings nationally on radio and television. At the same time, warnings are transmitted to prefectures and to local authorities via LADESS, the Local Automatic Data Editing and Switching System. At the local level, warnings are then issued via the Simultaneous Announcement Wireless System (SAWS). This system can switch on sirens and bells, and even radios in individual homes. Mobile loudspeakers mounted on fire trucks will also cruise the area broadcasting the warning. In extreme cases, a network of individual contacts has been established and the tsunami warning can be transmitted by word of mouth or over the telephone. Warnings issued within 15 minutes may not be good enough to save lives. Local authorities may hesitate to initiate SAWS and wait for confirmation of a tsunami warning for their particular coast to appear in map form on television. These maps take time to be drawn and do not appear as part of the initial warning. Even where a direct warning is heeded, it may be insufficient. In the Sea of Japan, the lapse time between the beginning of an earthquake and the arrival at shore of the resulting tsunami can be as low as 5 minutes. For example, a tsunami warning was broadcasted directly to the public, via television and radio, within 5 minutes of the Okushiri, Sea of Japan earthquake of July 12, 1993. However, by then, the tsunami had already reached shore and was taking lives.

All of the warning systems in the Pacific assume that a teleseismic tsunami originates in some underpopulated country far, far away. Chile is one of those faraway countries, but with a significant coastal population. As shown in Chapters 4 and 5, tsunamigenic earthquakes here have tended to occur every 50 years with a deadly impact. Chile does not have the privilege of being able to rely upon the Pacific Tsunami Warning System, because what is a distant earthquake to the PTWS can well be a localized earthquake in Chile. Project THRUST (Tsunami Hazards Reduction Utilizing Systems Technology) was established offshore from Valparaiso, Chile, in 1986 to provide advance warning of locally generated tsunami along this coastline within 2 minutes. When a sensor placed on the seabed detects a seismic wave above a certain threshold, it transmits a signal to the GEOS geostationary satellite, which then relays a message to ground stations. The signal is processed, and another signal is transmitted via the satellite to a low-cost receiver and antenna, operating 24 hours a day, located along a threatened coastline. This designated station can be preprogrammed to activate lights and acoustic alarms, and to dial telephones and other emergency response apparatus when it receives a signal. The GOES satellite also alerts tide gauges near the earthquake to begin sending data, via satellite, both to local authorities and to the Pacific Tsunami Warning Center to confirm the presence of a tsunami. For a cost of $15,000, a life-saving tsunami warning can be issued to a remote location within 2 minutes of a tsunamigenic earthquake. The warning system is independent of any infrastructure that could be destroyed during the earthquake.

In August 1989, the THRUST system was integrated into the Chilean Tsunami Warning System with a response time of 17 s–88 s The system provides coverage of all but the southernmost tip of the South American continent (Figure 9.6). Response times of 5 s–10 s are now technically possible. Potentially, a GEOS satellite warning system could be installed for any coastline in the Pacific Ocean except eastern Asia.

HOW LONG HAVE YOU GOT?

Distant or teleseismic tsunami in the Pacific Ocean leave a signature that provides sufficient lead time for dissemination of a warning and evacuation. For example, the Hawaiian Islands will get more than six hours' warning of any tsunami generated around the Pacific Rim, while the west coast of the United States receives more than four hours' notice of tsunami originating from either Alaska or Chile. The real concern is the potential warning time, or margin of safety, if a tsunami originates near the edge of the continental shelf, off the Hawaiian Islands or the continental shelf of Washington State. There are two possible scenarios for locally generated tsunami. In the first scenario, a tsunamigenic earthquake is responsible for the tsunami. The earthquake can occur at the shelf break or in deeper water offshore. In either case, once the wave begins to cross the continental shelf, the depth of water determines its velocity. Hence the slope and width of the shelf dictate the tsunami's travel time. In the second scenario, the earthquake generates a submarine landslide on the shelf slope. In this case, the longer it takes a submarine slide to develop, the farther it has moved from shore and the longer it takes for the resulting tsunami to propagate to the coast.

A crude approximation of the time it takes tsunami spawned by these processes to cross a shelf can be determined by dividing the shelf into segments, and calculating the time it takes the wave to pass through each segment using Equation (2.2). The calculations are simplified if the shelf is assumed to have a linear slope. These results are presented in Figure 9.10 for different shelf slopes and widths. These relationships should be treated cautiously because they are based upon simplified assumptions. For example, the Grand Banks earthquake of November 18, 1929 occurred at the edge of the continental shelf, 300 km south of the Burin Peninsula of Newfoundland that was eventually struck by the resulting tsunami. This tsunami arrived two and a half hours after the earthquake—well within the four hours indicated in Figure 9.10. Tsunami induced by submarine slides may travel as fast as 1,500 km h^{-1}—much faster than linear theory would suggest. If anything, the margin of safety shown in Figure 9.10 is too lenient.

Figure 9.10 shows that there is a log-linear relationship between travel time and the distance to the shelf break. This relationship holds for shelf widths as narrow as 2 km and as wide as 500 km. The figure also indicates that the travel time for a tsunami asymptotically approaches 3.25 minutes for the steepest shelf slopes. These relationships can be put into a more familiar context using two examples, both of which have already been discussed in this text. In the first example—that of the east

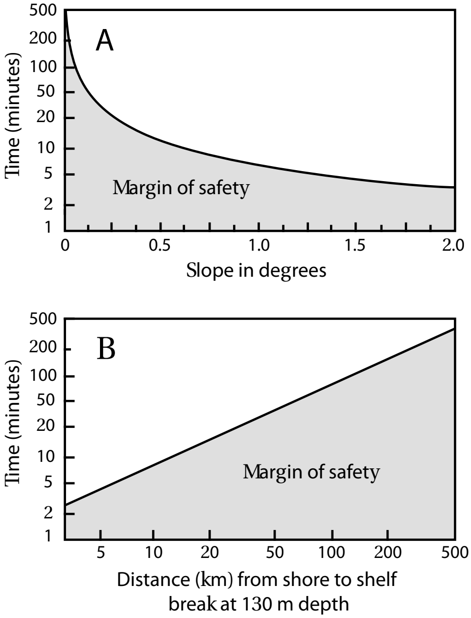


Figure 9.10. Travel time for tsunami moving across a continental shelf. (A) For various slopes. (B) For various shelf widths.

coast of the United States—the shelf break lies more than 165 km from shore. Here, a tsunami generated at the edge of the shelf would take over 135 minutes or 2.2 hours to reach the closest point at shore. This does not seem like much when compared with the time that residents along the west coast of the United States have for tsunami generated in Alaska or Chile, but it is more than sufficient when compared with the second example—that of Sydney, Australia—where the shelf is steep, being only 12 km–14 km wide. Unlike the east coast of the United States, substantial evidence has been found along this coast for the impact of mega-tsunami. Here, a tsunami generated on the continental slope would take only 10–12 minutes to reach shore. Within this time, one would be hard-pressed to reach safety if sunbathing on a local beach, or even worse, surfing off one of the headlands. At Wollongong, south of Sydney, the seabed also shows geological evidence for a submarine landslide measuring 20 km long and 10 kilometers wide positioned 50 km offshore. A tsunami generated by this slide would only take 40 minutes to reach shore.

WHERE SHOULD YOU GO IF THERE IS A TSUNAMI WARNING?

(Wiegel, 1970; Shuto, 1993)

While it may seem obvious from the previous sections, there is more to this question than meets the eye. Obviously one shouldn't rush to cliffs, take to boats inside harbors, or decide it is a good time to have lunch at your favorite quayside cafe.

Don't do what the residents of San Francisco did during the Alaskan tsunami of 1964 and flock to the coast to see such a rare event. And don't do what the residents of Hilo, Hawaii, did during the Alaskan tsunami event of April 1, 1946 (Figure 9.4), and hurry back to the coast following the arrival of the first few tsunami waves. Here, people returned to the coastal business area to see what damage had occurred, only to be swamped by the third and biggest wave. Big waves later in a wave train are more common than generally believed. For example, the eighth wave during the April 1 event was the biggest along the north shore of Oahu. Figure 2.3 also shows that the biggest wave can occur after the initial one. Under extreme conditions on coastlines where tsunami are recurrent (e.g., the Sanriku coast of northeastern Honshu Island, Japan), the government has gone to extreme lengths to build seawalls behind beaches to protect towns against tsunami. Figure 9.9 shows the walls protecting the town of Ryoishi against a tsunami 4.5 m high. Similar walls have been constructed in and around Tokyo and other metropolitan areas in Japan. Such walls offer a false sense of security. The southernmost part of Aonae, Okushiri Island, was completely surrounded by such a wall but was destroyed by the Hokkaido Nansei–Oki tsunami of July 12, 1993, which had a run-up height of 7 m–10 m. Events of this magnitude are common in Japan. The worse scenario for the town of Ryoishi shown in Figure 9.9 would be for the tsunami to overtop the seawalls. In this case, residents would be trapped against the barrier by the backwash.

Most people can escape to safety with as little as 10 minutes' warning of a tsunami. Along the northern coastline of Papua New Guinea, where the July 1998 tsunami had such an impact, people have been encouraged to adopt a tree. In Chapter 1, people who were stranded on the Sissano barrier with nowhere to flee did have an option. As shown in Figure 5.22, a substantial number of trees withstood the impact of the tsunami even though it was 15 m high and moved at a velocity of $10\,\mathrm{m\,s^{-1}}$–$15\,\mathrm{m\,s^{-1}}$. Notches can be cut into trees as toeholds, and people can easily climb a tree and lash themselves to the trunk in a matter of minutes. Urban dwellers may not have the opportunity to be as resourceful because of the lack of trees (Figure 9.1). It is an interesting exercise to stand with a group of people on an urban beach and say, "Where would you go if an earthquake just occurred and a tsunami will arrive in ten minutes?" Most people soon realize that they should run to the nearest hill, preferably to the sides of the beach and away from the coast. However, in a suburb such as that shown in Figure 9.1, this option may be neither obvious nor feasible. The only choice may be to seek safety in buildings. Personally I would look for the closest and tallest concrete building, preferably an office building (apartment buildings have secured access), run to the lobby, push the elevator button, and go to the top floor. Hopefully, the tsunami would not repeat the scene of the Scotch Cap lighthouse, which the April 1, 1946 tsunami wrecked (Figures 2.1 and 2.9).

Research has investigated the ability of buildings to withstand the force of a tsunami. Damage to structures by tsunami results from five effects. First, water pressure exerts a buoyant or lift force wherever water partially or totally submerges an object. This force tends to lift objects off their foundations. It is also responsible for entraining individual boulders. Second, the initial impact of the wave carries objects forward. The impact forces can be aided by debris entrained in the flow

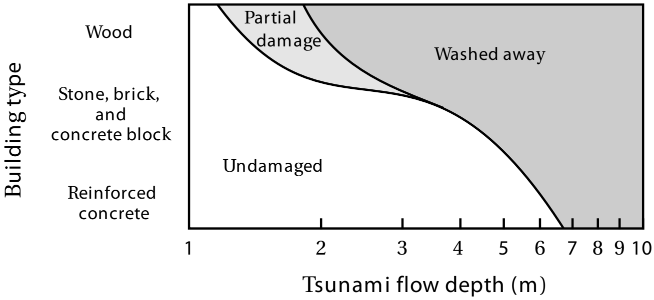


Figure 9.11. The degree of damage for different housing types produced by varying tsunami flow depths. Based on Shuto (1993).

or, in temperate latitudes, by floating ice. For these reasons, litter often defines the swash limit of tsunami waves. Third, surging at the leading edge of a wave can exert a rapidly increasing force that can dislodge any object initially resisting movement. Fourth, if the object still resists movement, then drag forces can be generated by high velocities around the edge of the object, leading to scouring. Finally, hydrostatic forces are produced on partially submerged objects. These forces can crush buildings and collapse walls. All of these forces are enhanced by backwash that tends to channelize water, moving it faster seaward.

Various building types and their ability to withstand tsunami are summarized in Figure 9.11. The data come from the 1883 Krakatau, 1908 Messina, 1933 Sanriku, 1946 Alaskan, and 1960 Chilean tsunami. Lines on this figure separate undamaged, damaged, and destroyed buildings. Wood buildings offer no refuge from tsunami. Fast-moving water greater than 1 m in depth will destroy any such structures unless they are perched on cross-linked iron struts sunk into the ground. Stone, brick, or concrete block buildings will withstand flow depths of 1 m–2 m. They are destroyed by greater flows. The Nicaraguan tsunami of September 2, 1992 destroyed all such buildings wherever the wave ran up more than 2 m (Figure 5.16). Even concrete pads that require significant force to be moved can be swept away by such flows. The National Oceanic and Atmospheric Administration (1998) in its publication *Tsunami! The Great Waves* states, "Homes and small buildings located in low-lying coastal areas are not designed to withstand tsunami impacts. Do not stay in these structures should there be a tsunami warning." Reinforced concrete buildings will withstand flow depths of up to 5 m. Such depths have only occurred during the severest tsunami, and then only along isolated sections of coastline. If there is no escape, the safest option is to shelter in a reinforced concrete building, preferably in the first instance above the ground floor level. One of the most poignant videos of the Indian Ocean tsunami of December 26, 2004 was taken in Banda Aceh from just such a vantage point as a raging torrent of water destroyed every other surrounding structure (Figure 5.24). The NOAA publication also states, "High, multi-story, reinforced concrete hotels are located in many low-lying coastal areas. The upper floors of these hotels can provide a safe place to find refuge should there be a tsunami warning and you cannot move quickly inland to higher ground."

WHAT IF IT IS AN ASTEROID OR COMET?

(Verschuur, 1996; Ward and Asphaug, 2000; Stuart and Binzel, 2004;
National Aeronautics and Space Administration, 2007)

Despite the image conveyed by recent disaster movies such as *Deep Impact* and *Armageddon*, the risk from large asteroids or comets is minor. The main perceived threat comes from objects 1 km–10 km in size that, before the 1990s, had escaped detection. However, NASA has since instituted a dedicated program called Spaceguard to detect 90% of objects greater than 1 km in size by the year 2010. As of June 2007, 713 near Earth asteroids larger than 1 km in diameter have been discovered, consisting dominantly of Apollo objects. Only 133 of these have the potential to get closer than 7,5000,000 km to the Earth. The largest of these objects is about 9 km in diameter. This threat from large asteroids may be illusionary when compared with that posed by objects between 200 m and 1,000 m in size. Any of these objects can still generate devastating basin-wide tsunami. Statistics on the frequency of these smaller near Earth objects (NEOs) are summarized in Table 9.1. There currently are estimated to be 1,090 ± 180 NEOs greater than 1 km in diameter, 4,000 greater than 0.5 km in diameter, and 85,000 greater than 100 m in diameter. Unless any of the larger objects are detected well in advance, the present threat is still random and unpreventable. The probability of an impact by a 1 km diameter object is estimated from the Spaceguard observations to be one every half-million years. While these estimates are based on sound data, they may be too low for smaller objects. For example, a 50 m diameter meteroid is hypothesized to strike the Earth once every 1,500 years. In Chapter 8, the return interval for this sized object was reported as once per century. These values only reinforce the view that present estimates of the rates of impacts and the height of their resulting tsunami vary tenfold. As of 2007, no feasible program has been developed to mitigate the threat from cosmogenic tsunami.

Table 9.1. Estimated number of near Earth objects (NEOs) by size and return interval of an impact with Earth.

Diameter (m)	*Possible number of objects greater in size*	*Return interval* (yr)
50	330,000	1,500
100	85,000	6,000
200	28,000	20,000
500	4,000	90,000
1,000	1,090	500,000

Source: Stuart and Binzel (2004).

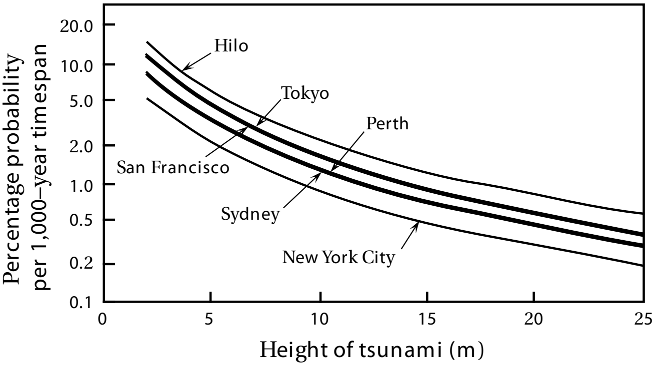


Figure 9.12. Probability of tsunami of various heights due to an asteroid affecting a selection of world cities. Based on Ward and Asphaug (2000). Values are for stony asteroids having a density of $3\,\mathrm{g\,cm^{-3}}$. The results take into account the effects of atmospheric ablation on the asteroids.

Finally, it is possible to calculate the probability of variously sized cosmogenic tsunami for any coastal location. The results for six coastal cities—San Francisco, New York, Tokyo, Hilo, Perth, and Sydney—are presented in Figure 9.12 for stony asteroids. This figure takes into account the effects of atmospheric ablation. San Francisco has the greatest exposure, facing $1.7 \times 10^8\,\mathrm{km}^2$ of ocean that plausibly could be struck by an asteroid impact. New York has the least exposure, facing only $0.64 \times 10^8\,\mathrm{km}^2$ of ocean. However, Hilo, Hawaii, has the highest probability of being struck by a cosmogenic tsunami. Here, the probabilities are 15.3% and 5.8% for a wave of 2 m and 5 m in height, respectively, occurring within the next millennium. At San Francisco, the probabilities for similarly sized waves are 12.0% and 4.1%, respectively. Sydney, which is situated on a 400-km stretch of coastline displaying the best evidence for catastrophic tsunami yet identified, has probabilities of 8.8% and 3.2%, respectively, for these two wave heights. Interestingly, the probabilities for asteroid impacts in the ocean are higher adjacent to Perth than to Sydney. Our recent fieldwork suggests that catastrophic tsunami have been as frequent along the southwest coast of Western Australia as along that of New South Wales. Note that, of the six cities, Sydney ranks fifth in terms of the risk from cosmogenic tsunami. However, to date it has the best-defined regional evidence of catastrophic tsunami. The challenge is now to find similar evidence for other coastlines and to unravel the chronology associated with them.

IS IT ALL THAT BAD? THE CASE OF SYDNEY

It is possible to assess the risk of tsunami to human life in urban areas. In the case of Sydney, which has a population of over 4 million people, very few people would ever witness a large tsunami event occurring, let alone become a casualty of one. The evidence for mega-tsunami along the coast of New South Wales shown in Chapters 3

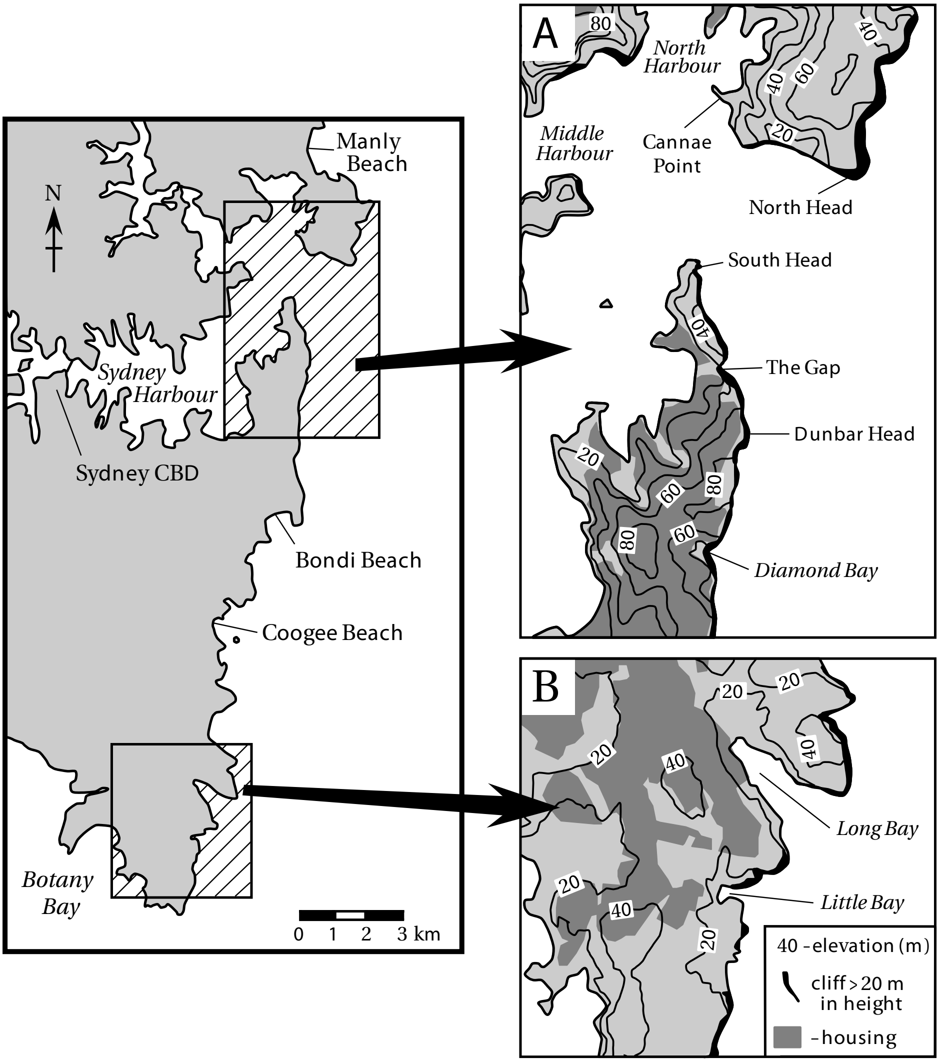


Figure 9.13. A sampling of coastal areas in Sydney with urban development that could be affected by large tsunami. (A) The Gap. (B) Little Bay.

and 4 extends along the Sydney coastline. Detailed maps of two sections along this coast are shown in Figure 9.13. Boulders similar in size and imbrication to those at Gum Getters Inlet (Figure 8.11) are piled along the cliffs north of Little Bay. Many have been moved with ease in suspension onto ledges and clifftops (Figure 9.14). Large imbricated boulders trail around the cliffs into Sydney Harbor at South Head. Cannae Point on the north side of the harbor's entrance has all the appearances of a toothbrush-shaped headland. Gravelly sands were dumped in a sandsheet downslope from The Gap towards the harbor after being swept over cliffs 22 m high. The first

Figure 9.14. A boulder transported by tsunami at the front of cliffs at Little Bay, Sydney. The boulder lies 7 m–8 m above sea level and 50 m from the ocean. Each corner of the boulder rests on a smaller boulder or on bedrock. The contacts are clean without any evidence of the fracturing or crushing that should have occurred if the boulder had been tossed up onto the ledge. Instead, the boulder was transported in suspension and gently settled from turbid flow. Note the imbricated boulders at the base of the cliff in the background.

impression is one of devastating damage were such an event to recur. However, this is not necessarily the case.

In each of the detailed maps, the extent of residential buildings is also shown. In the first case, that of Little Bay where boulders were transported by mega-tsunami and stacked against cliffs 20 m high (Figure 9.14), remarkably little damage to buildings would occur because houses have been set back from a coast that is fringed by golf courses and a military reserve. Certainly, the residents of houses at the head of the gully draining into Little Bay would get an impressive view of the tsunami racing towards them up the coast. However, the hinterland behind this bay is relatively sheltered from the coast. The mega-tsunami event that occurred around AD 1500, while overtopping some of the cliffs, stopped just short of the houses, which lie 30 m above sea level and 600 m from the shore. Farther north at The Gap, where the evidence for mega-tsunami is just as impressive, the impact would be similar. Very little development exists on the headlands bracketing the entrance to Sydney Harbor. The mega-tsunami of 1500 does not appear to have overtopped the cliffs at Dunbar Head, which are 70 m high, because the wave was traveling northwards at an angle to the coast. The tsunami, however, did overtop the cliffs on North Head, which lay directly in the path of the wave. These latter clifftops are uninhabited. The wave would also have funneled up the gullies leading inland from embayments such as Long Bay, Coogee Beach, Bondi Beach, and Diamond Bay. These gullies are densely urbanized with single- and multi-story dwellings. However, no more than 10,000 people would be threatened, and most of these could be evacuated to safety with sufficient warning. If a submarine landslide on the adjacent continental shelf caused the tsunami, the lead time could be as little as 15 minutes with a resulting high death toll. The warning time would be insufficient. However, if an earthquake or an asteroid impact in the south Tasman Sea caused the tsunami, people would have several hours warning to evacuate threatened areas. The latter scenario of course assumes that the threatened areas have been identified, and that the State Emergency Service has drawn up adequate evacuation plans.