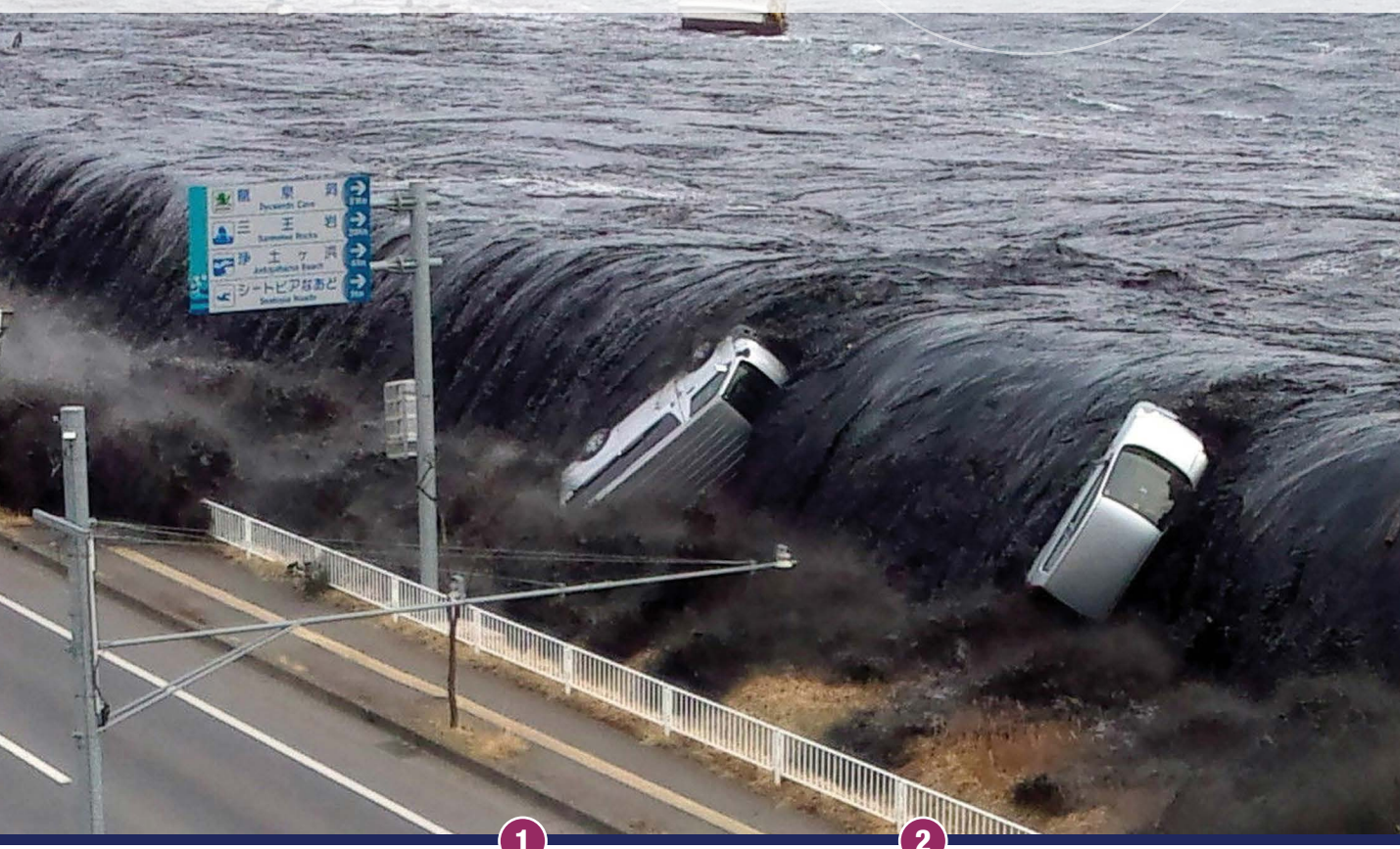
Cooling systems failed as pumps used to circulate cooling water in three nuclear reactors were flooded by the tsunami

4



APPLYING the 5 fundamental concepts Japan 2011 Tsunami and Nuclear Disaster

1

Science helps us predict hazards.

Tsunamis result from large vertical movement of the ocean floor. Such movement is typical of large subduction zone earthquakes, like the 2011 Tohoku earthquake. By understanding this relationship, our ability to predict regions susceptible to the effects of tsunamis is greatly improved.

2

Knowing hazard risks can help people make decisions.

Following the 2011 tsunami, Japan has reevaluated the risk of damage to land and property from future large tsunamis. Continued risk analysis provides an important example of how future natural hazards need to be viewed from a risk management perspective and how risk is linked to numerous changing factors, such as population growth.

Tsunamis

Japan 2011: Tsunami and Nuclear Disaster

The Pacific Ocean bottom 130 km (~80 mi.) offshore of Fukushima, Japan was vertically displaced by as much as 9 m (~30 ft.) due to the 2011 magnitude 9.0 Tohoku earthquake. This displacement of the ocean floor generated a large set of tsunami waves up to about 40 m (~130 ft.) high at the shore. These waves quickly reached the coastline of northern Japan where millions of people live and several nuclear power plants were located.

Within seconds to 3 minutes of the earthquake, an automated tsunami warning system alerted the people of coastal communities to evacuate to high ground as they had been taught, and the nuclear power plants immediately shut down as they were designed to do. Although the warning system greatly minimized the loss of life, the nuclear reactor shutdown did not prevent a disaster that was ultimately more serious than any other nuclear accident of the last several decades. Like many of the sea walls that protect 40 percent of Japan's coastline from tsunami waves, the 6 m (~20 ft.) high sea wall designed to keep the power plant from flooding was quickly overtopped. Cooling systems failed when back-up diesel generators powering the circulation pumps were inundated by seawater,

< Tsunami Overriding Seawall Defenses

About 1 hour and 30 minutes after the Tohoku earthquake, the 6 m (~20 ft.) high sea wall protecting this seaside village on the east coast of Japan is overtopped by the first tsunami wave to hit the coast. In this photograph, the seawall is completely obscured by the sea water cascading over it onto the road below. *(Toru Yamanaka/AFP/Getty Images)*

LEARNING Objectives

The tsunami is one of Earth's most destructive natural hazards. These ocean waves are both fascinating in their behavior and awesome in their power. Tsunamis are common in some coastal regions and rare in others. Although they have long been known to cause disasters and catastrophes, the hazard posed by tsunamis has generally been underestimated. Translating the increased hazard awareness into improved warning, preparedness, and mitigation is proceeding at an excruciatingly slow pace. This chapter will explain the natural tsunami process and assess the hazard that these waves pose to people.

After reading this chapter, you should be able to:

LO:1 Explain the process of tsunami formation and development.

LO:2 Locate on a map the geographic regions that are at risk for tsunamis.

LO:3 Synthesize the effects of tsunamis and the hazards they pose to coastal regions.

LO:4 Summarize the linkages between tsunamis and other natural hazards.

LO:5 Understand that tsunamis are not caused by or affected by human activities, but damages are compounded as coastal populations increase.

LO:6 Discuss what nations, communities, and individuals can do to minimize the tsunami hazard.

LO:7 Identify the actions you should take and not take if a tsunami warning is issued.

3

Linkages exist between natural hazards.

Flooding and coastal erosion due to earthquake-generated tsunami waves serves as an exceptional example of how different natural hazards are linked.

4

Humans can turn disastrous events into catastrophes.

Nuclear reactor meltdown following tsunami inundation triggered the world's second worst nuclear disaster. Although no deaths are attributed directly to the meltdown, evacuation of the contaminated region doubled the loss of life in the region.

5

Consequences of hazards can be minimized.

The high level of Japanese tsunami preparedness, including an advanced early warning system, elaborate tsunami seawall defense, and a well-informed, vigilant population, resulted in a 96 percent survival rate for those living in the areas inundated by the tsunami.

resulting in a nuclear meltdown (overheating of the reactor core causes nuclear fuel to melt). The disaster was compounded by explosions of hydrogen gas that built up in the reactor core containment buildings due to the meltdown, causing a significant release of radiation into the atmosphere[1–5] and the need to evacuate nearly 200,000 people living in the region. Six years after the disaster (March 2017), the Japanese are still pumping several hundred tons of water through the buried hot nuclear fuel in an attempt to cool it. The water becomes contaminated with radiation and is collected and stored in over 1,000 large tanks. The Japanese are struggling with how the radioactive water might be treated and disposed of when storage space for more new tanks runs out.

Due to the 2011 and nuclear incident, Japan initiated new research regarding its tsunami hazard, and other countries around the world have begun a new discussion about the safety of nuclear power.

4.1 Introduction to Tsunamis

Tsunamis (the Japanese word for "large harbor waves") are produced by the sudden vertical displacement of ocean water.[6] These waves are a serious natural hazard that can cause a catastrophe thousands of kilometers from where they originate. They may be triggered by several types of events, including a large earthquake that causes a rapid uplift or subsidence of the seafloor; an underwater landslide that may be triggered by an earthquake; the collapse of part of a volcano that slides into the sea; a submarine volcanic explosion; and an impact in the ocean of an extraterrestrial object, such as an asteroid or comet. Asteroid impact can produce a "mega" tsunami, a wave that is about 100 times higher than the largest tsunami produced by an earthquake, that could put hundreds of millions of people at risk.[6] Fortunately, the frequency of large asteroid impact is low. Of the previously mentioned potential causes, tsunamis produced by earthquakes are by far the most common.

Damaging tsunamis in historic times have been relatively frequent, mostly in the Pacific Basin, and include the following:[7,8]

- The 1755 (~**M** 9) Lisbon, Portugal, earthquake produced a tsunami that, along with the earthquake and resulting fire, killed an estimated 20,000 people. Tsunami waves that crossed the Atlantic Ocean amplified to heights of 7 m (~23 ft.) or more in the West Indies.
- The 1883 violent explosion of Krakatoa volcano in the Sundra Strait between Java and Sumatra caused the top of the volcano to collapse into the ocean. This sudden collapse produced a giant tsunami more than 35 m (~115 ft.) high that destroyed 165 villages and killed more than 36,000 people.
- The 1946 (**M** 8.1) Aleutians (Alaska) earthquake produced a tsunami in the Hawaiian Islands that killed about 160 people.
- The 1960 (**M** 9.5) Chile earthquake triggered a tsunami that killed 61 people in Hawaii after traveling for 15 hours across the Pacific Ocean.
- The 1964 (**M** 9.2) Alaska earthquake generated a deadly tsunami that killed about 130 people in Alaska and California.
- The 1993 (**M** 7.8) earthquake in the Sea of Japan caused a tsunami that killed 120 people on Okushiri Island, Japan.
- The 1998 (**M** 7.1) Papua New Guinea earthquake triggered a submarine landslide that produced a tsunami that killed more than 2,100 people.
- The 2004 (**M** 9.1) Sumatra earthquake generated a tsunami that killed about 230,000 people (see Case Study 4.2: Indonesian Tsunami).
- The 2009 (**M** 8.1) Samoa earthquake generated a tsunami that killed about 200 people.
- The 2010 (**M** 8.8) Chile earthquake generated a tsunami that killed about 700 people in coastal towns.
- The 2011 (**M** 9.1) Japan earthquake generated a tsunami that killed over 20,000 people (see Applying the Fundamental Concepts).

HOW DO EARTHQUAKES CAUSE A TSUNAMI?

An earthquake can cause a tsunami by causing the seafloor to move or by triggering a landslide. Seafloor movement is probably the more common of these two mechanisms. This movement occurs when the seafloor sits on a block of Earth's crust that shifts up or down during a quake. In general, it takes an earthquake of **M** 7.5 or greater to create enough displacement of the seafloor to generate a damaging tsunami. The upward or downward movement of the seafloor displaces the entire mass of water from the sea bottom to the ocean surface. This starts a four-stage process that eventually leads to landfall of tsunami waves on the shore (Figure 4.1):

1. For example, if an earthquake rupture uplifts the seafloor, the water surface above the uplift initially forms an elongated dome parallel to the geologic

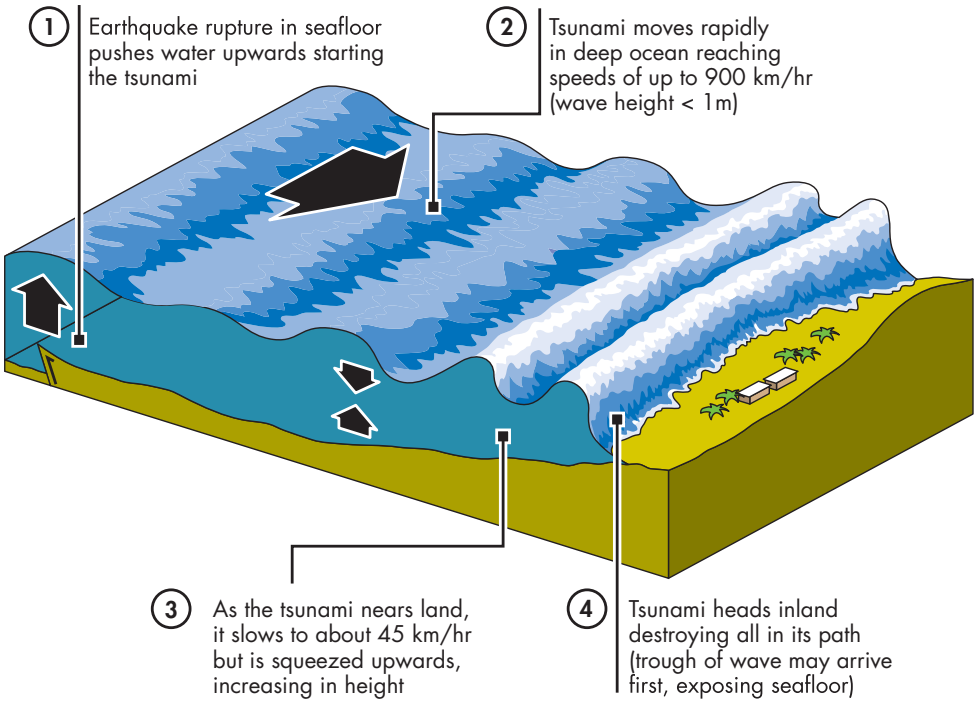


FIGURE 4.1 Tsunami
Idealized diagram showing the process of how a tsunami is produced by an earthquake. *(Modified after the United Kingdom Hydrographic Office)*

fault. That dome collapses and generates a tsunami wave. Oscillations of the water surface and, in some cases, aftershocks along the fault produce additional waves. These waves radiate outward like the pattern made by a pebble thrown into a pond of water.

2. In the deep ocean, the tsunami waves move very rapidly and are spaced long distances apart. Their velocity is equal to the square root of the product of the acceleration of gravity and the water depth. The acceleration of gravity is approximately 10 m/sec^2 and average water depth in deep ocean is 4000 m (~13,100 ft.). Thus, when we do the math, by taking the product of 10 m/sec^2 and 4000 m and then taking the square root of that number, we arrive at a velocity of 200 m/sec. Converting 200 m/sec to km/hour, we find that tsunamis travel at 720 km (~450 mi.) per hour, close to the average airspeed of a jetliner, but they can reach up to 900 km/hr. In the deep ocean, the spacing between the crests of tsunami waves may be more than 100 km (~60 mi.), and the height of the waves is generally less than 1 m (~3 ft.). Consequently, sailors rarely notice a passing tsunami in the deep ocean.
3. As the tsunami nears land, the water depth decreases, so the velocity of the tsunami also decreases. Near land, the forward speed of a tsunami may be about 45 km (~28 mi.) per hour—too fast to outrun but not nearly as fast as in the open ocean. This decrease in velocity also decreases the spacing between wave crests, that is, the wavelength. As the water slows down and piles up, the height of the waves increases.
4. When the first tsunami wave reaches the shore and moves inland, it may be several meters to several tens of meters high and destroys everything in its path. Sometimes the trough of the wave may arrive first, which exposes the seafloor. When tsunamis strike the coast, they generally do not come in as a giant breaking wave as you might see on the surfing beaches of the north shore of Oahu or the California coast. Instead, when the wave arrives, it is more like a very strong and fast-rising increase in sea level. On the rare occasions when tsunamis do break, they may appear as a vertical wall of turbulent water. The movement of a tsunami inland is called the **runup** of the wave. Runup refers to the furthest horizontal and vertical distance that the largest wave of a tsunami

moves inland. Runup from tsunamis varies considerably with the shape of the seafloor immediately offshore and with the type of topography and vegetation landward of the beach. Both the offshore and shoreline topography can greatly accentuate tsunami wave height. Figure 4.2 shows the runup (~wave height at coast) from the 2011 tsunami. Notice that the greatest runup of about 25 m+ occurred directly offshore from the earthquake. Near the nuclear power plant (red circle), it was about 12 m (~40 ft.). Other coastal areas received runup of less than 5m (16ft). The 2011 tsunami moved inland from 1 to 8 km (0.6 to 5 mi.), depending on wave height and topography. Once a wave has moved to its farthest extent inland, most of the water then returns back to the open ocean in a strong and often turbulent flow. A tsunami can also generate other types of waves, known as *edge waves*, that travel back and forth parallel to the shore. The interaction between edge waves and additional incoming tsunami waves can be complex. As a result of this interaction, wave amplification may occur, causing the second or third tsunami wave to be even larger than the first (see Case Study 4.1: Survivor Story). Most commonly, a series of tsunami waves will strike a particular coast over a period of several hours.[9]

When an earthquake ruptures and uplifts the seafloor close to land, both distant and local tsunamis may be produced (Figure 4.3). The initial fault displacement and uplift raise the water above mean sea level. This uplift creates potential energy that drives the horizontal movement of the waves. The uplifted dome of water collapses downward and expands radially, splitting into two waves. One wave, known as a **distant tsunami**, travels out across the deep ocean at high speed. Distant tsunamis can travel thousands of kilometers across the ocean to strike remote shorelines with little loss of energy. The second wave, known as the **local tsunami**, heads in the opposite direction toward the nearby land. A local tsunami can arrive quickly following an earthquake, giving coastal residents and visitors little warning time. When the initial tsunami wave is split, each (distant and local) tsunami has a wave height about one-half of that of the original dome of water.[9]

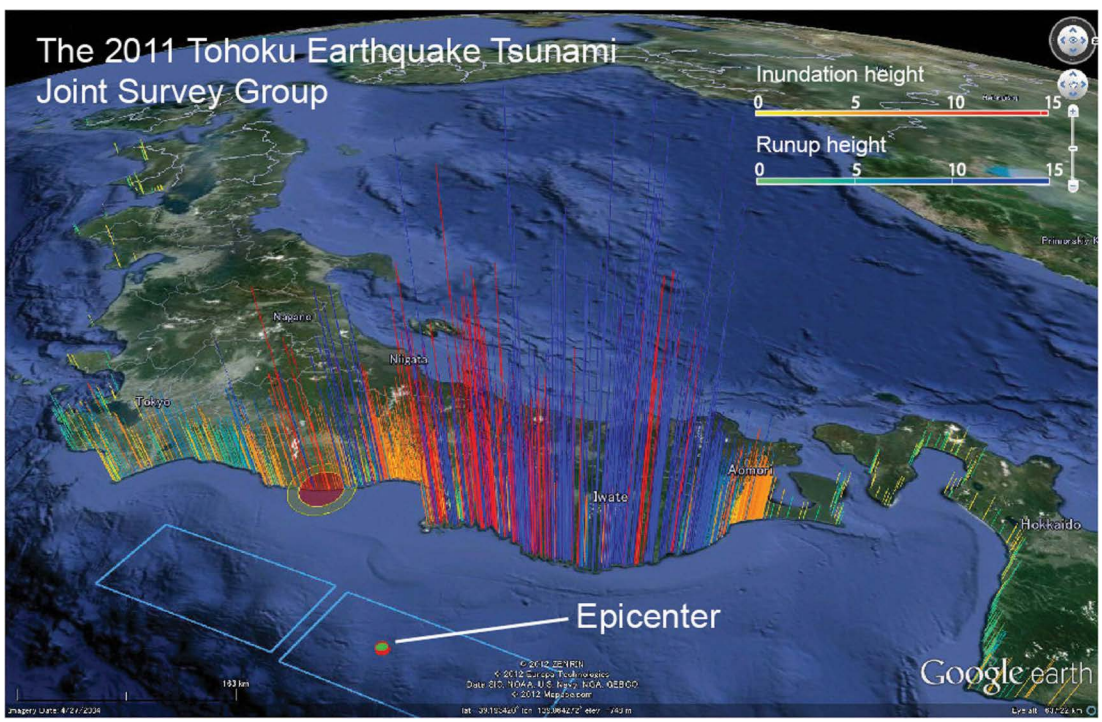


FIGURE 4.2 Tsunamis runup height and inundation from the 2011 Tsunami
The epicenter of the earthquake is 130 km offshore. The red circle is the location of a nuclear power plant. Notice the height is extremely variable, depending on location. *(The 2011 Tokohu Earthquake Tsunami Joint Joint Survey Group, 2012)*

CASE study

4.1 Survivor Story

Tsunami in the Lowest Country on Earth

Boxing Day, December 26, 2004, was a hot sunny day in the Maldives, a beautiful group of atolls in the Indian Ocean west of India (Figure 4.1.A). The Republic of Maldives is the lowest country on Earth; its highest point is only 2.4 m (~8 ft.) above sea level. Dave Lowe was working in his office at a resort on South Ari Atoll when he heard a strange bump on the door, and outside people were screaming "the children." He opened the door, and to his horror, the ocean was level with the island, and a boiling, frothing wall of water was bearing straight down on him: "There was a strange mist that looked like a fog, so I stopped breathing and tried to decide where to run."

The resort had no two-story buildings, and he was just a meter (~3 ft.) above sea level! He ran to the reception area where there were pillars to hold on to. Others were there screaming as the first waves began to hit: "Three glass windows exploded, and, within seconds, the water was up to my waist. I couldn't tell if the island was sinking or if the sea was rising."

Dave made his way to the reception counter, grabbing two children

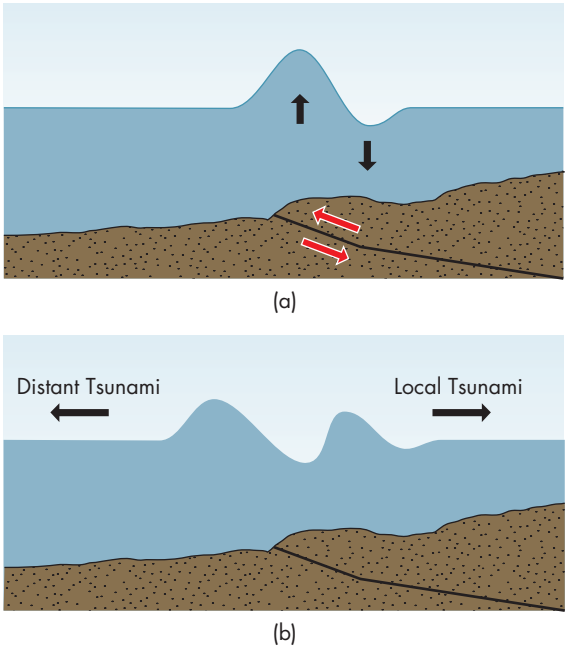


FIGURE 4.1.A Resort Employees Climb Down from Tsunami Refuge
The roof of this South Ari Atoll resort in the Maldives Islands was the highest place to take refuge from the multiple tsunami waves that flooded the island. On islands closer to the earthquake epicenter, this building would have been destroyed by the waves. *(SIPA Press)*

who were being swept out to sea, and threw them up onto the counter. Wave after wave hit, and water passed over his head: "I knew I was going to die and blacked out from fear. I became conscious when a receptionist was yelling, 'What is happening?'"

As quickly as the water came up, it was gone, leaving fish flopping on the lobby floor and seaweed draped everywhere. The resort guests regrouped. Then Dave saw a second wave coming. It was worse than the first. People desperately tried to hang onto anything they could. Wave after wave came for the next 6 hours, as the sea gradually calmed down. Guests suffered in the hot sun, and the resort staff built a shelter for 15 children whose parents were missing. When darkness came, people stood watch, looking for more waves under a full moon. No one slept, and in the morning, debris was everywhere: "It looked like *Titanic*, *Lost*, *Lord of the Flies*, and *Survivor* all rolled into one." Dave and other employees were evacuated by seaplane two days later. As they flew over the islands, they saw the unbelievable devastation, and several staff broke down crying.

They had survived, but they didn't know how



▲ FIGURE 4.3 Distant and Local Tsunamis
(a) Fault displacement lifts the water above mean sea level, which creates potential energy that drives the horizontal propagation of the waves. In these diagrams, wave height is greatly exaggerated compared to the depth of the water. Actual height of the waves is at most a meter or so, but it is spread out to tens or several hundreds of kilometers in length. (b) The initial wave is split into a tsunami that travels out across the deep ocean (distant tsunami) and another tsunami that travels toward nearby land (local tsunami). The wave heights are also split, and each (distant and local) tsunami has a height about one-half the original wave in (a). *(Based on U.S. Geological Survey; http://walrus.wr.usgs.gov/tsunami/basics.html)*

An example of a local tsunami occurred on the island of Okushiri in western Japan. On July 12, 1993, a **M** 7.8 earthquake in the Sea of Japan produced a local tsunami that extensively damaged Anoae, a small town on the southern tip of the island. The town was struck several times by 15 to 30 m (~50 to 100 ft.) waves coming around both sides of the island. There was virtually no warning because the earthquake epicenter was very close to the island. The huge waves arrived only 2 to 5 minutes after the earthquake, killing 120 people and causing $600 million in property damage.[10]

HOW DO LANDSLIDES CAUSE A TSUNAMI?

Although most large tsunamis are produced by fault rupture along subduction zones at tectonic plate boundaries, landslides have both generated and contributed to huge tsunamis.[11,12]

These landslides can take place underwater, where they are referred to as *submarine landslides*, or they can be large rock avalanches that fall from mountains into the sea. In most cases, the landslides are triggered by an earthquake. For example, in 1998, a **M** 7.1 earthquake occurred off the north shore of the island of New Guinea. The earthquake was felt at Sissano Lagoon, and shortly thereafter a tsunami arrived with little warning. In less than an hour, coastal villages were swept away, leaving 12,000 people homeless and more than 2,000 dead. The tsunami waves, which reached heights of 15 m (~50 ft.), appeared to have resulted primarily from a submarine landslide triggered by the earthquake.[13] The epicenter of the earthquake was only about 50 km (~30 mi.) offshore, so there was little, if any, warning time for coastal residents. This event emphasized the potentially devastating damage that can occur from a large tsunami produced by a nearby earthquake and submarine landslide.[8,13] The earthquake itself probably would not have generated a large tsunami had it not been combined with a landslide that displaced water at the bottom of the sea.

A submarine landslide may have significantly contributed to the 2011 Japan tsunami,[11] and recent studies of seafloor images have apparently solved the 1964 mystery of the tsunami associated with the Great Alaskan Earthquake that hit the Alaskan village of Chenega in the Prince William Sound. The tsunami destroyed all but two of the buildings and killed 23 of the 75 people living there. The origin of the tsunami was uncertain; was the tsunami due to the earthquake alone or to the combination of the earthquake and landslides? The discovery of a large underwater landslide deeper than the area studied in 1964 suggests the tsunami that destroyed the village was largely due to submarine landsliding.[12]

Perhaps the most famous landslide-induced giant wave occurred at Lituya Bay, Alaska, in 1958. The landslide was set in motion by a **M** 7.7 earthquake on a nearby fault. Approximately 30.5 million cubic meters (~46 million cubic yards) of rock fell from a cliff into the bay, instantly displacing a huge volume of seawater.[7] That volume of earth material would fill the National Mall in Washington, DC, to a height of about 25 m (~80 ft.). The huge mass of broken rock caused waters in the bay to surge upward to an elevation of about 524 m (~1,720 ft.) above the normal water level.[7] This splash of water was so tall that it would have washed over the Sears Tower in Chicago with 82 m (~269 ft.) to spare! Although the wave that swept out of the bay into the ocean wasn't nearly as large, it did pick up a fishing boat with two people onboard. The boat's captain estimated that the tsunami wave was 30 m (~100 ft.) high when it lifted the boat over the sand spit at the mouth of the bay. Two other fishing boats in the bay disappeared after being caught in the wave.[14] A panoramic view of the bay taken a few days after the tsunami shows that the erosive force of the wave stripped the shoreline bare of trees (Figure 4.4). In the area beyond the direct splash effect of the fallen rock, the high waterline above the barren shoreline indicates that the local tsunami had a runup height of 20 to 70 m (~65 to 230 ft.).[7]

The tsunami risk of high, unstable rock slopes associated with fjords (long, narrow, deep, cliff-sided inlets along the coast), such as in Alaska and Norway, that collapse by rockfall landslides into the sea is now recognized.[15] Norway experienced three tsunami disasters due to subareal rockslides in the twenty-first century. One in 1934 was up to 60 m (~200 ft) high and killed 40 people. A potential tsunami from one 900 m high mountain looming over a fijord with unstable slopes (large cracks have been mapped) could generate a giant landslide with local a tsunami up to 80 m (~260 ft) high. As a result, Norway is working on hazard risk evaluation from tsunamis. Included are hazard risk maps and land-use planning, including hazard zoning to restrict building in hazardous areas. The most recent event in Nowway was in 2014 when an apparent submarine rock slide produced a tsunami as much as 15 m high that damaged or destroyed homes, boats, and vehicles. So, both subareial and submarine landslides can produce a serious to catastrophic tsunami risk.[15]

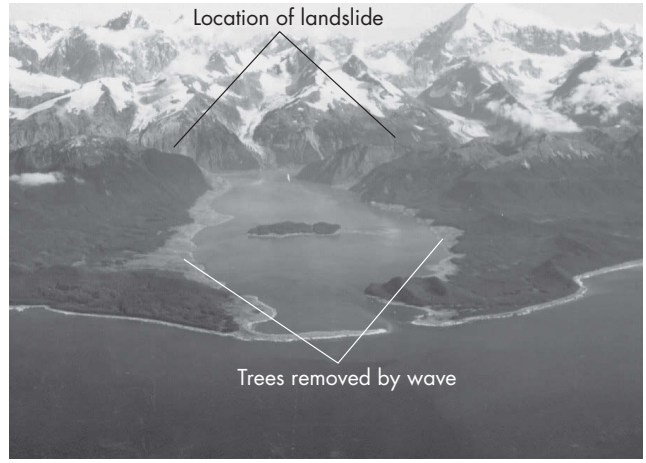


FIGURE 4.4 Landslide-Produced Giant Wave
Lituya Bay, Alaska, following local tsunami. Denuded shoreline of the bay was produced as trees were removed by the erosive force of the wave. *(USGS)*

4.1 CHECK your understanding

1. Define *tsunami* and identify several tsunami trigger events.
2. Describe how earthquakes produce a tsunami.
3. What is the difference between a local tsunami and a distant tsunami?
4. Define tsunami *runup*.

4.2 Geographic Regions at Risk from Tsunamis

Although all ocean and some lake shorelines are at risk from tsunamis, certain coasts are more at risk than others. The heightened risk comes from the geographic location of a coast in relation to potential tsunami sources, such as earthquakes, landslides, and volcanoes. Coasts in near proximity to a major subduction zone, or directly across the ocean basin from a major subduction zone, are at greatest risk. For the purpose of this discussion, a major subduction zone is considered to be capable of periodically generating a major earthquake of

M 9 or greater. Ruptures produced by these great earthquakes may extend for 1000 km (~625 mi.) or more along the subduction zone and produce significant uplift of the seafloor (see Case Study 4.2: Indonesian Tsunami). Earthquake and subduction zone processes that can lead to a large tsunami are illustrated in Figure 4.5 and discussed in the following paragraph.

As you recall from Chapter 3, the interval between large earthquake-generating fault slip events along any one particular plate boundary segment may be hundreds of years. In subduction zones, this is due to an area of strong coupling between the overriding and subducting plates, where no fault slip occurs. Such a fault segment is referred to as a *locked fault* (Figure 4.5a). Because there is no displacement along the interface between the two plates, the plates must deform elastically. As Figure 4.5b shows, as the subducting plate drags the leading edge of the overriding plate downward, subsidence (sinking) occurs offshore while onshore uplift occurs. Between earthquakes, there is distortion, deformation, or bulging (uplift) and leading-edge subsidence (sinking). When the fault finally slips and a tsunami-generating earthquake occurs, the overriding plate rebounds elastically. This causes the ocean floor to uplift, triggering a tsunami, and the on-land bulge to collapse and coastal areas to subside (Figure 4.5c,d). Sometimes, forests near a shoreline may sink several meters (up to 10 feet) or so, leaving a drowned forest (called a ghost forest; see Figure 4.6).[16] The 1964 great Alaskan earthquake caused coastal forests to be inundated by salt marshes as the land subsided. These drowned, dead trees may persist long enough in the landscape to be recognized, while others are buried by coastal sediment to become part of the recent geologic record.

The greatest tsunami hazard, with return periods of several hundred years, is adjacent to those major subduction zones with a convergence of a few centimeters per year. These include the Cascadia subduction zone in the Pacific Northwest, the Chilean trench along southwestern South America, and the subduction zones off the coast of Japan.

Tsunamis can range in height from a few centimeters to 30 m (~100 ft.) or more. Those with a runup height of at least 5 m (~16 ft.) are considered significant tsunamis and are commonly produced by high-magnitude earthquakes and associated submarine slides. One assessment of global tsunami hazard ranks the hazard from relatively low to greatest based on the return period of a significant tsunami (at least 5 m [~16 ft.] runup) (Figure 4.7). However, not enough is known about

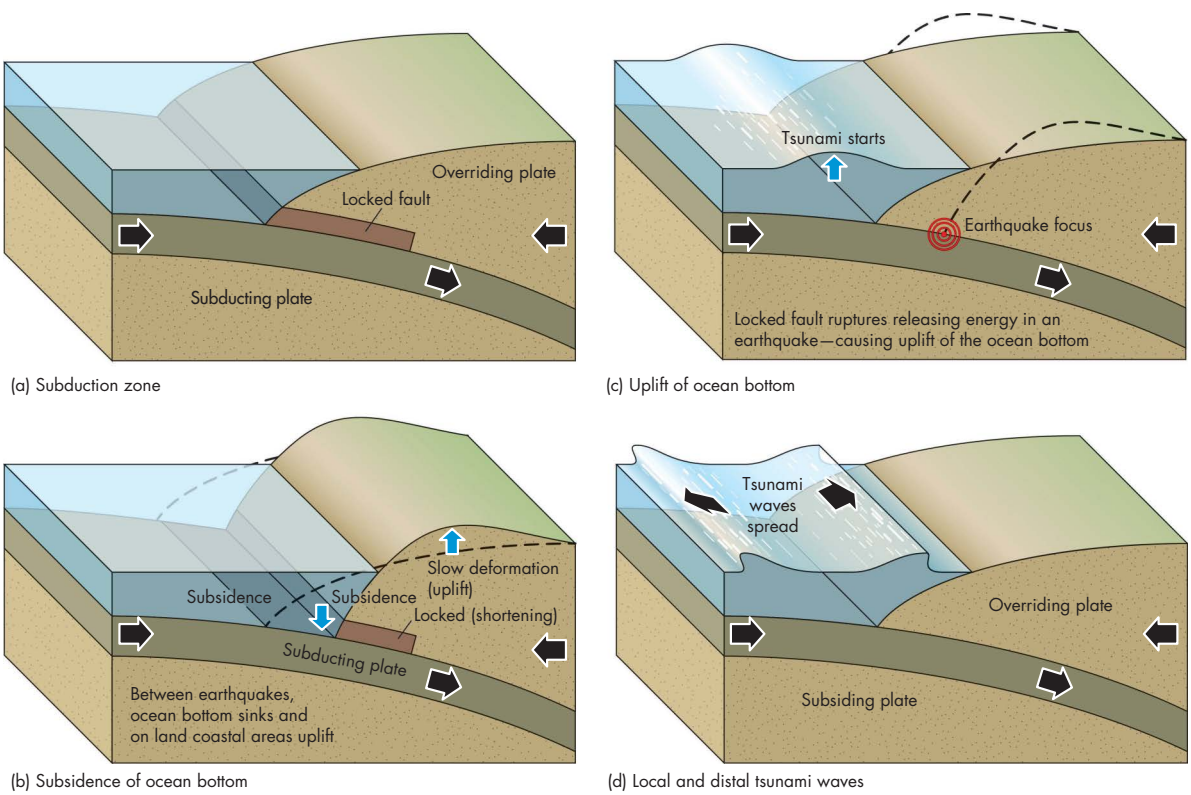
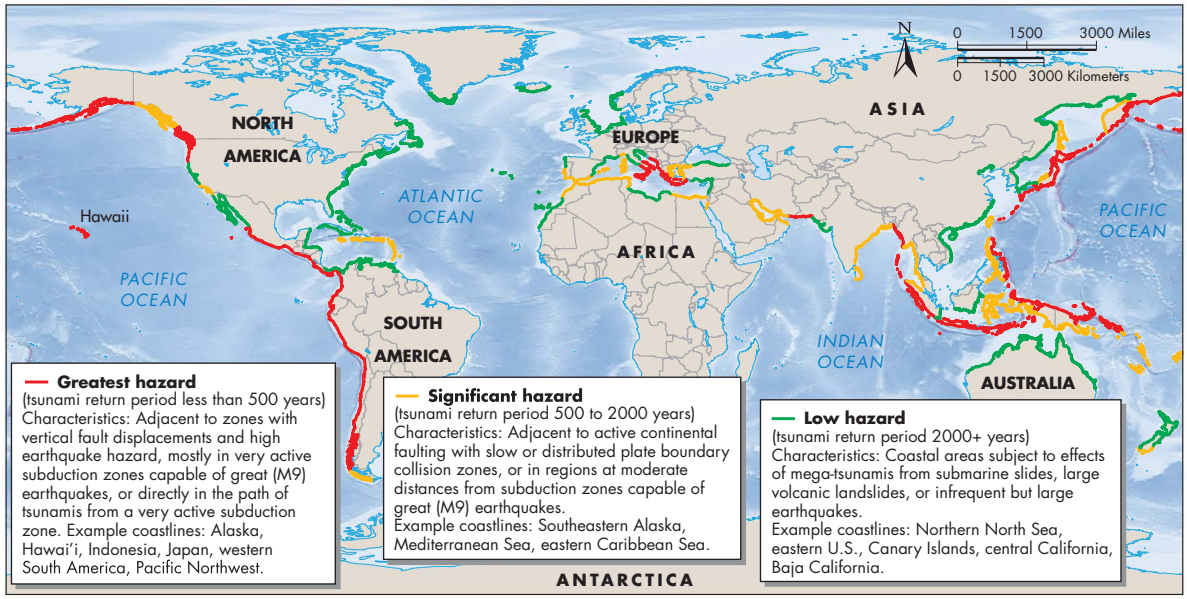


FIGURE 4.5
Idealized diagram of subduction zone cycle that produces large earthquakes and tsunamis.
(Based on U.S. Geological Survey Circular 1187)



< FIGURE 4.6 Ghost Forest
Drowned forest in Washington produced by subsidence during an earthquake about 300 years ago. *(USGS/http://pubs. usgs. gov/pp/pp1707/)*



^ FIGURE 4.7 Global Tsunami Hazard
Map of the relative hazard of coastlines to experience a tsunami that is at least 5 m (~16 ft.) high. Fjords in Norway (not shown) also have a very significant hazard from landslide generated local tsunamis.
(Modified from Risk Management Solutions. 2006. 2004 Indian Ocean Tsunami report. *Newark, CA: Risk Management Solutions, Inc.)*

global seismicity to accurately predict return periods of earthquakes of **M** 9 or above—those quakes most likely to produce a significant tsunami. Examination of the map reveals that most zones of greatest hazard surround the Pacific Ocean. This is no surprise, given that most major subduction zones are found on the margins of the Pacific. Other regions judged to have the greatest hazard are parts of the Mediterranean, as well as the northeastern side of the Indian Ocean. The good news about the risk from significant tsunamis is that almost all of them will cause substantial damage only within a couple of hundred kilometers from their source. However, the very largest subduction zone earthquakes may cause substantial damage several thousands of kilometers from the source. That certainly was the case with the 2004 Indonesian tsunami, which raced across the Indian Ocean causing death and destruction as far away as the east coast of Africa. However, most of the death and destruction occurred much closer to the earthquake epicenter, as described in Case Study 4.2: Indonesian Tsunami.

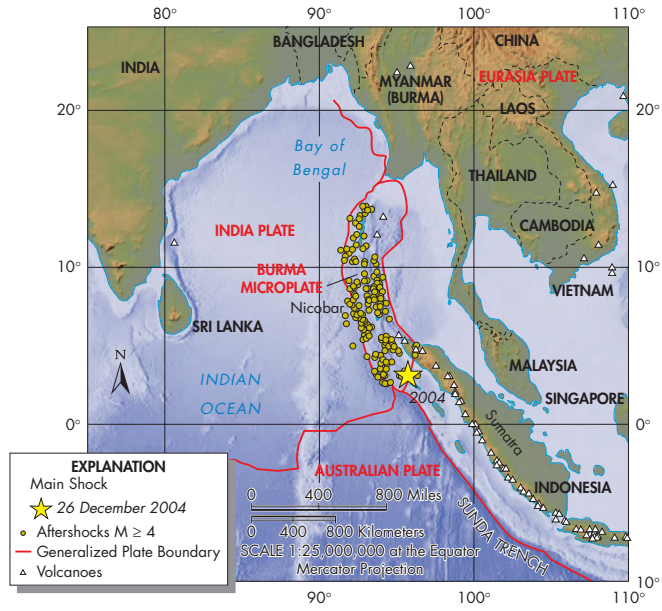


FIGURE 4.8 Geologic Setting of the Indonesian Tsunami
The gold star locates the epicenter of the mainshock of the **M** 9.1 earthquake on December 26, 2004. *(Based on U.S. Geological Survey)*

4.2 CASE study

Indonesian Tsunami

Prior to December 26, 2004, few people knew what the Japanese word *tsunami* meant. That changed in the span of only a few hours, as close to 230,000 people were killed, many hundreds of thousands injured, and millions displaced in more than a dozen countries surrounding the Indian Ocean. With no warning system in place, residents of coastal area after coastal area around the Indian Ocean were struck by a series of tsunami waves without notice.

The source of this tsunami was the world's largest earthquake in the past four decades that struck on the morning of December 26, just off the west coast of the Indonesian island of Sumatra (Figure 4.8). Now assigned a magnitude of at least 9.1, this earthquake caused the most lethal tsunami in recorded history.[17] The earthquake occurred where the giant Indian and Australian plates are being subducted to the northeast beneath the Burma microplate. In this earthquake, the Burma microplate moved about 20 m (~65 ft.) to the west-southwest along a gently inclined subduction zone (Figure 4.9). Because of the large amount of displacement along the thrust faults in the subduction zone, geologists classify this type of earthquake as a "mega-thrust event." Seismic waves generated by the rupture caused several minutes of shaking on nearby islands. The total length of the rupture along the subduction zone was more than 1500 km (~930 mi.), about the length of the state of California. Not only did the seafloor shift about 20 m (~65 ft.) horizontally, but also it rose several meters vertically.[14] Displacement of the sea bottom disturbed and displaced the overlying waters of the Indian Ocean, and a series of tsunami waves was generated. Waves radiated outward at high speed across the Indian Ocean (Figure 4.10).

Unlike the Pacific Ocean, there was no tsunami warning system for the Indian Ocean, and people were mostly caught by surprise. Scientists on duty at the Pacific Tsunami Warning Center in Hawaii recognized that the earthquake could potentially produce a tsunami, but the geophysical techniques to calculate the size of an earthquake of such magnitude were not immediately available to them.[18] Once they determined that a tsunami was likely, the scientists managed to contact other scientists in Indonesia and have the U.S. State Department relay its concerns to some nations surrounding the Indian Ocean. Unfortunately, the warnings did not reach authorities in time to take action, and even if they had, there was no system in place for directly notifying coastal residents. If the warnings had been received in time, tens of thousands of lives could have been saved because the tsunami waves took several hours to reach some of the coastlines where people died (Figure 4.10). Even a warning of half an hour or so before the tsunami hit would have given sufficient time to move many people from the low-lying coastal areas.[6]

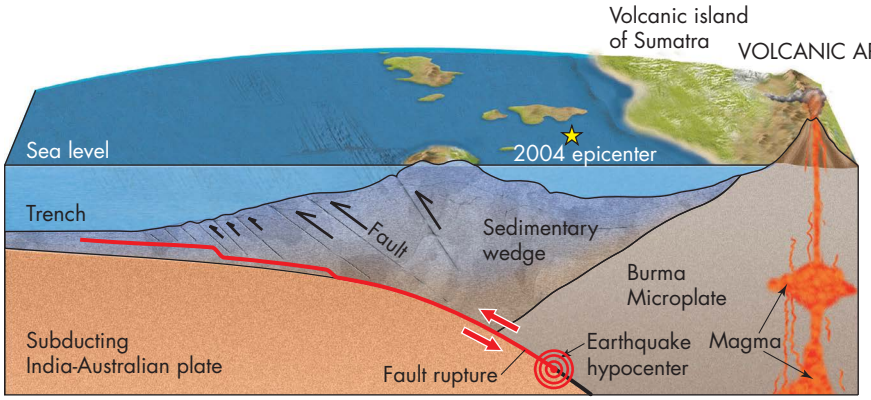


FIGURE 4.9 Earthquake in Subduction Zone
Idealized cross-section of the Sumatran subduction zone and 2004 earthquake fault rupture (red line). *(Based on US Geological Survey Data)*

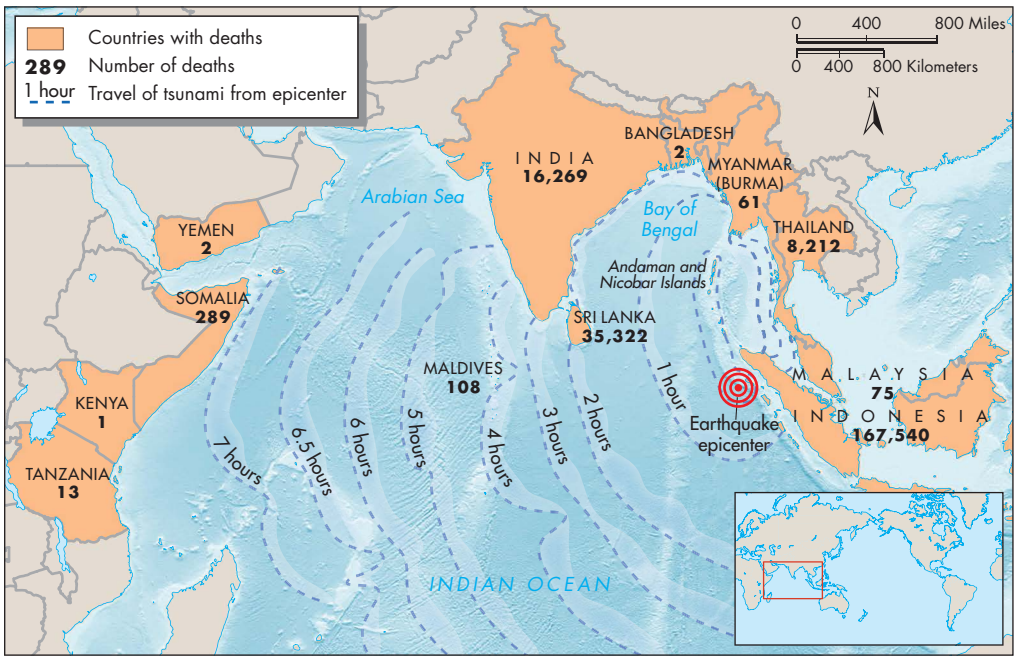


FIGURE 4.10 2004 Tsunami Killed People on Both Sides of Indian Ocean
Map showing the path of the tsunami produced by a **M** 9.1 earthquake off the west coast of Sumatra, Indonesia, on December 26, 2004. Shown with blue dashed lines is the location of the lead tsunami wave each hour after the earthquake. Note that the tsunami waves took approximately 7 hours to reach Somalia on the east coast of Africa. Most deaths were in Indonesia, where the first local tsunami wave arrived an hour or less after the earthquake. The number of deaths shown in each country is the total number of people dead or still missing. *(Data from Causalities summarized in Telford, J., and Cosgrave, J.,* Joint Evaluation of the International Response to the Indian Ocean Tsunami: Synthesis Report. *London: Tsunami Evaluation Coalition; Tsunami travel time data from NOAA, 2006)*

More than three-quarters of the deaths were in Indonesia, which experienced both the intense shaking from the earthquake and the inundation by tsunami waves within less than an hour. In contrast, the first tsunami wave took between 90 minutes and 2 hours to reach Sri Lanka and India, where many thousands died, and more than 7 hours to reach Somalia on the east coast of Africa (see Figure 4.10). The first of many tsunami waves reached other locations earlier or later, depending on their distance from the rupture in the subduction zone.

At the northern tip of the island of Sumatra, the Indonesian provincial capital of Banda Aceh was nearly destroyed (Figure 4.11). Destruction was caused by

shaking from the earthquake, the force of the tsunami waves, and flooding as the land subsided following the earthquake. Coastal subsidence of a tectonic plate is common in megathrust events along a subduction zone (see Chapter 3).

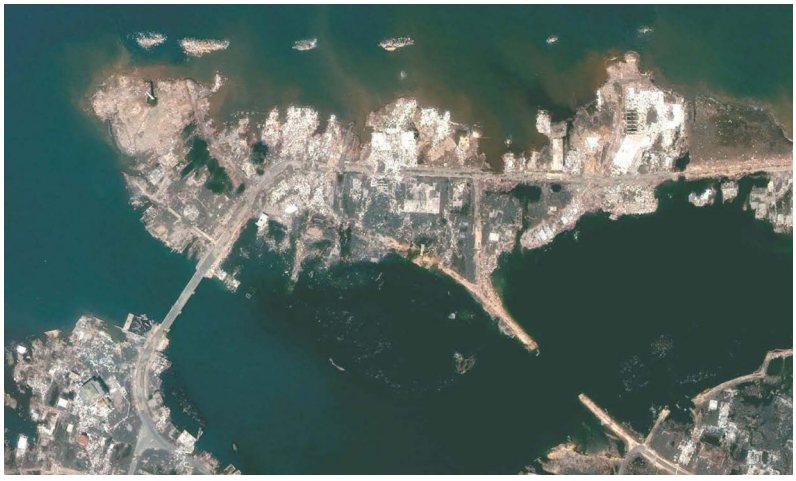
Tourist areas in the region were hard hit, especially in Thailand where several thousand tourists from Europe, the United States, and elsewhere were killed. Most visitors, and many first-generation residents, were unfamiliar with tsunamis. They did not know how to recognize that a tsunami was about to take place or what to do if one occurred. This was true for many people in Phuket, Thailand (Figure 4.12). Some people seemed to be mesmerized by the approaching waves, while others ran in panic.

On some coastlines, not everything was quite as bleak. In Thailand, a 10-year-old British girl sounded the warning in time for 100 people to evacuate a resort beach. Only a few weeks before going to Thailand, she had received a lesson in school about plate tectonics, earthquakes, and tsunamis. As part of that lesson, she learned that sometimes the sea recedes prior to the arrival of a tsunami wave. That is precisely what she observed, and her screaming to get off the beach eventually convinced her mother and others to take action. Thanks to her persistence, the beach was successfully evacuated. Her mother later stated she did not even know what a tsunami was but that her daughter's school lesson had saved their lives.

On another beach in Sri Lanka, a scientist on vacation witnessed a small wave rise up and inundate the hotel swimming pool. In the next 20 minutes, the sea level dropped by around 7 m (~23 ft.). The scientist recognized these events as a sign that a big wave was



(a)



(b)

< FIGURE 4.11 Nearly Complete Destruction Associated with Indonesian Tsunami of 2004

(a) Satellite view of Banda Aceh, the Indonesian provincial capital on the northern end of the island of Sumatra, before the earthquake and tsunami of December 26, 2004. *(AFP/GETTY IMAGES/Newscom)* (b) Two days after the tsunami, it is apparent that nearly all the development has been damaged or destroyed. Note that the shoreline at the top of the photograph has been extensively eroded, leaving behind only a few small islands. Large parts of the city flooded because of subsidence caused by the earthquake that combined with inundation from the tsunami. *(AFP/GETTY IMAGES/Newscom)*

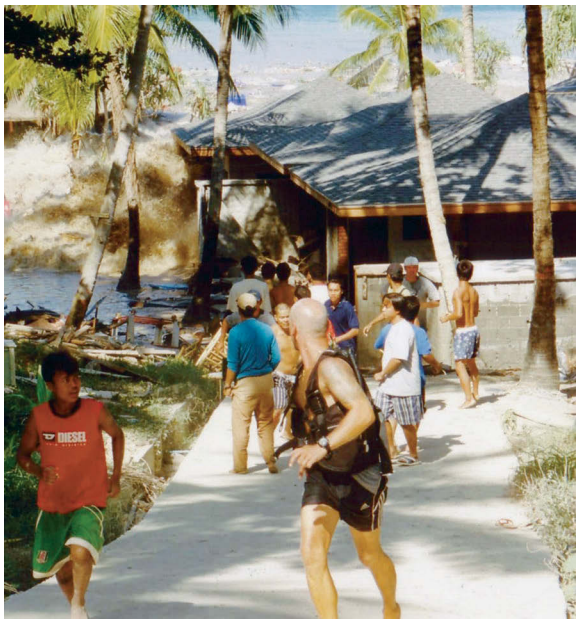


FIGURE 4.12 Tourists Running for Their Lives
Man in the foreground is looking back at a brown wave of the 2004 Indonesian tsunami rushing toward him. The wave is higher than the building behind him at this Phuket, Thailand, resort. Many people living there, as well as the tourists, did not initially think the wave would inundate the area where they were, and when the waves arrived, they thought they would be able to outrun the rising water. In some cases, people did escape, but all too often they drowned. *(John Russell/The Age/ZUMAPRESS/Newscom)*

coming and sounded the alarm. A hotel employee then used a megaphone to warn people to get off the beach. Many people had gone down to the beach out of curiosity to see the exposed seafloor. Shortly thereafter, the sea rose 7 m (~23 ft.) above its normal level. Fortunately, most people were either near hotel stairs or had escaped to higher floors. None of the staff or guests drowned, but several people on the ground floor were swept out and survived only by clinging to palm trees in the hotel garden.[19]

In the Andaman and Nicobar Islands in the northeastern Indian Ocean, as well as in parts of Indonesia, some native people have a collective memory of tsunamis. When the earthquake occurred, they applied that knowledge and moved to high ground, saving entire small tribes on some islands.

In Khao Lak, Thailand, elephants rather than people sounded the warning and saved lives.[20] The elephants started trumpeting about the time the **M** 9.1 earthquake occurred more than 600 km (~370 mi.) to the west. The elephants then became agitated again about an hour later. Those elephants not taking tourists for rides broke loose from their strong chains and headed inland. Other elephants carrying tourists on their backs ignored their handlers and climbed a hill behind the beach resort, saving the tourists from the fate that fell upon about 4,000 people who were killed by the tsunami at the resort. When handlers recognized the advancing tsunami, they got other elephants to lift tourists onto their backs with their trunks and proceed inland. The elephants did so even though they were accustomed only to people mounting them from a wooden platform. Tsunami waves then surged about 1 km (~0.5 mi.) inland. The elephants stopped just beyond where the waves ended their destructive path.

Did the elephants know something that people did not? Animals have sensory ability that differs from humans. It's possible the elephants heard the earthquake, because earthquakes produce sound waves with low tones referred to as *infrasonic sound*. Some people can sense infrasonic sound, but they don't generally perceive it as a hazard. The elephants may also have sensed the motion as the land vibrated from the earthquake. In either case, the elephants fled inland away from the advancing tsunami. Although the link between the elephants' sensory ability and their behavior is still speculative, the actions of the elephants nevertheless saved at least a dozen lives.[20]

Numerous reports received after the Indonesian tsunami indicate the vital role of education in tsunami preparedness. Thousands of lives would have been saved had more people recognized from Earth's behavior that a tsunami was likely. Those people who felt the large earthquake would have known that a tsunami might be coming and could have evacuated to higher ground. Even thousands of miles away where the seismic waves were not felt, there were still signals of what was about to happen. As the British schoolgirl knew, if the water suddenly recedes from the shore and exposes the sea bottom, you can expect it to come back as a tsunami wave. This is the signal to move to higher ground. People should also be informed that tsunamis are seldom one wave but are, in fact, a series of waves, with later ones many times larger and more damaging than earlier ones. Educating people close to where a tsunami may originate is particularly important, as waves may arrive within 10 to 15 minutes following an earthquake. Geologists have warned that it is likely another large tsunami will be generated by earthquakes offshore of Indonesia in the next few decades.[21,22] In fact, during the past 2,800 years, there have been four tsunamis identified by shallow excavations (Figure 4.13). The most recent tsunami before the 2004 event occurred 500 to 700 years ago.[23]



FIGURE 4.13 Shallow Excavation Following the 2004 Tsunami
The top layer of light sand is the 2004 tsunami deposit. Three older light-colored tsunami deposits, all less than 2,800 years old, are shown here. *(Brian Atwater/USGS)*

Since 2004, an ocean-bottom tsunami warning system consisting of sensors that recognize tsunami waves has been put in place in the Indian Ocean, and sirens are now in place in some coastal areas around the Indian Ocean to warn of an approaching tsunami. In addition, much more has been done to educate people about the tsunami hazard. A tsunami in 2009 generated by a **M** 8.1 earthquake struck American Samoa and other islands in the region. The number of lives lost was about 200, fewer than might have occurred without the program of tsunami awareness and education. People got the word out about the tsunami hazard and what to look for, which resulted in evacuations that saved lives. However, with even more education and improved warning systems linked to evacuation processes, more lives could have been saved.[24]

TSUNAMI THREE CENTURIES AGO

An interesting example of damage from a distant earthquake comes from three centuries ago. In the year 1700, a tsunami generated by an estimated **M** 9 earthquake on the Cascadia subduction zone reached the shores of Japan approximately 12 hours later (Figure 4.14). You might wonder how we are able to determine the magnitude of the earthquake and know that it created a tsunami in Japan. This detective story started with geologic investigations in North America that found logs and soil that were buried below a tsunami deposit sometime after 1660. The logs and other plant material in the soil were radiocarbon dated to determine when they were last alive, and the

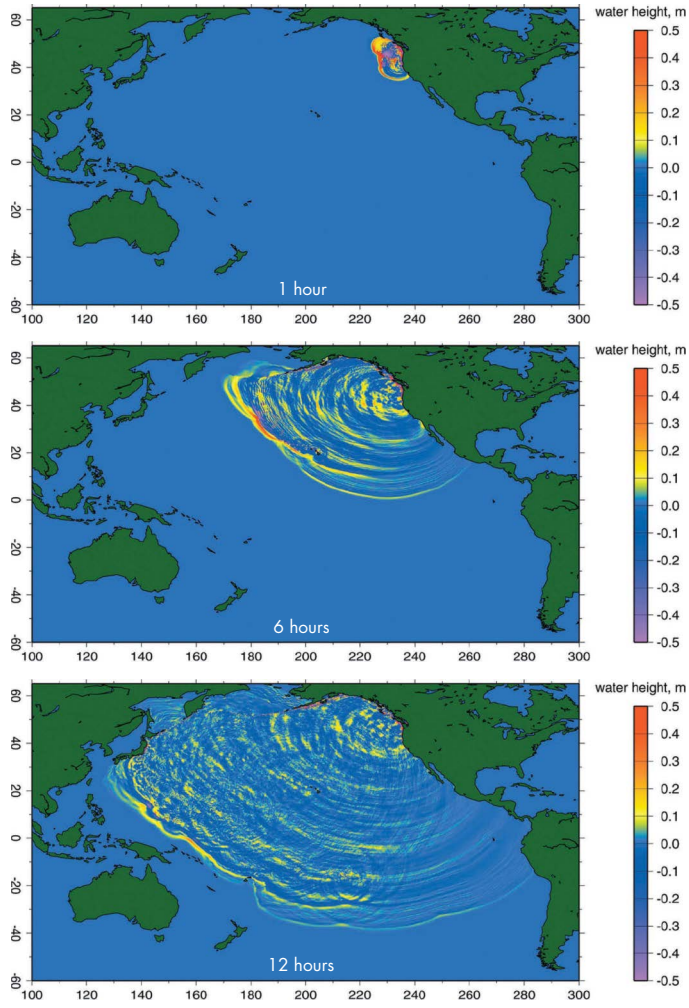


FIGURE 4.14 Tsunami of 1700
This output from a computer model of the January 1700 tsunami is based on arrival times at several sites in Japan. The maps show wave height and location 1 hour, 6 hours, and 12 hours after an ~**M** 9 earthquake occurred on the Cascadia subduction zone. Such an earthquake would produce a fault displacement of around 19 m (~60 ft.) over a distance of about 1100 km (~680 mi.) from British Columbia south to northern California. *(Used by permission of Kenji Satake)*

deposits showed evidence of subsidence at the time of the earthquake. Based on the geologic evidence, the length of rupture was estimated to be about 1000 km (~620 mi.).[25,26,27] The evidence from Japan consists of historical descriptions of a tsunami with a 1 to 5 m (~3 to 16 ft.) runup height that took place in 1700. Knowing the time of arrival of the tsunami in Japan, scientists have inferred that the tsunami originated at the Cascadia subduction zone about 9:00 P.M. PST on January 26, 1700.[25]

4.2 CHECK your understanding

1. Why do subduction zones produce the largest earthquakes?
2. What are the main lessons learned from the 2004 tsunami?

4.3 Effects of Tsunamis and Linkages with Other Natural Hazards

The effects of tsunamis are both primary and secondary. Primary effects are related to the inundation of the water and the resulting flooding and erosion. Virtually nothing can stand in the path of a truly high-magnitude tsunami. The wave energy is sufficient to tear up beaches and most coastal vegetation, as well as all homes and buildings in its path. These effects diminish with distance from the coast. Much of the damage both to the landscape and to human structures results from the tremendous amount of debris carried by the water as it moves inland and then back out again to the ocean. What is left behind is often bare, eroded ground and areas covered with all sorts of human and natural debris (Figure 4.15).

Secondary effects of tsunamis occur in the hours, days, and weeks following the event. Immediately following the tsunami, fires may start in urban areas from ruptured natural gas lines or from the ignition of flammable chemicals released from damaged tanks. Water supplies may become polluted from floodwaters, damaged wastewater treatment systems, and rotting animal carcasses and plants. Disease outbreaks may occur, as people surviving the tsunami come in contact with polluted water and soil. Following the 2004 Indonesian tsunami, public health officials were initially concerned that there would be outbreaks of waterborne illnesses, such as malaria and cholera. Fortunately, this did not become a serious problem because of the quick action of relief agencies and the destruction of mosquito breeding grounds by saltwater flooding. What did occur is a pneumonia-like disease known as "tsunami lung," a condition that developed in people who inhaled bacteria in muddy salt water. Because the disease was not initially recognized and there were few antibiotics or medical personnel available for treatment, many of the patients developed advance lung infections that resulted in paralysis. Fortunately, treatment with antibiotics eventually brought the infections under control.[28]



(a)



(b)

▲ FIGURE 4.15 Damage and Debris from 2004 Indonesian Tsunami

(a) In some areas, the tsunami removed all but the most sturdy buildings, such as this mosque in Aceh Province, Indonesia. *(Spencer Platt/Getty Images)* (b) In other areas, such as this part of the Indonesian resort town of Pangandaran, the tsunami piled up huge amounts of human and natural debris. This made it difficult for these soldiers to locate victims. *(Dimas Ardian/Getty Images)*

Several linkages exist between tsunamis and other natural hazards. Tsunamis are obviously closely linked to submarine and coastal earthquakes and landslides, as well as island volcanic explosions and oceanic impacts of asteroids and comets. For earthquake-generated tsunamis, coastal communities near the epicenter experience casualties and property damage from both the ground shaking of the earthquake (see Chapter 3) and the inundation by the tsunami. Powerful tsunami waves interact with coastal processes to change the coastline through erosion and deposition of sediment. There was dramatic evidence of this interaction following the 2004 tsunami in the area near Banda Aceh, Indonesia (see Figure 4.11). A combination of erosion caused by

the tsunami and subsidence caused by the earthquake has altered the coastal area to the point that it scarcely resembles what it was prior to the event.

4.3 CHECK your understanding

1. What are the primary and secondary effects of tsunamis?
2. List the ways tsunamis are linked to other hazards.

4.4 Natural Service Functions of Tsunamis

Large tsunamis are capable of causing catastrophic death and destruction. It is hard to imagine much in the way of benefits from such disasters. The movement of vast amounts of seawater on land undoubtedly brings many chemicals from the ocean to the land, which may have long-term effects on ecosystems that might otherwise be deprived of nutrients. Tsunamis also bring ashore a large volume of sediment that, over a long period, contributes to the general development of the landscape. In the coming years, studies of landscape and ecosystem changes following the 2004 Indonesian tsunami may reveal other natural service functions of tsunamis.

4.4 CHECK your understanding

1. What are potential natural service functions of tsunamis?

4.5 Human Interaction with Tsunamis

We cannot prevent tsunamis, and few, if any, tsunamis have been influenced by human activities. The magnitude and frequency of these events are not in any way tied to human activity. As with hurricanes and rising sea level, people who move to coasts that have an elevated risk for tsunamis are increasing the likelihood that they will be affected by this natural process. As populations of countries around the globe increase and more people inhabit coastal areas, the number of people affected by a given tsunami event will likely rise.

Damage from tsunamis is regrettable, but there are some lessons from past tsunamis that can be applied to reduce the damage from future events. For example, we can plant buffer zones of trees along a coast that will absorb some of the impact of incoming tsunami waves. We might also consider constructing our buildings to withstand the onslaught of moderate tsunamis and moving other structures inland where they are less likely to be damaged.

4.5 CHECK your understanding

1. How do growing populations and changing land uses influence the incidence and consequences of tsunamis?

4.6 Minimizing the Tsunami Hazard

A number of strategies are available for minimizing the tsunami hazard, including detection and warning, structural control, construction of tsunami runup maps, land-use planning, probability analysis, education, and implementation of tsunami-ready status.

DETECTION AND WARNING

Since nearly all large tsunamis are associated with giant earthquakes, our first warning comes from an earthquake in an offshore area that is large enough to produce a tsunami. We have the capability to detect distant tsunamis in the open ocean and accurately estimate their arrival time to within a few minutes. This information has been used to create a successful tsunami warning system in the Pacific Ocean.

A tsunami warning system has three components: a network of seismographs to accurately locate and determine the depth and magnitude of submarine and coastal earthquakes, automated tidal gauges to measure unusual rises and falls of sea level, and a network of sensors connected to floating buoys (Figure 4.16). Surface buoys with a bottom sensor, known as a *tsunameter*, detect small changes in the pressure exerted by the increased volume of water as a tsunami passes overhead (Figure 4.16a). This information is relayed by satellite to a warning center and is combined with tidal gauge information to predict tsunami arrival times. For example, an underwater earthquake in Hawaii could produce a tsunami that would radiate outward across the entire Pacific Ocean and arrive at different times in California, Alaska, Japan, and Papua New Guinea (Figure 4.16b). Following the Indonesian tsunami, similar systems are being created in the Indian Ocean and

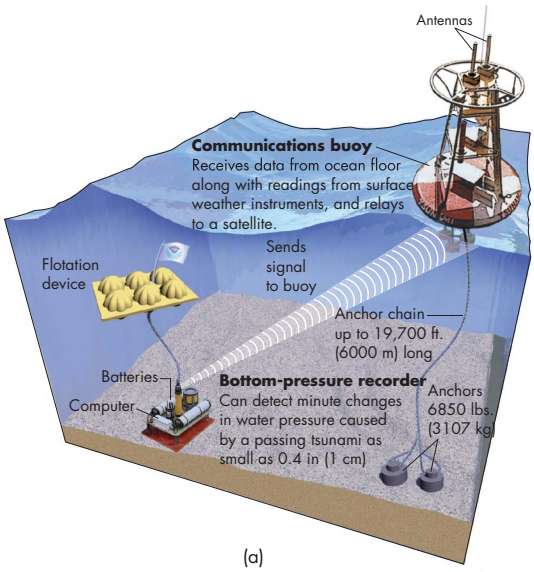
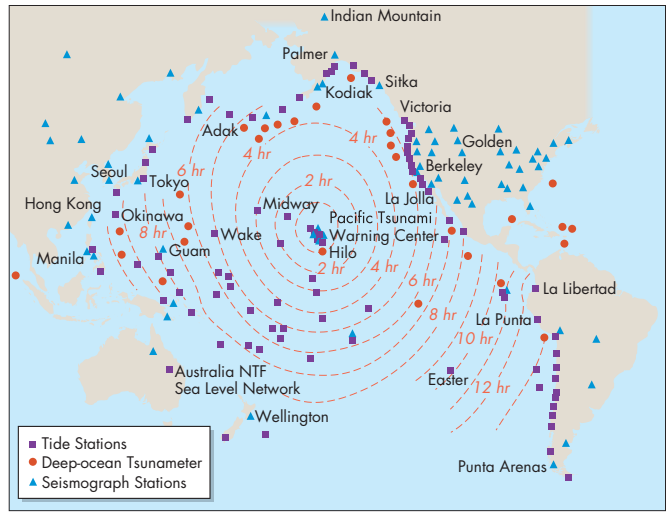


FIGURE 4.16 Tsunami Warning System

(a) A surface buoy and bottom sensor to detect a tsunami. *(From "Dart Mooring System," NOAA, http://nctr.pmel.noaa.gov/Dart/dart_ms1.html)* (b) Travel time (each band is 1 hour) for a tsunami generated in Hawaii. The wave arrives in Los Angeles in about 5 hours. It takes about 12 hours for the waves to reach South America. Locations of 30 DART tsunameter buoys are shown with red dots. At least 14 additional DART tsunameter buoys are planned for the Pacific Ocean and Atlantic Ocean. *(From "Dart Locations," NOAA Magazine, www.noaanews.noaa.gov/stories2007/s2904.htm)*



Atlantic Ocean, including warning sensors for Puerto Rico and the east coast of the United States and Canada.

For a local tsunami that strikes land very close to the source of the earthquake, there may be little warning time. People close to the source, though, will probably feel the earthquake and can immediately move inland to higher ground. Certainly, if one observes the water receding, it is a sign to run inland. Some coastal communities in Hawaii, Alaska, the Pacific Northwest, British Columbia, Japan, and elsewhere also have warning sirens to alert people that a tsunami may soon arrive.

STRUCTURAL CONTROL

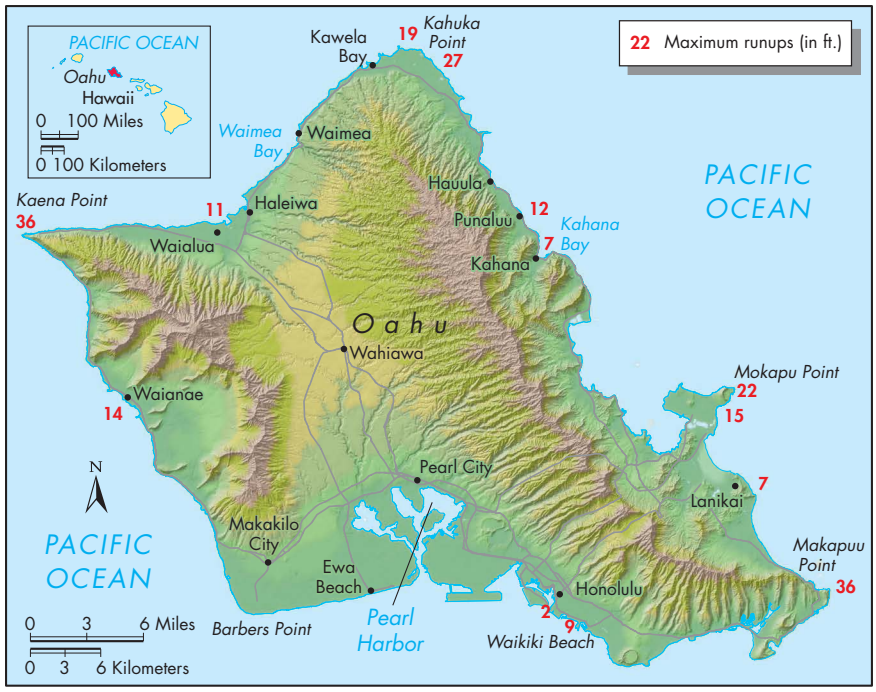
Tsunamis that are even a meter or two high have such power that houses and small buildings are unable to withstand their impact.[7] However, building designs for larger structures, such as high-rise hotels and critical facilities, can be engineered in such a way as to greatly reduce or minimize the destructive effects of a tsunami. For example, the city of Honolulu, Hawaii, has special requirements for construction of buildings in areas with a tsunami hazard. However, for most hazard areas, the current building codes and guidelines do not adequately address the effect of a tsunami on buildings and other structures.[29]

Building seawalls is another type of structural control. The goal is to have walls that will not allow tsunamis to move from the coast inland. The hard part is deciding how high walls should be. Walls that are not sufficiently high to protect a city can lead to a false sense of security.

TSUNAMI RUNUP MAPS

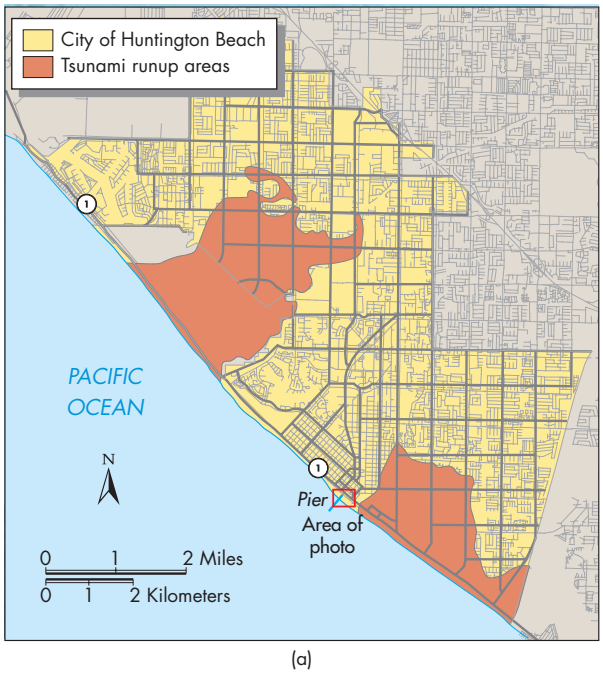
Following a tsunami, it is a fairly straightforward procedure to produce a **tsunami runup map** that shows the level to which the water traveled inland. Such a map was created for the island of Oahu, Hawaii, following the 1946 tsunami that originated from an earthquake in Alaska's Aleutian Islands (Figure 4.17). That map illustrates the tremendous variability of runup height from a typical tsunami. The runup from the 1946 tsunami varied from about 0.6 m (~2 ft.) in Honolulu to 11 m (~36 ft.) at Kaena Point and Makapuu Point on opposite ends of the island.

Before a tsunami strikes, a community can produce a hazard map that shows the area that is likely to be inundated by a given height. Huntington Beach, California, one of a number of American and Canadian communities that has a significant tsunami hazard, has prepared such a map (Figure 4.18a). Although the probability of a large tsunami in southern California is relatively low, the consequences of such an event could be catastrophic. For example, the entire city of Huntington Beach has an elevation of less than 33 m (~110 ft.), and three-quarters of the city is less than



< FIGURE 4.17 Tsunami Runup on Oahu, Hawaii

Map of Oahu showing runup of the 1946 tsunami that originated from an earthquake in the Aleutian Islands, Alaska. Maximum runups are indicated in feet. *(Based on Walker, D., "Tsunami Facts,"* SOEST Technical Report *94–03. School of Ocean and Earth Science and Technology, 1994)*



(a)



(b)

< FIGURE 4.18 Huntington Beach, California, Tsunami Runup Map

(a) Predicted runup map showing areas likely to be inundated by tsunami runup in red. These areas are more susceptible to runup due to their lower elevations with respect to yellow regions. *(From the City of Huntington Beach)* (b) The popular beach with pier and area to the southeast. *(Arthur Eugene Preston/Shutterstock)*

8 m (~25 ft.) above sea level. Huntington Beach itself faces to the southwest and, as such, is vulnerable to a tsunami from either the south or west. Such an event, for example, might originate in Alaska, Japan, or the South Pacific. The beach attracts up to 100,000 people or more each day during the summer, so the city is giving serious consideration to the possibility of a tsunami. Many other cities and areas have produced tsunami runup maps, and this trend will undoubtedly continue in the future.



FIGURE 4.19 Tsunami Damage to Trees
(a) Before and (b) after 2004 Indonesian tsunami removed many trees. *(© Getty Images/DigitalGlobe/ScapeWare3d/Contributor)*

LAND USE

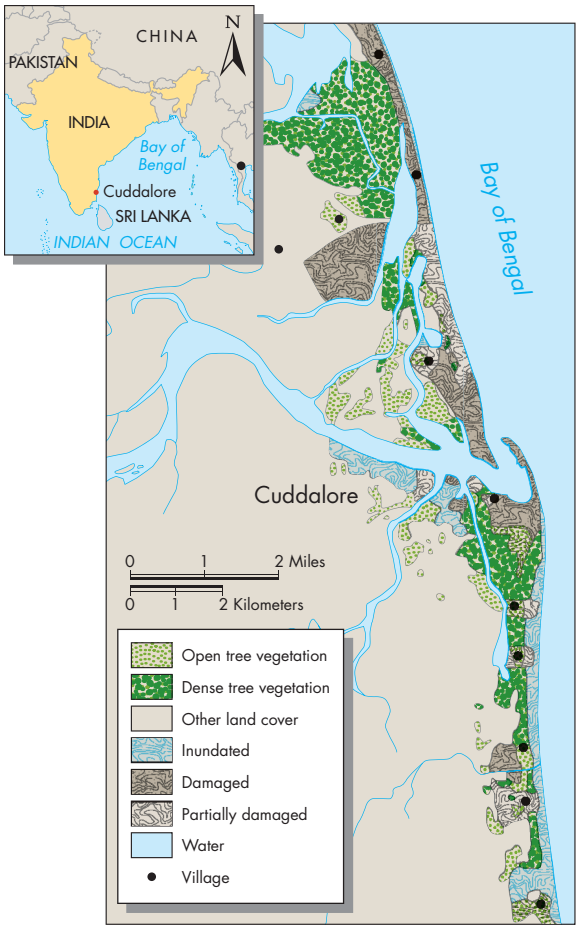
In the aftermath of the 2004 Indonesian tsunami, scientists discovered that tropical ecology played a role in determining tsunami damage. Where the largest waves struck the shore, there was inevitably massive destruction (Figure 4.19). In other areas, the damage was not uniform. Some coastal villages were destroyed, whereas others were less damaged. Those villages that were spared destruction were partly protected from the energy of the tsunami by either a coastal mangrove forest or several rows of plantation trees that reduced the velocity of incoming water.[30] Coastal land-use and land-cover studies have documented the advantage of locating villages inland behind a coastal forest (Figure 4.20). It has been suggested that places where the forest grows naturally may be somewhat protected from wave attack by the nearshore and land topography. Thus, development in areas with a tsunami hazard might look to land-use planning that includes identifying where serious tsunami damage has occurred in the past and avoiding the most hazardous places. That is using the principle of uniformitarianism discussed in Chapter 1.

With rapid coastal development for a variety of purposes, including tourism, coastal mangroves are often removed and replaced by homes, high-rise hotels, and other buildings. These structures are often located close to the beach and, thus, are vulnerable to tsunami attack. Although it may not be practical to move tourist areas inland, planting or retaining native vegetation could provide a partial buffer from a small-to-moderate tsunami attack. However, large tsunami waves can erode large trees from the soil, and their trunks and branches can then move inland with the water, producing a serious hazard to people and structures. The best and safest approach to lessen the tsunami hazard is always quick evacuation.

PROBABILITY ANALYSIS

The risk of a particular event may be defined as the product of the probability of that event occurring and the consequences should it occur. Thus, determining the likelihood or probability of a tsunami is an important component in analyzing the potential hazard. For the most part, the hazard analysis for tsunamis has relied on evidence from past tsunamis to determine the hazard rather than to attempt to calculate the probability of a future tsunami. The more deterministic approach is simply to derive a tsunami inundation map, such as that shown in Figure 4.18a, and use that to develop evacuation maps. In contrast, analysis of the probability of a tsunami hazard provides information not only on the likelihood of the event but also on other aspects as well, such as location of the event, the extent of the runup, and the possible severity of damage. The approach taken in developing a probabilistic analysis of the tsunami hazard should include the following steps:

- Identify and specify the potential earthquake sources and their associated uncertainties.
- Specify relationships that will either attenuate or reduce tsunami waves as they travel from the source area.
- Apply probabilistic analysis to the tsunami hazard similar to what is currently being done for earthquake hazard analysis. However, with tsunamis,



▲ FIGURE 4.20 Trees Provide Some Protection from Tsunami Damage

Tree cover existing pre-tsunami with post-tsunami damages to the land and villages in the Cuddalore District of India. *(Based on Danielsen, F, Serensen, M. K., Olwig, M. F, Selvam, V., Parish, F, Burgess, N. D., Hiraishi, T., Karunagaran, V. M., Rasmussen, M. S., Hansein, L. B., Quarto, A., and Suryadiputra. N. 2005. "The Asian Tsunami: A Protective Role for Coastal Vegetation,"* Science *310: 643)*

the analysis must consider the fact that tsunamis can originate from multiple sources, including ones that are far away from the location where the hazard is present.

This probabilistic approach to tsunami hazard assessment is still being developed. One difficulty is that tsunamis at a particular location are generally rare events. If there is not sufficient activity in the past to develop the probability of future events, then the analysis depends on a statistical technique known as Monte Carlo simulation. This technique has been used to simulate the behavior of earthquakes and tsunamis. The overall objective is to determine tsunami return periods and probabilities for both distant and local sources. To apply this technique, the Monte Carlo simulation selects a random sample of earthquakes of various magnitudes and determines the tsunamis that would be propagated from these quakes. Using these tsunamis, a mathematical model is then constructed to estimate the tsunami amplitude or runup along a particular coast. This must be done for each of the potential seismic sources for a particular coastline.[31]

EDUCATION

Education concerning the tsunami hazard is critical to minimizing risk (see Case Study 4.3: Professional Profile). This was shown dramatically during the 2004 Indonesian tsunami when numerous lives were saved because people recognized that the receding seawater was a warning sign of an impending tsunami. Likewise, it is important to teach coastal residents and visitors the difference between a **tsunami watch**, which is notification that an earthquake that can cause a tsunami has occurred, and an actual **tsunami warning** that a tsunami has been detected and is spreading across the ocean toward their area. For a distant tsunami, there will likely be several hours before the waves arrive after a warning has been issued. In a local tsunami, there may be little warning time; therefore, more attention must be given to nature's warning systems, such as earthquake shaking or water receding from a shoreline. People must also be taught that tsunamis come in a series of waves and that the second and third waves may be larger than the first one. Finally, people must be informed that the water returning to the ocean once a wave has run up is just as dangerous as the incoming water.

TSUNAMI-READY STATUS

In order for a community to be prepared, or **tsunami ready**, it must follow these steps:

- Establish an emergency operation center with 24-hour capability.
- Have ways to receive tsunami warnings from the National Weather Service, Canadian Meteorological Centre, Coast Guard, or other agencies.
- Have ways to alert the public.
- Develop a tsunami preparedness plan with emergency drills.
- Promote a community awareness program to educate people concerning a tsunami hazard.

These guidelines for tsunami-readiness status are being applied to a number of communities in California and other areas. For example, the University of California,

Santa Barbara, and the city of Huntington Beach, California, have been certified as tsunami ready (see Figure 4.18).

The educational component is of particular importance. Most people may not know what to do if a tsunami watch or warning is issued. For example, in 2005, there was an earthquake far away from the city of Santa Barbara in the Pacific. As it turned out, a tsunami did not occur, but a tsunami watch was placed up and down the California coastline. Since nothing was said about the size of the possible tsunami, some people, on hearing the notice, drove to the top of a nearby mountain pass thousands of feet above sea level. Those locations were great for views, but people certainly did not need to drive that far or that high to evacuate the potential danger zone. There was no plan in place to directly observe the tsunami, and the news media reported that some people perched on a sea cliff at night, whereas others climbed palm trees to see if the wave was coming. This experience in Santa Barbara, and other West Coast communities, suggests that even many "tsunami-ready" communities are not adequately prepared for the tsunami that will eventually strike their coasts.

4.6 CHECK your understanding

1. How are tsunamis detected in the open sea?
2. What are structural control options to reduce tsunami damage?
3. How can producing a tsunami runup map help reduce potential tsunami damage?
4. How can vegetation help minimize tsunami damage?
5. What are the three parts of developing a probabilistic approach to analyze future tsunami damages?
6. What is the role of education in minimizing the consequences of a tsunami?
7. What factors are necessary for obtaining tsunami-ready status?

4.7 Perception and Personal Adjustment to Tsunami Hazard

The preceding discussion suggests that many people do not know the signs of an approaching tsunami or what to do if a watch or warning is issued. From a personal perspective, if a warning is issued, you can take the following actions and follow tsunami safety rules:[32,33]

- Because large earthquakes have the potential to cause tsunamis, if you feel a strong earthquake and are at the beach, leave the beach and low-lying coastal area immediately.
- A small tsunami at one beach can be a giant a few miles away. Don't let the modest size of a tsunami in one location make you lose respect for what may strike your location.
- If the trough of a tsunami wave arrives first, the ocean will recede, exposing the seafloor. This is one of nature's warning signs that a wave is on the way and that you should run from the beach for higher ground.
- Although a tsunami may be relatively small at one location, it may be much larger nearby. Therefore, do not assume that all locations are safe because of an absence of dangerous waves elsewhere.
- Homes and other buildings located in low-lying coastal areas are not safe from tsunamis. Do not remain in such buildings if there is a tsunami warning. Upper floors or the roof of high, multistory, reinforced concrete buildings can provide refuge from a tsunami. Use them if there is no time to quickly move inland or to higher ground. If all else fails, climb a tall, strong tree.
- If you are on a boat and weather and time-permit, move your boat to deeper water at least 50 m (150 ft.). If there is concurrent severe weather, it may be safer to leave the boat at the pier and physically move to higher ground.
- Unpredictable currents from tsunamis can affect harbor conditions for a period of time after the tsunami's arrival. Be sure conditions are safe before you return your boat to the harbor.
- Approaching large tsunamis are usually accompanied by a loud roar that may sound like a train. If a tsunami arrives at night when the ocean cannot be seen, this is one of nature's tsunami warnings and should be heeded.
- As coastal communities gain tsunami-readiness status, they will have warning sirens; if you hear a siren, move away from the beach to higher ground (at least 20 m [~60 ft.] above sea level) and listen for emergency information.
- If you are aware that a tsunami watch or warning has been issued, do not go down to the beach to watch the tsunami. If you can actually see the wave, you are probably too close to escape. These waves look small out at sea because of the vast distance to the horizon. Remember that these waves move fast and can be deadly. A 2 m (~6 ft.) tall person is very small compared to a 15 m (~50 ft.) tsunami

CASE study

4.3 Professional Profile

Jose Borrero—Tsunami Scientist

Tsunami scientist Jose Borrero has witnessed firsthand the combined powers of land and sea unleashed (Figure 4.3.A). As a researcher with the University of Southern California Tsunami Research Center, he has traveled to areas hit by some of the most massive natural disasters in recent decades.

When a 10 m (~30 ft.) tsunami killed 2,100 people in New Guinea in 1998, Borrero and his colleagues were there just a week later to study the extent of the wave damage. "It looked like a hurricane came through. We saw dead bodies on the beach, ghost towns that looked completely bombed out—it was shocking," Borrero said.

The researchers traveled up and down the coast, looking for flattened trees, measuring waterlines on house walls, and asking local people what they remembered about the timing and size of the waves. Back home, they used their wave damage data, seismometer measurements, and computer models to reconstruct the events leading up to the tsunami. Their work revealed that an underwater landslide triggered by a relatively small earthquake created the large and powerful tsunami.

After the 2004 Indonesian earthquake and tsunami, Borrero and a team of *National Geographic* filmmakers were among the first outsiders to reach one of the hardest-hit areas—the city of Banda Aceh, Indonesia. What Borrero saw horrified him: "It was the worst of the worst of what I saw in New Guinea, except that, instead of being confined to just one town, it went on for 200 miles." In some areas, 10 m (~30 ft.) waves had pushed boats onto balconies and stripped the trees off the side of a mountain 24 m (~80 ft) up.

Back home, Borrero and colleagues used the data to develop a report about the risk Sumatra faces from future earthquakes and tsunamis along the next segment of



FIGURE 4.3.A Dr. Jose Borrero
A research professor at the University of Southern California Department of Civil Engineering Tsunami Research Group, Dr. Borrero was part of an international damage assessment team that studied the effects of the 2004 Indonesian tsunami. Dr. Borrero is shown here with boats that were destroyed by the tsunami in Banda Aceh, Indonesia. *(Dr. Jose Borrero/USC Tsunami Research Group)*

the earthquake fault. "If you know what's possible, you can make a plan. We can give that information directly to cities and towns so they can make evacuation routes and public awareness programs," he said.

Tsunami education, according to Borrero, is critical for coastal areas located directly on top of earthquake faults that produce tsunamis. "Tsunami warning systems only work for areas that are more than two hours away from the area of ground shaking. The only way to alert people is through education. If you feel an earthquake, and you're near the coast, don't sit and wait—head for high ground."

Growing up surfing in California, Borrero always wanted a career in which he could work directly with the ocean. "There's this primal fear people have of giant walls of water. Many people have told me they have this recurring nightmare where they're trapped in a tsunami and can't escape. I've never had dreams like that; maybe understanding it keeps me from worrying too much."

— KATHLEEN WONG

wave (Figure 4.21). Tsunamis can move faster than a person can run.

- If trapped in the water and swept away, look for something that floats to use as a raft.
- Tsunamis generally consist of a series of waves with possibly up to an hour between waves. Therefore, stay out of dangerous areas until a notice that all is clear is given by the proper authorities.
- During a tsunami watch or warning, stay tuned to your local radio, marine radio, NOAA Weather Radio, or television stations during a tsunami emergency – bulletins issued through your local emergency management office and National Weather Service offices can save your life.

4.7 CHECK your understanding

1. What are two warnings from nature that a tsunami may be coming?
2. What should you do if a tsunami warning is issued?
3. What can you do if you have had little warning and tsunami waves will arrive before you can evacuate?

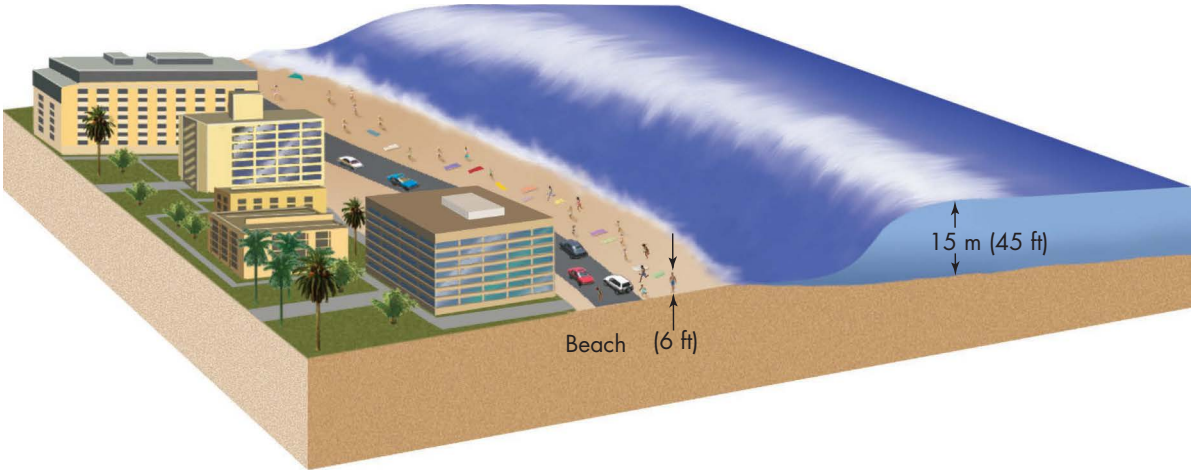


FIGURE 4.21 A Person Versus a Tsunami
Tsunami height can be huge compared to the waves we normally see on a beach.

APPLYING the 5 Fundamental Concepts

Japan 2011: Tsunami and Nuclear Disaster

1. **Science helps us predict hazards.**
2. **Knowing hazard risks can help people make decisions.**
3. **Linkages exist between natural hazards.**
4. **Humans can turn disastrous events into catastrophes.**
5. **Consequences of hazards can be minimized.**

The Japanese people have studied earthquakes and tsunamis for decades and have been keeping records of their experiences with both for hundreds of years. People in Japan are well aware that large earthquakes in the region and resulting tsunamis are likely in the future. Major earthquake faults lie about 100 km (~65 mi.) offshore of the east coast of Japan where the Pacific Plate is forced beneath the Eurasian Plate. These faults have been studied for decades and are known to be capable of producing **M** 7 to **M** 8 tsunami-generating earthquakes (see Chapter 3: Applying the Fundamental Concepts).

With more than 12,500 km (~7750 mi.) of tsunami seawalls protecting about 43 percent of Japan's coastline, the country has invested billions of dollars on these concrete barriers to minimize the tsunami risk. For example, the deepest tsunami defensive barrier ever constructed was completed in 2009 outside the historic town of Kamaishi at a cost of $1.6 billion. The Kamaishi wall is anchored to the sea floor at a depth of 65 m (~215 ft.), and is about 2000 m (~6400 ft.) long, 60 m (~207 ft.) wide, and stands 6 m (~20 ft.) above sea level. Like most of Japan's seawalls, however, the Kamaishi wall was designed to minimize the effects tsunami waves with heights up to 5 m (~16 ft.). This design specification means that most of Japan's seawalls are capable of protecting the coastline from typical tsunami waves that result from **M** 8 or less subduction zone earthquakes, which occur every 100 to 150 years.

The unexpectedly large magnitude (**M** 9) of the earthquake that struck the Tohoku (northeastern) region of Japan on March 11, 2011, was a surprise to most, as was the height of the tsunami. Following the earthquake, tsunami warnings were issued, giving coastal communities nearest the epicenter about 12 to 15 minutes to evacuate. Although the Japanese population is well educated and trained on how to survive an earthquake, many people underestimated the tsunami risk to their communities because of a false sense of security provided by the extensive seawall network. With waves approximately 10 m (~30 ft.) high and some locally exceeding 40 m (~130 ft.), seawalls were quickly overtopped and destroyed by the tsunami waves (Figure 4.22), including the Kamaishi seawall. The deluge of water caused extensive coastal erosion and destroyed almost everything in its path, carrying debris such as cars, houses, and large sea-going vessels as far as 10 km (~6 mi.) inland. Of the approximately 16,000 people killed by the 2011 Tohoku earthquake and tsunami, most died as a result of flooding by the tsunami wave and not the earthquake.

A decade earlier, a Japanese scientist had suggested that larger than expected tsunamis were possible and that existing tsunami protection barriers may not be large enough. The existence of very large tsunamis in the region with long return periods of about a thousand years was discussed as early as 2001. Buried tsunami deposits were found inland about as far as the 2011 tsunami inundated the land. Unfortunately, these scientific findings were either not believed or not taken seriously. In other words, warnings from scientists were largely ignored, except in scientific circles.[1,2] Interestingly,



FIGURE 4.22 Tsunami Wave Reaches the Coast of Japan
Over-topping 4 m high sea walls, the first tsunami wave inundates Sendai, one of the first coastal communities to be flooded by the 2011 Tohoku tsunami. *(z03/ZUMA Press/Newscom)*

the small village of Fudai survived the tsunami because in the late 1960s the mayor insisted on building a much higher wall—about 16 m (~52 ft.), which at the time people in the village thought to be foolish and too expensive (Figure 4.23). But the mayor remembered burying people after the 1933 tsunami and had knowledge of a large killer tsunami that had occurred in 1896. He persisted in building the higher wall, and the village survived the 2011 tsunami, while others in the region were completely destroyed.

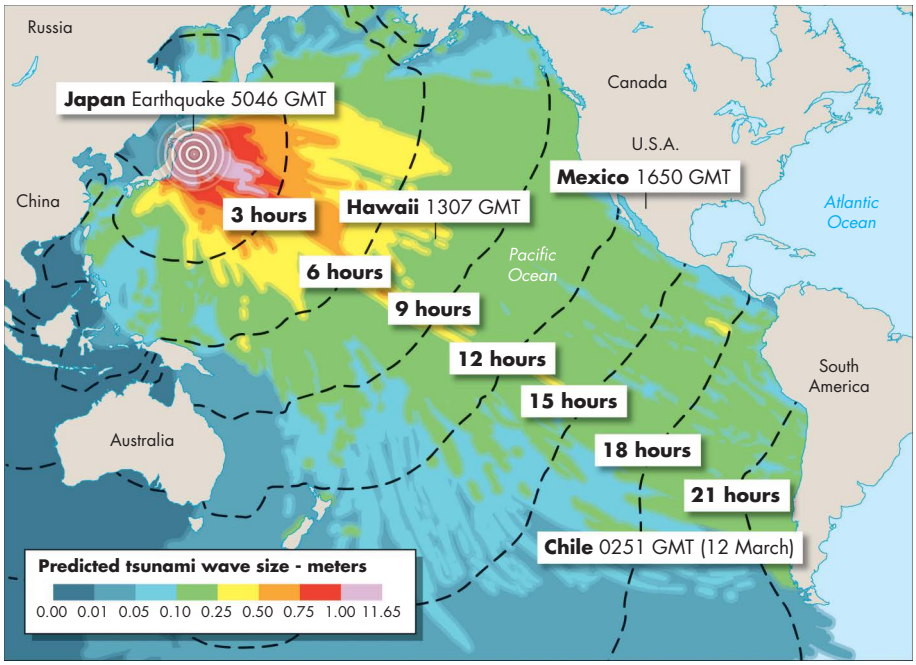


FIGURE 4.23 Village of Fudai Saved by Seawall
Fudai's current mayor, Hiroshi Fukawatari, near the 16 m (~52-ft) seawall (not shown) that protected homes from the tsunami waves. The seawall and floodgates were a project begun by former mayor Kotaku Wamura, who remembered the devastation of a tsunami in 1933. *(AP Photo/Hiro Komae)*

Tsunami warnings were also issued across the Pacific as distant tsunamis raced across the ocean, reaching Hawaii in about 7 hours and California in about 10 hours (Figure 4.24). Tsunami waves of 1–2 m (~3–6 ft.) inundated California harbors, costing millions of dollars in damages.

About the time the distant tsunami was arriving on the shores of Hawaii, an evacuation order was issued for all persons within a 3 km (~1.9 mi.) radius of the Fukushima Daiichi nuclear power station. The Fukushima power station is one of 23 reactor complexes in the country and one of six located on Japan's east coast impacted by the 2011 tsunami. Although backup power generators for the reactor cooling system were functioning within two minutes of the automated earthquake shutdown procedure, less than an hour later tsunami waves breached the power station's seawalls, flooding the generators. With no way to cool the reactor cores, it was only a matter of time before the nuclear fuel in the three active reactors at the Fukushima complex would melt down. Over the next few days, several massive hydrogen gas explosions within the containment buildings led to release of radiation into the atmosphere.

At first, people outside the 3 km (~1.9 mi.) evacuation zone were advised to stay in their homes and keep their doors and windows closed to minimize protect themselves from the



< FIGURE 4.24 Tsunami Prediction
Predicted arrival times and average wave heights of tsunami waves from the March 11, 2011 event are shown. Maximum observed wave heights in Hawaii and California were several times the predicted average. *(NOAA)*

radiation. However, authorities soon realized that the hydrogen explosions had released particles of radioactive cesium dust, which had blanketed the landscape and was being remobilized every time the wind blew.[3] Twenty-eight hours after the earthquake and four hours after the first hydrogen explosion, the mandatory evacuation radius around the Fukushima Daiichi power station was expanded to 20 km (~12.5 mi.), displacing about 200,000 people.

When a catastrophe occurs, government and people sometimes "freeze" at first, which inhibits proper response. Nearly 25 percent of the people in Japan are over age 65, compared to about 12 percent in the United States. Many of the elderly were stranded for several days as they tried to survive in freezing weather. Imagine being an elderly patient at a hospital near the damaged power plants. Now imagine being ordered to evacuate, but no vehicles are available that could take you, along with a hundred other elderly patients, to safety. These patients had to wait in the freezing cold with no electricity until help finally came. When these elderly patients were finally evacuated to another location (a temporary move to a high school), many died in transit, and the new site lacked running water and had little medicine or food.

Although evacuation conditions improved over the next few years, much of the 20 km evacuation zone is still off limits, and the town of Tomioka, near the failed reactor, is not expected to be habitable until 2017. Current death toll estimates of refugees from the Fukushima nuclear meltdown due to poor evacuation conditions is about 1,600, which exceeds the number killed by the earthquake and tsunami for the region.

Leaks of radioactive material into the environment were thought to have been contained within the first few months following the meltdown. However, in the summer of 2013, it was discovered that the plant was actively leaking radioactive water into the Pacific Ocean and had likely been leaking since the incident began in 2011. As of late 2013, it is estimated that about 120 tons of radioactive water have been leaked into the world's oceans. No clear solution for stopping the leak had yet been devised.

The 2011 Tohoku tsunami and nuclear disaster has invigorated a global discussion about defending against infrequent, larger-than-expected hazardous natural events and how humans can compound their destructive effects. For example, following several months of anti-nuclear protests in Germany following the

events of March 2011, Germany's government announced it would close all nuclear power plants by 2022, in large part due to the perception that the safety of nuclear power generation could not be ensured.

Although about 180 km (~112 mi.) of the 300 km (~186 mi.) of seawalls impacted by the 2011 tsunami were destroyed and the seawall network largely failed in stopping coastal flooding, studies suggest that some seawalls delayed coastal inundation by the first tsunami wave by several minutes, saving countless lives. Japan is already reconstructing many destroyed seawalls, but can they be built high enough to protect against the combined effects of sea-level rise due to global warming and long frequency extreme events like the one the struck in 2011? In the United States, we should learn from Japan's catastrophe and ensure that we are ready when a large tsunami occurs. Along the Pacific coast, from northern California to Seattle, Washington, large subduction zones have periodically produced giant earthquakes that presumably could produce large damaging tsunamis every few hundred years.[34]

APPLYING THE 5 FUNDAMENTAL CONCEPTS

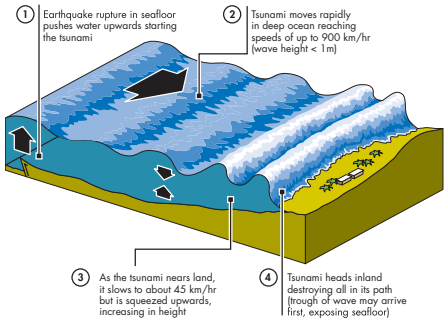
1. Evaluate Japan's overall level of preparedness for the tsunami hazard of the region and discuss the successes and failures of the country to predict the 2011 Tohoku tsunami (see also Chapter 3, Applying the 5 fundamental concepts: 2011 Tohoku Earthquake).
2. Discuss the factors that led the scientific community and the general population of Japan to underestimate the tsunami risk presented by an event like the one that struck in 2011.
3. Describe how the 2011 tsunami is linked to other hazards. What are the temporal and spatial aspects of these hazards?
4. Explain how and why the 2011 tsunami became a much worse catastrophe due to human error before and following the event.
5. Discuss Japan's successes and failures to minimize the effects of the 2011 tsunami. How might Japan and its population better minimize the consequences of future events?

CONCEPTS in review

4.1 Introduction to Tsunamis

LO:1 Explain the process of tsunami formation and development.

- A tsunami is produced by the sudden vertical displacement of ocean water. Several possible processes can produce tsunamis, including underwater landslides, submarine volcanic explosions, and impact of extraterrestrial objects.
- The major source of large damaging tsunamis over the past few millennia has been giant earthquakes associated with the major subduction zones on Earth. These tsunamis have formed where geologic faulting ruptures the seafloor and displaces the overlying water.
- When seafloor earthquakes occur, both distant and local tsunamis may be produced. Distant tsunamis can travel thousands of kilometers across the ocean to strike a remote shoreline. On the other hand, local tsunamis head toward a nearby coast and can strike with little advance warning.



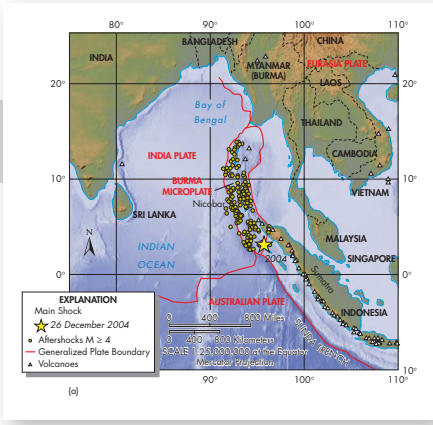
KEY WORDS

distant tsunami (p. 126), **local tsunami** (p. 126), **runup** (p. 125), **tsunamis** (p. 124)

4.2 Geographic Regions at Risk from Tsunamis

LO:2 Locate on a map the geographic regions that are at risk for tsunamis.

- The largest tsumanis generated by earthquakes are produced at subduction zones.



4.3 Effects of Tsunamis and Linkages with Other Natural Hazards

LO:3 Synthesize the effects of tsunamis and the hazards they pose to coastal regions.

LO:4 Summarize the linkages between tsunamis and other natural hazards.



- Effects of a tsunami are both primary and secondary. The primary effects are related to the powerful water from the tsunami runup that results in flooding and erosion. Virtually nothing can stand in the path of a large-magnitude tsunami. In 2004 in Indonesia, huge concrete barriers were moved by the force of the waves. Secondary effects of a tsunami include a potential for water pollution, fires in urban areas, and disease to people surviving the event.
- Tsunamis are linked to other natural hazards. They are obviously tightly linked to the earthquakes that cause them; thus, their effects are often combined with the ground shaking, fires, and subsidence associated with the quakes. Tsunami waves also interact with coastal processes to change the coastline through erosion and deposition of sediment. Following an earthquake and tsunami, a coastal area may scarcely resemble what it was prior to the event.

4.4 and 4.5 Natural Service Functions of Tsunamis Human Interaction with Tsunamis

LO:5 Understand that tsunamis are not caused by or affected by human activities, but damages are compounded as coastal populations increase.



- Tsunamis can move sediment and nutrients inland with long-term ecosystem benefits.
- Occurrences of tsunamis are not influenced by human activities, but we can take actions to reduce their potential impacts.

4.6 Minimizing the Tsunami Hazard

LO:6 Discuss what nations, communities, and individuals can do to minimize the tsunami hazard.

- A number of strategies are available to minimize the tsunami hazard, including detection and warning, structural control, construction of tsunami runup maps, land-use practices, probability analysis, education, and achieving tsunami-ready status. Of these, the detection and warning system is of paramount importance.
- We can detect distant tsunamis in open ocean and accurately estimate their arrival time to within a few minutes. It is more difficult to provide adequate warning for local tsunamis, as tsunami wave formation quickly follows an earthquake or earthquake-produced landslide. In this case, warning sirens can alert people that a tsunami may soon arrive.
- Without adequate education, watches and warnings are often ineffective because many people do not know how to recognize a tsunami or take appropriate action to save themselves and others. People can learn the natural warning signs of an approaching tsunami, which may include the earthquake shaking and withdrawal of seawater prior to arrival of the large wave. People must understand that tsunamis come in a series of waves and that the second or third wave may be even larger than the first wave. In addition, the water returning to the ocean following tsunami inundation can cause as much damage as the runup of the incoming water.
- Along coasts with great or significant tsunami hazard, most communities have not adequately prepared for this underestimated natural hazard. Adequate preparation includes improved perception of the hazard, development of ways to alert the public, preparation and implementation of a tsunami-readiness plan, and promotion of community awareness and education concerning the hazard.



KEY WORDS

tsunami ready (p. 142), **tsunami runup map** (p. 139), **tsunami warning** (p. 142), **tsunami watch** (p. 142)

4.7 Perception and Personal Adjustment to Tsunami Hazard

LO:7 Identify the actions you should take and not take if a tsunami warning is issued.

There are several personal adjustments to minimize your tsunami hazard.

- Most important is to heed tsunami warnings.
- Local tsunamis may arrive quickly following a tsunami-generating event; leave the beach if you feel a strong earthquake or if the water suddenly withdraws.
- Remember that tsunami waves often arrive as a series of waves separated by a variable time period.



CRITICAL thinking questions

1. You are placed in charge of developing an educational program with the objective of raising a community's understanding of tsunamis. What sort of program would you develop and on what would it be based?
2. What do you think the role of the media should be in helping to make people more aware of the tsunami hazard? How should scientists be involved in increasing the perception of this hazard?
3. You live in a coastal area that is subject to large but infrequent tsunamis. You are working with the planning department of the community to develop tsunami-ready status. What issues do you think are most important in obtaining this status and how could you convince the community that it is necessary or in everyone's best interest to achieve tsunami-ready status?

References

1. **Normile, D.** 2011. Scientific consensus on great quake came too late. *Science* 322: 22–23.
2. **Fackler, M.** 2012. Nuclear disaster in Japan was avoidable, critics contend. *New York Times*, Asia Pacific edition, March 9.
3. **Gupta, T.** 2011. Exploring the nuclear accidents of Japan: A tremor, a tsunami, and a dark cloud left behind. *US Science Review*. www.scf.usc.edu/~uscience/radiation_nuclear_accidents.html. Accessed 5/21/12.
4. **Meyers, C.** 2012. Japan earthquake anniversary: Nuclear evacuees scarred by disaster one year later. www.huffingtonpost.com/2012/02/13/japan-earthquake-anniversary_n_1272447.html#254326. Accessed 5/21/12.
5. **Author unknown.** 2011. Hot spots and blind spots. *The Economist*, October 8.
6. **U.S. Geological Survey.** 2005. *Magnitude 9.1—off the west coast of northern Sumatra.* U.S. Geological Survey Earthquake Hazards Program.
7. **Bryant, E.** 2001. *Tsunami: The underrated hazard.* New York: Cambridge University Press.
8. **Bolt, B. A.** 2006. *Earthquakes*, 5th ed.; 2006 Centennial update. New York: W. H. Freeman.
9. **U.S. Geological Survey.** 2005. *Life of a tsunami.* Western Coastal and Marine Geology Program. http://walrus.wr.usgs.gov/tsunami/basics.html. Accessed 5/25/07.
10. **Hokkaido Tsunami Research Group.** 1993. Tsunami devastates Japanese coastal region. *EOS, Transactions American Geophysical Union* 74(37): 417–32.
11. **Tappin, D. R. and 9 others.** 2014. Did a submarine landslide contribute to the 2011Tokohu tsunami ? *Marine Geology* 357: 344–61.
12. **Brothers, D. S. and 6 others.** 2016. A submarine landslide source for the devastating 1964 Chenega tsunami, southern Alaska. *Earth and Planetary Science Letters* 438: 112–21.
13. **Tappin, D. R., Watts, P., McMurtry, G. M., Lafoy, Y.,** and **Matsumoto, T.** 2001. The Sissano, Papau New Guinea tsunami of July 1998—offshore evidence of the source mechanism. *Marine Geology* 175: 1–23.
14. **Stover, C. W.,** and **Coffman, J. L.** 1993. *Seismicity of the United States, 1958–1989* (revised). U.S. Geological Survey Professional Paper 1527.
15. **Harbitz, C. B.** and **5 others**. 2014. Rockslide tsunamis in complex fjords: From an unstable rock slope at Akerneset to tsunami risk in western Norway. *Coastal Engineering* 88: 101–22.
16. **Sataki, K.,** and **Atwater, B. F.** 2007. Long-term perspectives on giant tsunamis at subduction zones. *Annual Review of Earth and Planetary Sciences* 35: 349–74.
17. **Subarya, C., Chlieh, M., Prawirodirdjo, L., Avouac, J.-P., Bock, Y., Sieh, K., Meltzner, A. J., Natawidjaja, D. H.,** and **McCaffrey, R.** 2006. Plate-boundary deformation associated with the great Sumatra-Andaman earthquake. *Nature* 440: 46–51.
18. **Kerr, R. A.** 2005. Failure to gauge the quake crippled the warning effort. *Science* 307: 201.
19. **Chapman, C.** 2005. The Asian tsunami in Sri Lanka: A personal experience. *EOS, Transactions, American Geophysical Union* 86(2): 13–14.
20. **Bendeich, M.** 2005. *Elephants saved tourists from tsunami.* Reuters. http://savetheelephants.org. Accessed 5/25/07.
21. **Achenbach, J.** 2006. The next big one. *National Geographic* 209(4): 120–47.
22. **Sieh, K.** 2006. Sumatran megathrust earthquakes: From science to saving lives. *Philosophical Transactions Royal Society* 364: 1947–63.
23. **Jankew, K. et al.** Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand. *Nature* 455: 1232–34.
24. **Jaffe, B. E., Gelfenbaum, G., Buckley, M. L., Watt, S., Apostos, A., Stevens, A. W.,** and

Richmond, B. M. 2010. *The limit of inundation of the September 29, 2009 tsunami in Tutuila, American Samoa.* U.S. Geological Survey Open File Report 2010–1018.

25. Satake, K., Wang, K., and **Atwater, B. F.** 2003. Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami descriptions. *Journal of Geophysical Research* 108(B11): 148–227.

26. Nelson, A. R., Atwater, B. F., Bobrowsky, P. T., Bradley, L.-A., Clague, J. J., Carver, G. A., Darienzo, M. E., Grant, W. C., Krueger, H. W., Sparks, R., Stafford Jr., T. W., and **Stuiver, M.** 1995. Radiocarbon evidence for extensive plate-boundary rupture about 300 years ago at the Cascadia subduction zone. *Nature* 378: 371–74.

27. Atwater, B. F. 1992. Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington. *Journal of Geophysical Research* 97(B2): 1901–19.

28. Potera, C. 2005. In disasters wake: Tsunami lung. *Environmental Health Perspectives* 113(11): A734.

29. California Seismic Safety Commission. 2005. The tsunami threat to California: Findings and recommendations on tsunami hazards and risks. Report CSSC 05–03.

30. Danielsen, F., Serensen, M. K., Olwig, M. F., Selvam, V., Parish, F., Burgess, N. D., Hiraishi, T., Karunagaran, V. M., Rasmussen, M. S., Hansen, L. B., Quarto, A., and **Suryadiputra**, N. 2005. The Asian tsunami: A protective role for coastal vegetation. *Science* 310: 643.

31. Geist, E. L., and **Parsons, T.** 2006. Probabilistic analysis of tsunami hazards. *Natural Hazards* 37: 277–314.

32. Atwater, B. F. 1999, updated 2012. Surviving a tsunami—Lessons from Chili, Hawaii, and Japan. *U.S. Geological Survey Circular 1187.*

33. Tsunami Safety Rules. 2017. National Ssunami Warning Center. ntwc@noaa.gov.

34. Valentine, D. W., Keller, E. A., Carver, G., Li, W.-H., Manhart, C., and **Simms, A. R.** 2012. Paleoseismicity of the southern end of the Cascadia Subduction Zone, Northwestern California. *Bulletin of the Seismological Society of America* 102(3): 1059–2078.