CHAPTER 3

▶ **KUSOL WETCHAKUL** offers prayers for the soul of his sister on the beach near Khao Lak, Thailand. She was swept out to sea by the tsunami of December 26, 2004, as she sold goods to tourists on a popular tourist beach north of Phuket. *(AP Images/David Longstreath)*

Tsunami

Learning Objectives

In this chapter we focus on one of Earth's most destructive natural hazards—tsunami. These devastating waves are commonly called "tidal waves," but they are not tidal; the name is misleading. Tsunami* are common in some coastal regions and very rare in others. For years, scientists attempted to persuade public officials to expand tsunami warning systems outside the Pacific Ocean basin, but it took the catastrophe of the Indian Ocean tsunami of 2004 for many governments and communities to take the tsunami hazard seriously. However, as often occurs after such catastrophes, translating increased awareness of a hazard into improved warning, preparedness, and mitigation is proceeding at a slow pace. This chapter explains tsunami and assesses the hazard they pose to people. Your goals in reading the chapter are to:

- Understand the process of tsunami formation and propagation.
- Understand the effects of tsunami and the hazards they pose to coastal regions.
- Know what geographic regions are at risk from tsunami.
- Recognize the linkages between tsunami and other natural hazards.
- Know what nations, regional and local governments, and individuals can do to minimize the tsunami hazard.

Prior to 2004, few people knew what the Japanese word ***tsunami*** meant. That changed in late December that year when close to 230 000 people were killed, many hundreds of thousands were injured, and millions were displaced in more than a dozen countries surrounding the Indian Ocean. With no warning system in place, residents of coastal areas around the Indian Ocean were picked up and swept away without notice by onrushing waves.

The source of the tsunami was a moment magnitude-9.1 quake just off the Indonesian island of Sumatra on Sunday morning, December 26, 2004 (Figure 3.1). The earthquake was the third largest in recorded history—only an earthquake off the coast of Chile in 1960 and another in Alaska in 1964 were larger.[1]

The December 26 earthquake was a subduction event, similar to earthquakes that happen at the Cascadia subduction zone off the coasts of British Columbia, Washington, and Oregon (see Chapter 2). It occurred along the fault that separates the Indo-Australia and Burma plates, west and northwest of the island of Sumatra. There, the Indo-Australia plate slowly moves eastward at an angle of about 10 degrees beneath the Burma plate along the Sunda Trench west of Thailand and Indonesia.

The Indo-Australia and Burma plates had been locked before the quake. Strain had accumulated along the subduction zone for more than 150 years as a result of convergence of the two plates, and the accumulated strain was released in less than a minute by the earthquake.

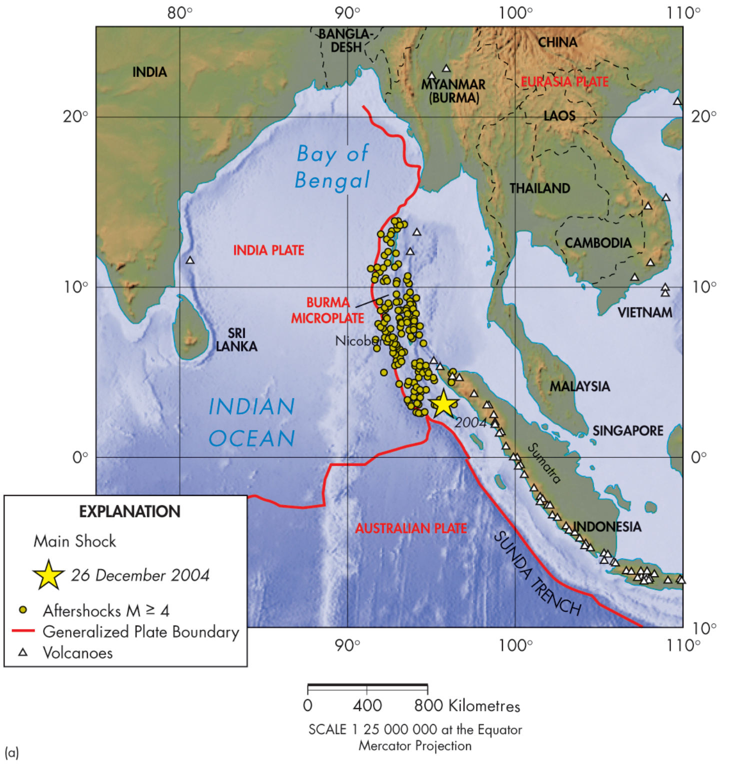
The fault separating the two plates ruptured over a distance of more than 1200 km. Measurements and computer models indicate that the seafloor slipped as much as 5 m vertically and 15 m horizontally along the fault. Parts of the Andaman and Nicobar islands were elevated by these movements, whereas land along the western coast of Sumatra subsided up to 2 m, moving parts of the coastline below sea level.

The movement on this fault displaced the entire mass of overlying water and produced a series of waves that moved rapidly away from the seafloor. They reached nearby Indonesian islands within minutes and other countries hours later (Figure 3.2).

Countries bordering the Indian Ocean did not have a tsunami warning system like the one in the Pacific, and people were, for the most part, caught by surprise.

Scientists at the Pacific Tsunami Warning Center in Hawaii identified the earthquake and recognized that it might trigger a tsunami, but were not immediately able to determine the size of the quake.[2] Once

* In keeping with the Japanese origin of the word, "tsunami" is both singular and plural.



(a)

FIGURE 3.1 GEOLOGIC SETTING OF THE GIANT SUMATRA EARTHQUAKE OF DECEMBER 26, 2004 The yellow star locates the epicentre of the quake. *(U.S. Geological Survey)*

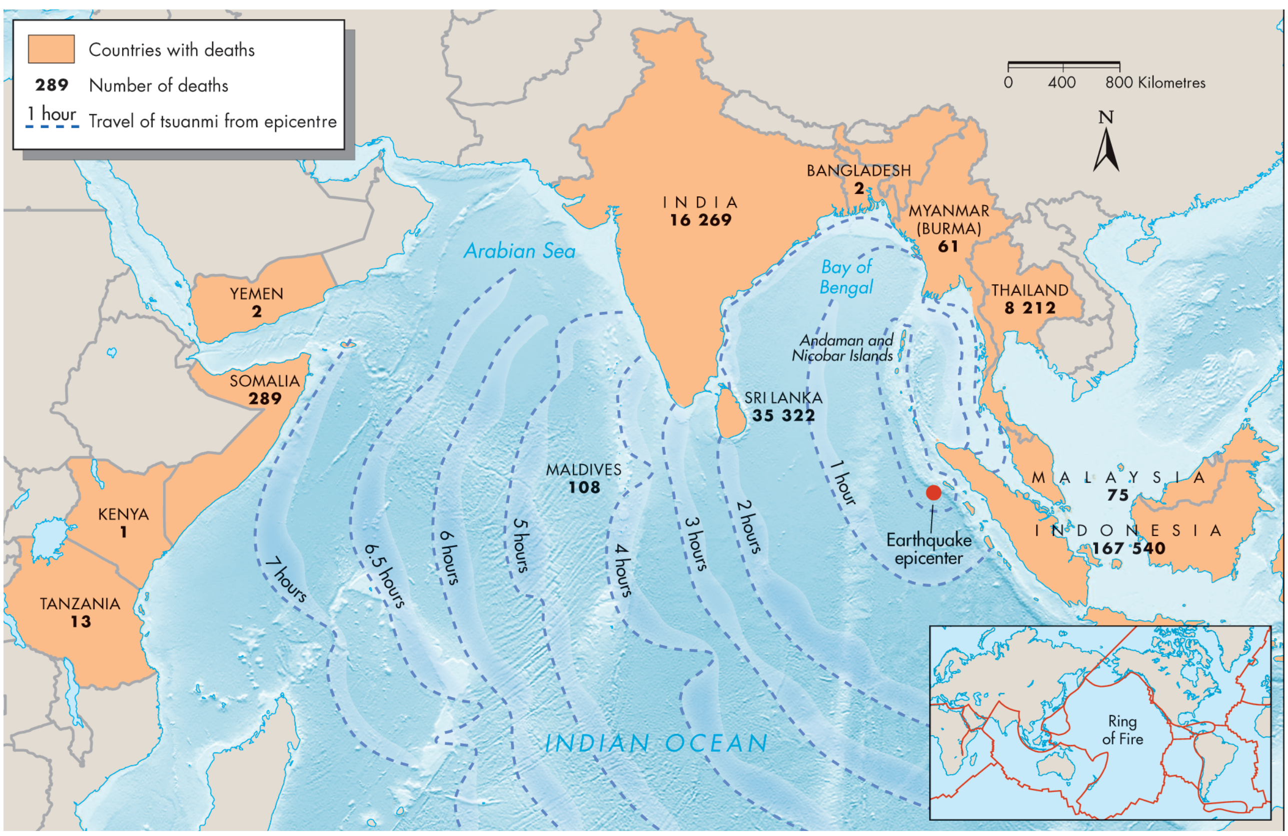
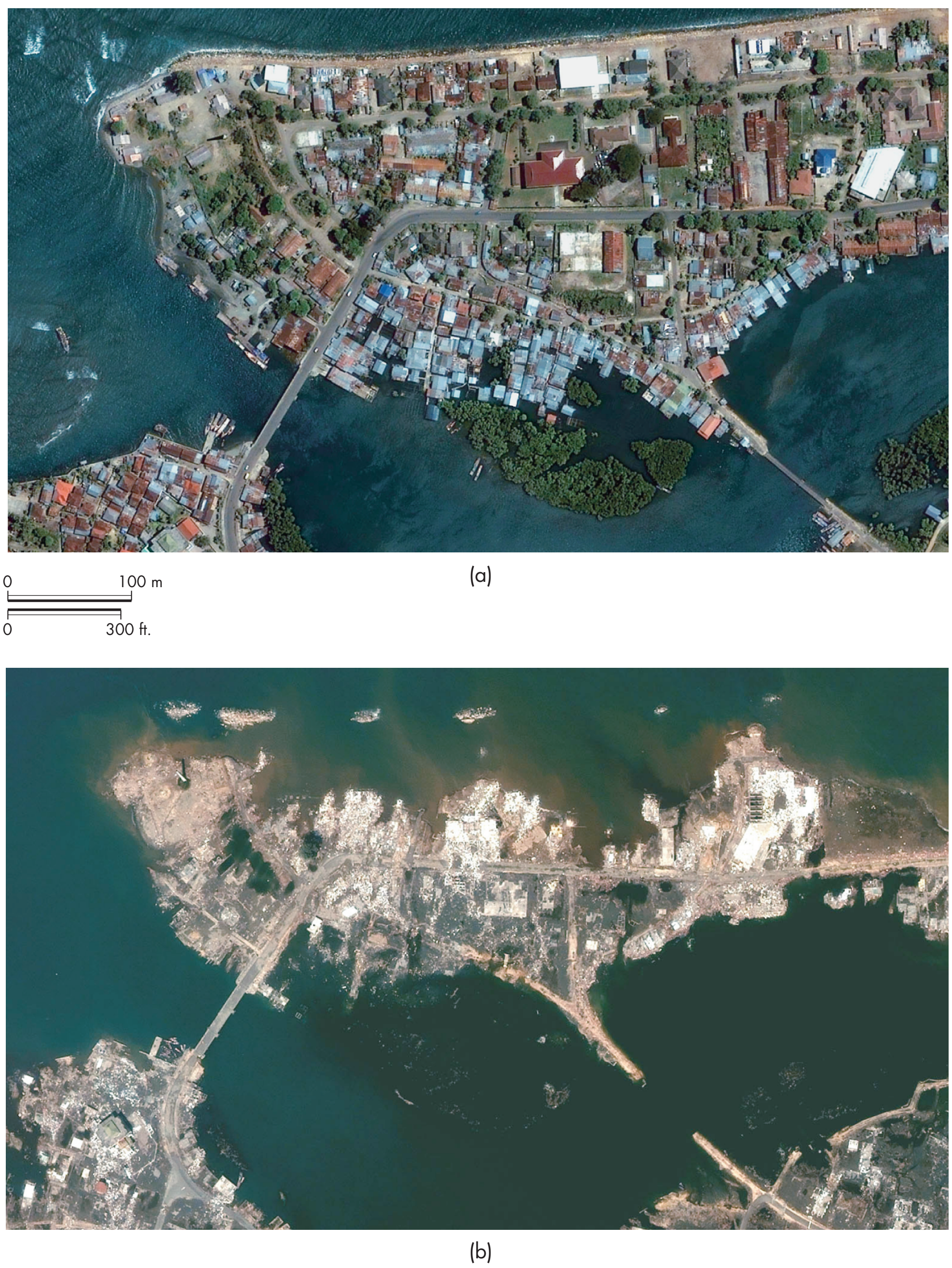


FIGURE 3.2 DEADLIEST TSUNAMI IN HISTORY The Indian Ocean tsunami of December 26, 2004, was by far the deadliest tsunami in history. It formed off the northwest coast of the island of Sumatra and spread damage and destruction across the Indian Ocean to the east coast of Africa. Dashed lines are the approximate positions of the lead wave or trough of the wave train at different times after the earthquake. *(Casualties summarized in Telford, J., and Cosgrave, J. 2006. "Joint evaluation of the international response to the Indian Ocean tsunami: Synthesis report." London: Tsunami Evaluation Coalition; Tsunami travel time data from NOAA)*

they recognized that a tsunami was likely, they contacted Indonesian colleagues and had the United States State Department relay their concerns to nations surrounding the Indian Ocean. By then, however, it was too late; even if their warnings had reached authorities in time, there was no system in place in the affected countries to notify coastal residents. Had an effective warning system existed, tens of thousands of lives could have been saved. The tsunami waves took more than seven hours to cross the entire Indian Ocean to the east African coast (Figure 3.2).

Deaths from the Indian Ocean tsunami probably exceeded 228 000, but the exact number will never be known. More than three-quarters of the deaths were in Indonesia, which suffered both the most intense earthquake ground shaking and the largest tsunami. Other countries with catastrophic loss of life included Sri Lanka, India, and Thailand. All houses, businesses, and other buildings in some areas were completely destroyed (Figure 3.3). Tourist areas of Thailand were also hit hard—several thousand visitors in tourist resorts at and around Phuket were killed (Figure 3.4).

People's reactions to the approaching waves differed. Some seemed mesmerized by them, whereas others recognized the danger and ran in panic. In most cases, however, it was too late. About 100 tourists and



◀ **FIGURE 3.3 BANDA ACEH BEFORE AND AFTER THE 2004 TSUNAMI** QuickBird satellite images of Banda Aceh, a provincial capital on Sumatra (a) on June 23, 2004, before the tsunami, and (b) on December 28, 2004, two days after the tsunami. All the buildings in this area were destroyed, including part of the bridge at the lower right. *(U.S. Geological Survey/DigitalGlobe)*

▲ **FIGURE 3.4 TSUNAMI STRIKES THAILAND** A huge wave surges into the tourist resort of Phuket on the morning of December 29, 2004. The tsunami killed nearly 10 000 people in Thailand, including almost 1000 foreign tourists and Thai citizens in Phuket. *(AP Photo/APTN)*

employees at a hotel in Phuket were saved when 10-year-old Tilly Smith sounded the warning. Tilly was on vacation with her family and recognized the signs of a tsunami from a lesson at her school in Oxshott, England, only two weeks before. She had learned that the sea sometimes recedes before the arrival of the first tsunami wave. Tilly observed an unprecedented withdrawal of the sea from the shore near her hotel and told her mother. When her mother didn't react, she started screaming that they were in danger and should get off the beach. Tilly finally convinced her family, as well as others, to return to the hotel. Shortly thereafter, the beach and hotel were hit by powerful waves. Her mother later admitted that she didn't know what a tsunami was. Her daughter's school lesson had saved her life and the lives of others.[3]

On the Nicobar Islands near the epicentre (Figure 3.2), Abdul Razzak, a port official, was awakened by the earthquake. He remembered from a *National Geographic* television program that tsunami were often produced by undersea quakes. Razzak sent two co-workers on a motorcycle to warn villages, and he ran to nearby areas yelling to people to go to the hills. About 1500 people obeyed the warnings and evacuated to the hillsides, where they watched in horror as the waves rolled in and destroyed their villages.[4]

On the Andaman Islands to the north, nearly 840 people in five Aboriginal tribes escaped injury. They had knowledge passed down from their ancestors about the relation between strong earthquakes and tsunami. In one instance, a Jarawa tribal elder led his people to the safety of a hilltop following the earthquake tremors after having been taught as a child to follow this procedure. Members of the Onge tribe also fled to the hills because their ancestors had taught them that if the level of the stream in their village suddenly dropped, it meant that the sea was pulling back and was "preparing to strike like a fist." In contrast, at least 48 recent settlers from the Indian mainland were killed on the Andaman Islands by the tsunami.[5] Long-time residents had a cultural memory of the natural hazard, whereas more recent immigrants did not.

In Khao Lak, Thailand, it was elephants, not people, who sounded the warning and saved lives.[6] Elephants started trumpeting about the time the earthquake occurred over 600 km to the west. Nearly an hour later, the elephants that were not taking tourists for rides broke loose from their strong chains and ran inland. Elephants carrying tourists ignored their handlers and climbed a hill behind the resort beach where close to 4000 people were soon to be killed. When handlers saw the tsunami in the distance, they got other elephants to lift tourists onto their backs with their trunks and proceed inland. The elephants did this even though they were only accustomed to people mounting them from a wooden platform. The elephants managed to take the tourists to safety before the tsunami arrived.

The Indian Ocean tsunami taught us several lessons:

- Tsunami are much less common in the Indian Ocean than in the Pacific Ocean, but the December 2004 event demonstrated that they can have catastrophic consequences.
- Effective tsunami warning systems are needed in all ocean basins where tsunami can occur: the Pacific Ocean, the Indian Ocean, the Atlantic Ocean, and the Caribbean, Mediterranean, and Black seas. These systems must be well funded and well maintained. They also must be reliable; at the time of the Indian Ocean tsunami, three of the six warning buoys in the Pacific were inoperative. In 2006, a new warning system became operational in the Indian Ocean.
- A high-tech tsunami warning system alone is not enough. Once a warning has been issued, emergency officials must rapidly and accurately transmit information and instructions to people in communities that may be affected. In addition, residents of those communities must respond in an appropriate way.

The responses of public officials and individuals to the tsunami warnings that were issued following large earthquakes off northern California in 2005 and Tonga in 2006 show that much more work needs to be done in regional and local planning for tsunami.

- Earthquake and tsunami education is necessary for people who live on or visit coastlines that are vulnerable. Warning systems, without education, are of limited value.

Like the port official on the Nicobar Islands, people who experience a large earthquake must understand that a tsunami could be coming, and they must immediately move to higher ground. Hundreds of kilometres away, in places where the earthquake was not felt, Earth still provided a signal of what was about to happen. The British schoolgirl in Thailand and people on the Andaman Islands realized that the sudden retreat of the sea was a signal of an impending tsunami. People must recognize these signs as warnings to move to higher ground immediately.

3.1 Introduction to Tsunami

In winter, tourists flock to the west coast of Vancouver Island, British Columbia, or the ocean beaches of Oregon and Washington to witness the full fury of a Pacific storm. Waves, metres high, rush ashore in turbulent fury, driven by storm-force winds blowing off the ocean. Yet powerful though they are, these waves pale in comparison to the waves of a large tsunami.

Tsunami are produced by the sudden displacement of ocean, lake, or river water.[7] Several types of events can trigger a tsunami, including a large earthquake, landslide, or explosive volcanic eruption, or an impact in the ocean of an asteroid or comet. Most disastrous tsunami are triggered by earthquakes or landslides. Earthquake, landslide, and volcanic triggers are discussed below; asteroid and comet impacts are considered in Chapter 13.

Recent examples of damaging tsunami include the following:[7,8]

- The 1755 (~**M** 9) Lisbon, Portugal, earthquake produced a tsunami that, along with the severe ground shaking and resulting fire, killed an estimated 20 000 people.
- The violent eruption in 1883 of Krakatoa in the Sundra Strait between Java and Sumatra produced a tsunami over 35 m high that destroyed 165 villages and killed more than 36 000 people.
- The 1946 (**M** 8.1) earthquake near the Aleutian Islands in Alaska produced a tsunami that killed about 160 people on the Hawaiian Islands.
- The 1960 (**M** 9.5) Chile earthquake triggered a deadly tsunami that killed 61 people in Hawaii after travelling 15 hours across the Pacific Ocean.
- The 1964 (**M** 9.2) Alaska earthquake was responsible for several 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 local tsunami that killed more than 2100 people.
- The 2004 (**M** 9.1) Sumatra earthquake generated a tsunami that killed almost 230 000 people.

Earthquake-Triggered Tsunami

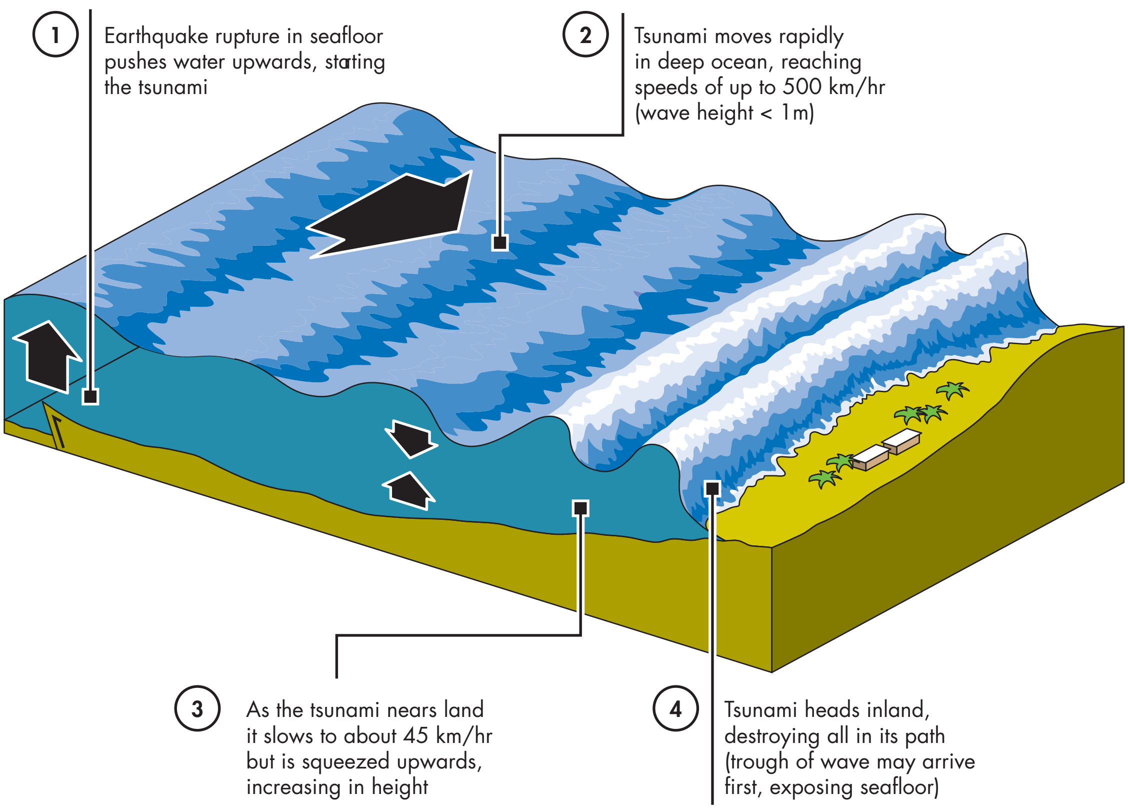
An earthquake can cause a tsunami by displacing the seafloor or the floor of a large lake, or by triggering a large landslide. Displacement of seafloor is probably the most common of these mechanisms and occurs when a block of Earth's crust moves rapidly up or down during an earthquake. In general, it takes an earthquake of magnitude 7.5 or larger to generate a damaging tsunami. The upward or downward movement of the seafloor displaces the overlying water and initiates a four-stage process that culminates with the tsunami rushing ashore, commonly far from the source (Figure 3.5):

- Displacement of the seafloor during an earthquake sets in motion oscillatory waves that transmit energy outward and upward from the source. These waves intercept the ocean surface and spread outward, much like ripples in a pond after it is struck by a pebble.
- In the deep ocean, the waves move rapidly and are spaced far 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 10m/sec^2. If we multiply the average ocean depth of 4000 m by 10m/sec^2 and then take the square root of that number, we arrive at a velocity of 200 m/sec, which is equivalent to a velocity of 720 km/h or about the maximum air speed of a jet passenger aircraft! In the deep ocean, the spacing between the crests of waves may be more than 100 km and the height of the waves is generally less than 1 m. You would not notice a passing tsunami in the deep ocean.
- As the tsunami nears land, both the water depth and the velocity of the tsunami decrease. Near land, the forward speed of a tsunami may be about 45 km per hour—too fast to outrun, but not nearly as fast as in the open ocean. The decrease in velocity is accompanied by a decrease in the spacing between wave crests and an increase in wave height.
- As the first tsunami wave approaches the shore, it transforms into a turbulent, surging mass of water that rapidly moves inland. Being several metres to several tens of metres high, the tsunami destroys everything in its path. During some tsunami, the trough of the wave arrives first, causing the sea to recede and exposing the seafloor.

A popular misconception is that a tsunami consists of a single immense wave that curls over and crashes on the shore. Instead, the waves are typically turbulent, onrushing surges of debris-laden water (Figure 3.4). In some instances, however, the level of the sea or lake simply rises very rapidly with no obvious turbulence. When one wave overtakes another, however, a steep wall of water, or bore, can be created. A tsunami also is not a single wave, but rather a series of waves separated by minutes to more than an hour.[9] Most of the deaths in Crescent City, California, during the great Pacific tsunami of 1964 occurred when residents who had returned to their homes after the first wave had withdrawn were swept away by a second, larger wave. The **run-up** of the tsunami is the maximum horizontal and vertical distances that the largest wave of a tsunami reaches as it travels inland. Once a wave has reached its farthest extent inland, the water returns back to the open ocean in a strong and often turbulent flow. A tsunami can also generate other types of waves, referred to as edge waves, that travel along the shore. The interaction between edge waves and later incoming tsunami waves can be complex. This interaction may produce wave amplification, causing the second or third wave of a tsunami to be larger than the first (see Survivor Story). Commonly, a series of tsunami waves will strike a coast over a period of several hours.[9]

Earthquakes can produce distant or local tsunami, and in some cases both. A **distant tsunami**, or *tele-tsunami*, travels thousands of kilometres across the open ocean and strikes remote shorelines with little loss of energy. Most such tsunami are produced by great subduction earthquakes. A **localt sunami** affects shorelines near the source of the earthquake. The distance of the affected shoreline from the source can be a few kilometres or 100 km or more. Great subduction earthquakes can produce both distant and local effects.

Tsunami generated by nearby earthquakes can be especially deadly because they arrive at the shoreline soon after the quake, with little or no warning. In 1993, an **M** 7.8 earthquake in the Sea of Japan triggered a tsunami that struck a small town on Okushiri Island, Japan, killing 120 people and causing US$600 million in property damage. The wave ranged from 15 to 30 m.[10] The tsunami arrived only two to five minutes after the earthquake, so no warning could be issued.



▲ **FIGURE 3.5 FORMATION AND DEVELOPMENT OF A TSUNAMI** Idealized diagram showing the process of how a tsunami is produced by an earthquake and travels away from the source. *(United Kingdom Hydrographic Office))*

SURVIVOR STORY

Christine Lang (Figure 3.6), a grade-two teacher and accomplished swimmer, left rainy Vancouver for a Christmas vacation in December 2004. What she thought would be the trip of a lifetime became a catastrophe in a Thai tourist resort on Phi Phi Island. Christine was one of more than 2000 tourists enjoying the Christmas break there when a tsunami, powered by a 9.1-magnitude earthquake off the coast of Sumatra, swept ashore.

On the morning of December 26, Christine and a friend were strolling down the main street of the tourist resort on Phi Phi Island in Thailand when something strange happened. An older Thai woman raced from a jewellery store, screaming hysterically and running inland away from the beach. Almost immediately, clerks sprinted from the currency exchange service. Confused, Christine stopped in her tracks, "What's going on?" she asked her friend.

Other shopkeepers filled the street, abandoning their businesses. As they darted past her, Christine realized they were not only running from their shops, but also from the sea. She looked toward the beach, but a row of buildings blocked her view.

Christine was beset by questions. "What's happening? Is there a fire? Has a boat crashed into the pier? Is this a terrorist attack? What are these people running from?"

Screams filled the air. More and more people joined the mob. A German man wrenched Christine's arm and screamed, "Run!" She and her friend began to race inland with the crowd. They passed the Phi Phi Hotel, the only high building on the island, and arrived at an abandoned intersection. At that moment, a monstrous wall of water, two storeys high, barrelled toward them. Christine tried to escape by running toward the Phi Phi Hotel but was caught in the turbulent water.

She braced herself, teeth and fists clenched, yelling, "No! No! No!" The tsunami pulled her in every direction. "I felt like a rag doll in a washing machine," she said.

▲ **FIGURE 3.6 TSUNAMI SURVIVOR** Christine Lang was engulfed in the great Indian Ocean tsunami when it struck Phi Phi Island, Thailand, on December 26, 2004. She survived the terrifying ordeal. *(Photo: Suzanne Munroe. Courtesy of Christine Lang)*

She was slammed against a building. Although underwater, she could hear the screech of metal and the crack of wood timbers. She struggled to reach the surface, but was pinned beneath debris. Aching for air, she realized she was drowning. Thoughts raced through Christine's mind: "I don't want to die. Not now. There's so much more I want to do. I can't believe I'm going to die on my Christmas vacation! I'm really drowning. How can this be? I need air. I need air."

A second rush of water blasted into Christine's death trap, freeing her arms and legs. Her body was swept forward like a torpedo. She slipped into unconsciousness, but awoke underwater and spotted a circle of light coming from above. Instinct and adrenaline kicked in, and she swam furiously toward the halo in the distance. Her head broke the surface as she gulped for air. Oxygen filled her lungs. "I can breathe," Christine screamed, "I'm not going to die here!"

Landslide-Triggered Tsunami

Some landslides that happen on the seafloor or in a lake can produce tsunami. Large landslides that fall from mountain slopes into a large body of water can also generate tsunami. In many cases, these landslides are triggered by earthquakes. An example is the deadly tsunami in July 1998 on the north shore of New Guinea. The tsunami occurred on the heels of an M 7.1 quake, which was centred beneath the seafloor north of the island. The earthquake was felt at Sissano Lagoon, 50 km away, and shortly thereafter a tsunami arrived with waves up to 15 m high. Coastal villages were swept away, leaving 12 000 people homeless and over 2000 dead.[11,12] A submarine landslide triggered by the earthquake caused the tsunami. The event highlighted the devastation that can result from a tsunami produced by a nearby earthquake and submarine landslide.[8,12] The earthquake alone probably would not have generated a large tsunami.

A similar event occurred on the east coast of Canada in November 1929. An **M** 7.2 earthquake at the southern edge of the Grand Banks, 250 km south of Newfoundland, triggered a huge submarine slump that in turn set off a tsunami.[13,14] The tsunami propagated across the Atlantic Ocean, registering on tide gauges as far away as South Carolina and Portugal. It damaged more than 40 coastal communities and claimed 27 lives in Newfoundland (Figure 3.7). Burin Peninsula was hardest hit. Three waves thundered up narrow channels and into bays over a half-hour period on the evening of November 18. The tsunami lifted small boats and schooners, snapping anchor chains and tossing the craft onshore or engulfing them. Houses floated from their foundations; some were splintered, and others were swept back and forth by the flooding and ebbing waters. Damage was made worse by the fact that the tsunami arrived near the peak of a very high tide. Maximum wave heights in communities that suffered the greatest damage ranged from 3 to 7.5 m.

The most spectacular landslide-generated tsunami of the twentieth century occurred on July 10, 1958, at Lituya Bay, Alaska.[15] A large earthquake triggered a rockslide at the head of the bay. The rockslide plunged into the bay and displaced seawater that ran up the opposite valley wall to an elevation of 525 m, destroying the forest in its path (Figure 3.8). A 30-m high wave surged 11 km to the mouth of the bay, where it swept away two fishing boats anchored inside a low, forested spit. One of the two boats, the *Badger*, was swept over the spit and into the ocean beyond. The crew of the *Badger* survived to tell their harrowing story.

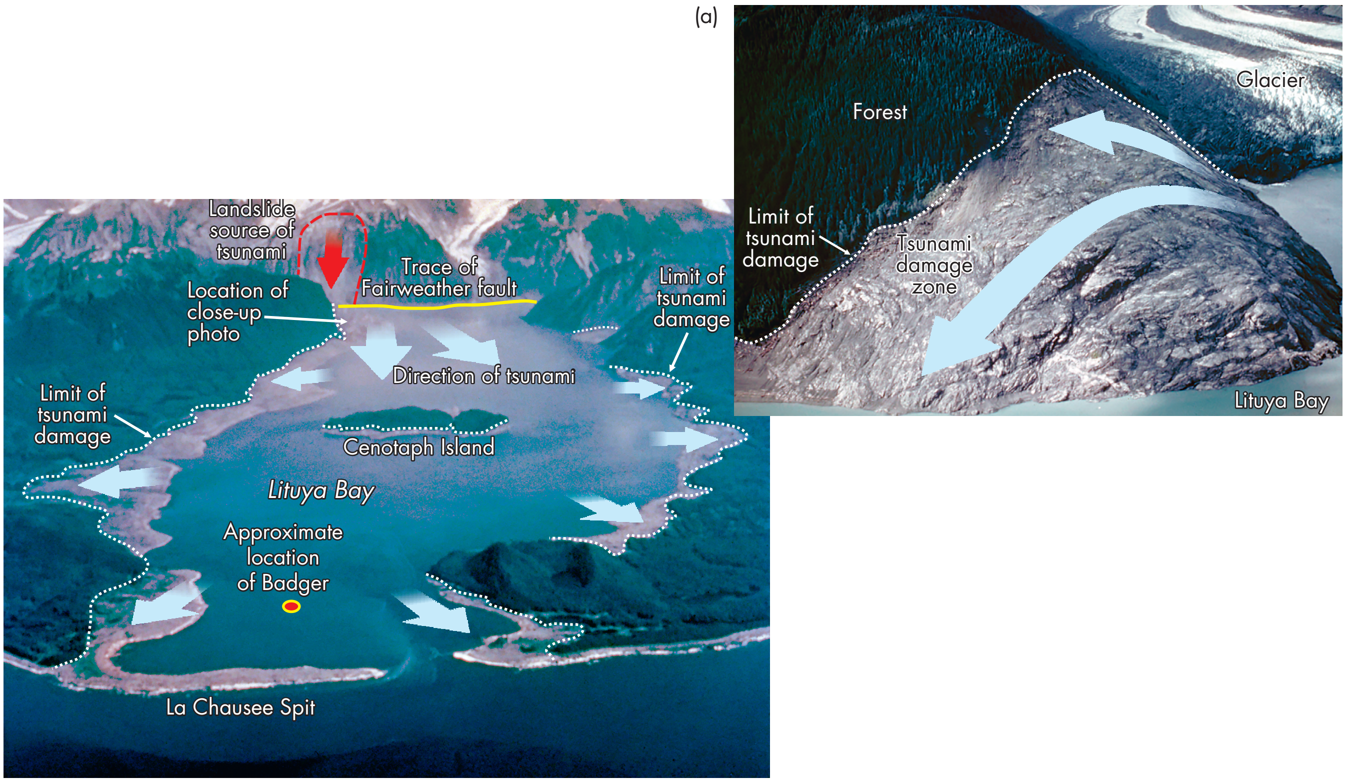
Geologists have suggested that even larger tsunami than the 1958 Lituya Bay event have been produced by collapses of the flanks of volcanoes on Hawaii in the Pacific Ocean and the Canary Islands in the Atlantic Ocean.[16,17] Massive hummocky landslide deposits have been mapped on the seafloor adjacent to the Hawaiian Islands; some of them extend dozens of kilometres from the shore. The deposits were emplaced during the collapse of the flanks of Mauna Loa and Kohala, two of the large volcanoes on Hawaii. Geologists infer that these collapses triggered large tsunami. In support of this idea, they note possible tsunami deposits on the slopes of Hawaii and Lanai, far above the present shore. The deposits contain fragments of coralline limestone that otherwise occur only at and below sea level. The inference is that the fragments were deposited by waves up to several hundred metres high. The Hawaiian Islands would be devastated if an event of this type were to occur today. It is unlikely, however, that distant parts of the Pacific Rim would be affected in the same way. A tsunami generated by a landslide, even a very large one, attenuates significantly over distances of thousands of kilometres, and wave run-ups on the west coast of North America would not be catastrophic.

Volcano-Triggered Tsunami

Tsunami caused by volcanic eruptions are much less common than earthquake- or landslide-triggered tsunami. However, the second most deadly tsunami in history was caused by a huge eruption of Krakatoa (also spelled Krakatau), an active volcano in the Sunda Strait between the Indonesian islands of Java and Sumatra. The massive eruptions on August 26 and 27, 1883, were among the largest in recorded history.[18,19] They produced nearly 21 km^3 of fragmented rock and ash and destroyed two-thirds of the island of Krakatoa. The cataclysmic explosion, which was heard as far as 5000 km away, triggered a tsunami that destroyed 165 villages along the shores of Sunda Strait, damaged 132 others, and killed over 36 000 people.

◄ **FIGURE 3.7 TSUNAMI STRIKES NEWFOUNDLAND** Coastal communities on Burin Peninsula bore the brunt of a 1929 tsunami. This photograph shows buildings in Lord's Cove that were tossed and smashed. *(Photo by Harris M. Mosdell, from the W. M. Chisholm collection, provided by A. Ruffman, GeoMarine Associates, Halifax))*

(a)



(b)

▲ **FIGURE 3.8 LITUYA BAY TSUNAMI** (a) The rocky headland directly west of the landslide at the head of Lituya Bay. Water displaced by the landslide surged up this slope, removing forest more than 500 m above sea level. (b) Photograph of Lituya Bay, Alaska, taken shortly after the tsunami of July 7, 1958. The prominent trimline (dotted line) delineates the upper limit of the tsunami. Forest below this line was obliterated by the surging waters. *(Clague, J., C. Yorath, R. Franklin, and B. Turner. 2006.* At Risk: Earthquakes and Tsunamis on the West Ccoast. *Vancouver, BC: Tricouni Press; photos by U.S. Geological Survey, Donald Miller) pp. 142–143*

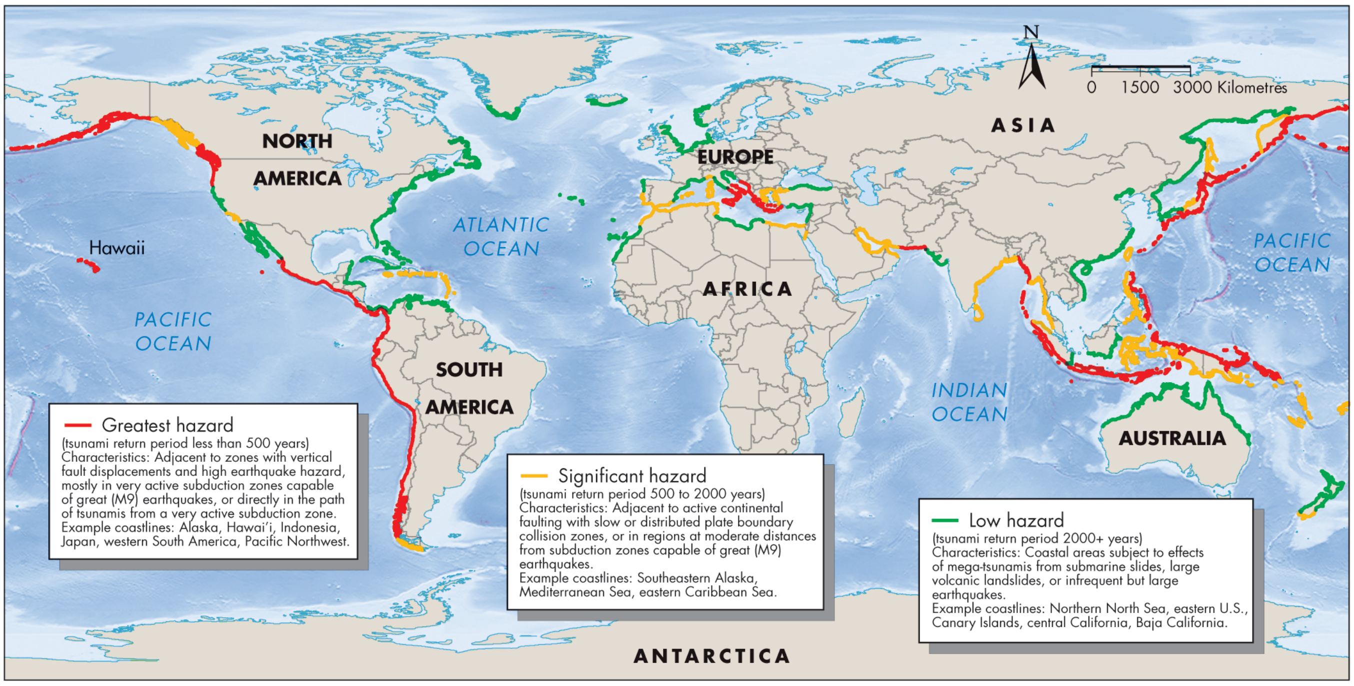
Smaller tsunami can be triggered by large lahars and pyroclastic flows (see Chapter 4) that enter the sea during explosive eruptions. These tsunami rapidly attenuate, or decrease in size, with distance from the volcano and thus are less hazardous than tsunami caused by large earthquakes. Several active volcanoes in the Aleutian Arc in southern Alaska could produce small tsunami by these mechanisms.

3.2 Regions at Risk

Although all ocean and some lake shorelines could experience a tsunami, some coasts are at much more risk than others due to their location with respect to earthquakes, landslides, and volcanoes. Coasts in proximity to a major subduction zone, or directly across the ocean basin from a subduction zone capable of generating **M** 9 earthquakes, are at greatest risk. About 85 percent of recorded tsunami have been in the Pacific Ocean because of their association with large earthquakes at subduction zones that surround much of the Pacific.[20] Areas at greatest risk from tsunami in the Pacific Basin are Japan, Kamchatka, Hawaii, islands in the southern and west Pacific, Chile, Peru, Mexico, and the northeast Pacific coast from Alaska to northern California (Figure 3.9). Other regions judged to have a high risk include parts of the Mediterranean and the eastern Indian Ocean.

Tsunami generated by underwater landslides unrelated to earthquakes and by the flank collapse of volcanoes are less common, but they still represent a hazard to the east and west coasts of the United States and Canada, and to Hawaii and Alaska.

The Pacific coast of North America has been struck by one large tsunami during historic time, and geological research has provided evidence for many others over the past few thousand years. The Alaska earthquake of March 27, 1964, the third largest of the twentieth century (**M** 9.2), was



▲ **FIGURE 3.9 GLOBAL TSUNAMI HAZARD** Map of the relative hazard of coastlines to experience a tsunami that is at least 5 m high. This map is generalized because tsunami run-up differs considerably over short distances depending on the form of the seafloor directly offshore and with the topography and vegetation landward of the beach. *(Modified from "Risk Management Solutions." 2006. 2004 Indian Ocean Tsunami Report. Newark, CA: Risk Management Solutions, Inc.)*

responsible for tsunami that killed 130 people, some as far away as California. The main tsunami swept southward across the Pacific Ocean at a velocity of about 830 km/h, reaching Antarctica in only 16 hours. It caused extensive damage on Vancouver Island, B.C., and claimed lives as far south as Crescent City in northern California. The town of Port Alberni, at the head of Alberni Inlet on Vancouver Island, was particularly hard hit.[21] Three main waves struck Port Alberni over a three-hour period on the morning of March 28. The second and most destructive wave surged 1 km inland, forcing the police to use boats to rescue guests from the upper floor of a local hotel. About 260 homes in Port Alberni were damaged by this tsunami, 60 extensively.

The risk that residents of the west coast of Canada and the United States face from tsunami has been investigated by geologists and geophysicists in both countries. The research involves excavation and radiocarbon dating of tsunami deposits, dating of the rings of trees killed by tsunami, computer modelling of tsunami propagation and run-up, searches of historical records in Japan, and study of the oral histories of Aboriginal peoples. Geological studies in Washington State and a search of Japanese historical records have shown that a huge tsunami occurred in the North Pacific Ocean on the evening of January 26, 1700, and that the tsunami was triggered by an **M** 9 earthquake at the *Cascadia subduction zone*, just off the west coast of British Columbia, Washington, and Oregon (Figure 3.10).[22,23,24] The earthquake and ensuing tsunami were eerily similar to the events in the Indian Ocean on December 26, 2004.

Some places, such as Japan and Hawaii, experience frequent tsunami. Honshu, the largest of the Japanese islands, is struck by a 10-m tsunami once every 10 years, on average.[25] Historical records in Hawaii dating back to 1813 indicate that a measurable tsunami occurs there about once every two years.[26] In contrast, other areas, such as the Gulf of Mexico and the Atlantic coast of the United States, have had no significant tsunami in historic time.

3.3 Effects of Tsunami and Linkages with Other Natural Hazards

Tsunami have both primary and secondary effects. Primary effects are related to the impact of the onrushing water and its entrained debris, and to the resulting flooding and erosion. The energy of the fast-moving, turbulent water is sufficient to tear up beaches, most coastal vegetation, and houses and other buildings. These effects diminish with distance from the coast. Much of the damage to both the landscape and human structures results from the return of water to the ocean. What is often left behind is bare or debris-covered ground (Figure 3.11). The majority of tsunami deaths are

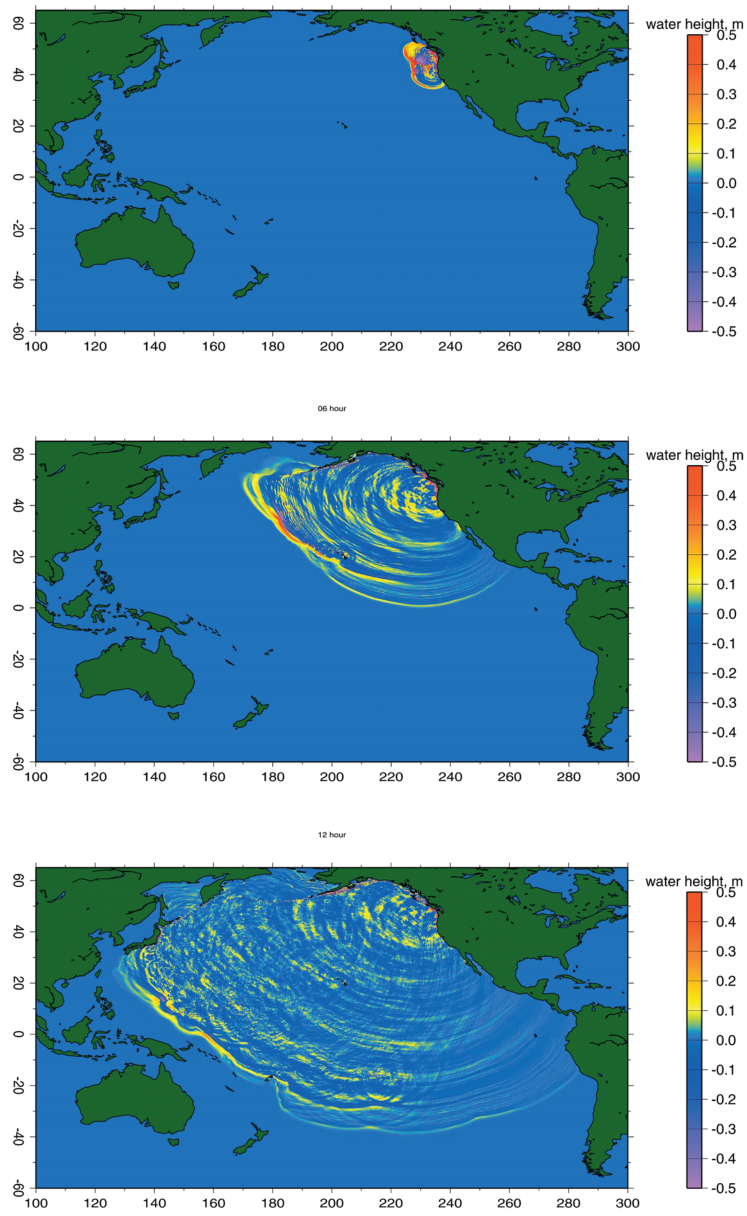


FIGURE 3.10 NORTH PACIFIC TSUNAMI OF JANUARY 1700 This output from a computer model of the tsunami triggered by the giant earthquake at the Cascadia subduction zone on January 26, 1700, is based on arrival times and run-up at several sites in Japan. The panels show wave height and location, from top to bottom, 1 hour, 6 hours, and 12 hours after the quake. *(Courtesy of Kenji Satake)*

from drowning. Death and injury also result from physical impact, either from floating debris or from being washed into stationary objects such as buildings or trees.

Secondary effects of tsunami are those that occur in the hours, days, and weeks following the event. Immediately after a tsunami, fires may start in developed 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. Outbreaks of disease may occur when people who have survived the tsunami come into contact with polluted water and soil. In the case of the 2004 Indian Ocean tsunami, public health officials were initially concerned that there would be outbreaks of waterborne illnesses, such as malaria and cholera, but there were few cases of these diseases due to quick action by relief agencies and saltwater inundation of mosquito breeding grounds. Loss of shelter exposes people to insects, extreme weather, and other environmental hazards.[27] The trauma of a tsunami can produce long-lasting mental health problems in survivors.

There are several linkages between tsunami and other natural hazards. As mentioned previously, tsunami are closely linked to offshore earthquakes, some landslides, explosive eruptions of island volcanoes, and asteroid and comet impacts. Coastal communities near the epicentre of a tsunami-producing earthquake experience casualties and property damage from both ground shaking and the tsunami itself. Powerful tsunami waves can dramatically change a coastline through erosion and sediment deposition, as illustrated by the 2004 Indian Ocean tsunami. A combination of tsunami erosion and coseismic subsidence drastically altered the shoreline near Banda Aceh (Figure 3.3).

(a)

(b)

▲ FIGURE 3.11 **DAMAGE AND DEBRIS FROM THE 2004 INDONESIAN OCEAN TSUNAMI** (a) In some areas, the tsunami removed all but the sturdiest 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)*

3.4 Natural Service Functions of Tsunami

Tsunami provide few benefits, but they may leave thin sheets of sand inland from the shore that are advantageous to some coastal ecosystems and contribute to coastal dunes. Ongoing and future studies of landscape and ecosystem changes resulting from the 2004 Indian Ocean tsunami may reveal other natural service functions.

3.5 Minimizing the Tsunami Hazard

Like many natural hazards, tsunami cannot be prevented. The damage they cause, however, can be greatly reduced through a variety of actions, including:[28]

- Detection and warning
- Structural control
- Construction of tsunami inundation maps
- Land use
- Probability analysis
- Education
- Tsunami readiness

Detection and Warning

The first warning of a possible tsunami comes when an earthquake of **M** 7.5 happens in an offshore area. Not all such earthquakes produce tsunami, but few that are smaller than this magnitude do. We are able to detect tsunami in the open ocean and accurately estimate their arrival time to within a few minutes. The travel times of tsunami produced by earthquakes off Japan, Kamchatka, and Alaska are sufficiently long that low-lying coastal areas of British Columbia, Washington, and Oregon can be evacuated following alerts.

Three types of warning systems exist for tsunami in the Pacific Ocean: a Pacific-wide system (the Pacific Tsunami Warning Center) located in Hawaii (Figure 3.12b); regional systems, including the West Coast and Alaska Tsunami Warning System, located in Alaska; and local systems in Chile and Japan.[28] The three systems use a network of seismographs to provide real-time estimates of earthquake magnitude and location before issuing a tsunami warning. The warning centres then use more than 100 coastal tidal gauges and sensors connected to floating buoys to verify that a tsunami was indeed produced. The bottom sensors, known as *tsunameters*, detect small changes in the pressure exerted by the increased volume of water as a tsunami passes over them. They transmit the pressure measurements to buoys at the ocean surface, which relay the data to NOAA's Geostationary Operational Environmental Satellite (GOES). The satellite in turn relays the information back to Earth, where it is sent through NOAA communication systems to warning centres (Figure 3.12a). After the Indian Ocean tsunami, similar systems were established in the Indian and Atlantic oceans, including warning sensors for Puerto Rico and the east coasts of the United States and Canada. By international agreement, information from the United States' warning system is shared with warning centres in 23 other countries. In Canada, tsunami information is disseminated through the British Columbia Provincial Emergency Program.

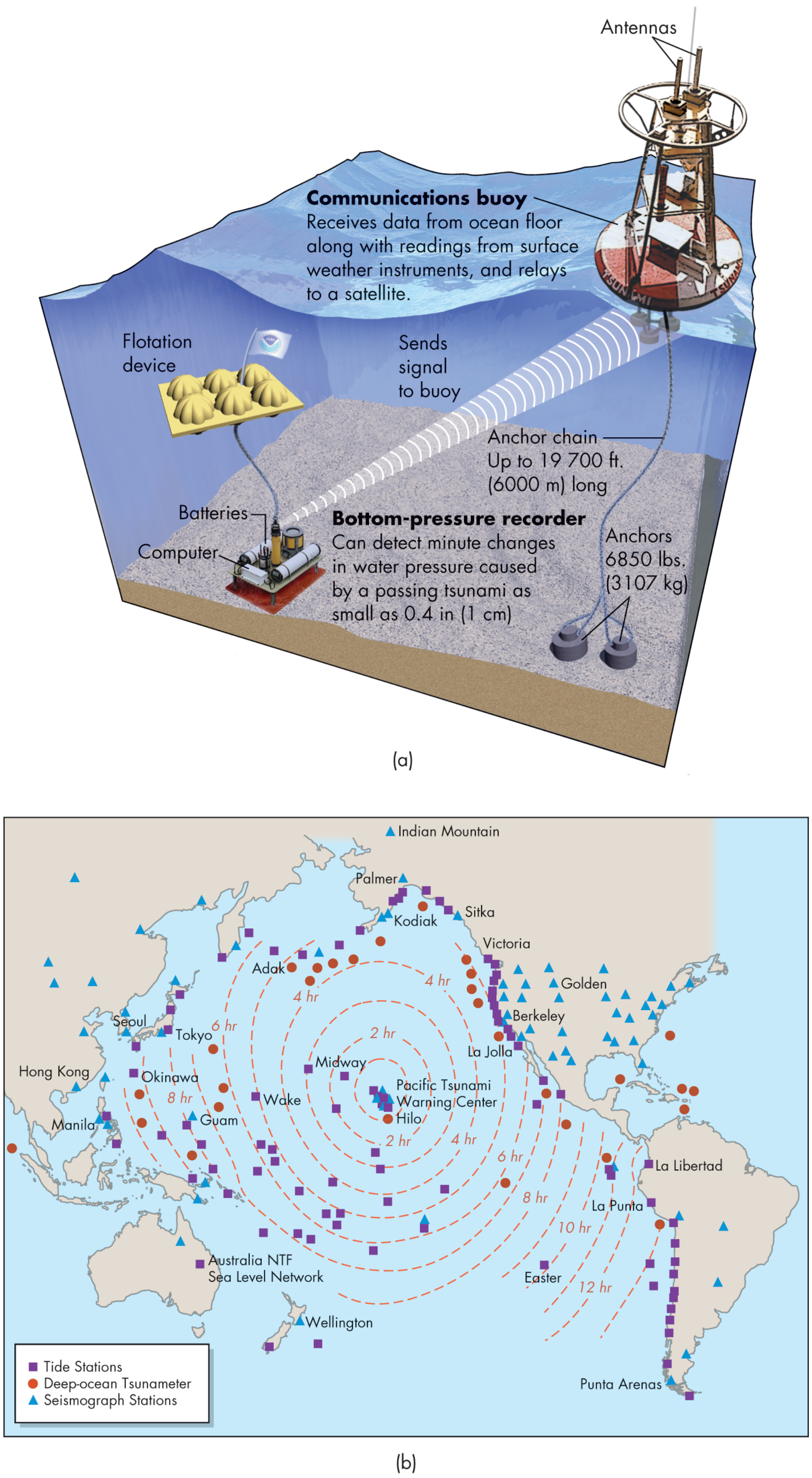


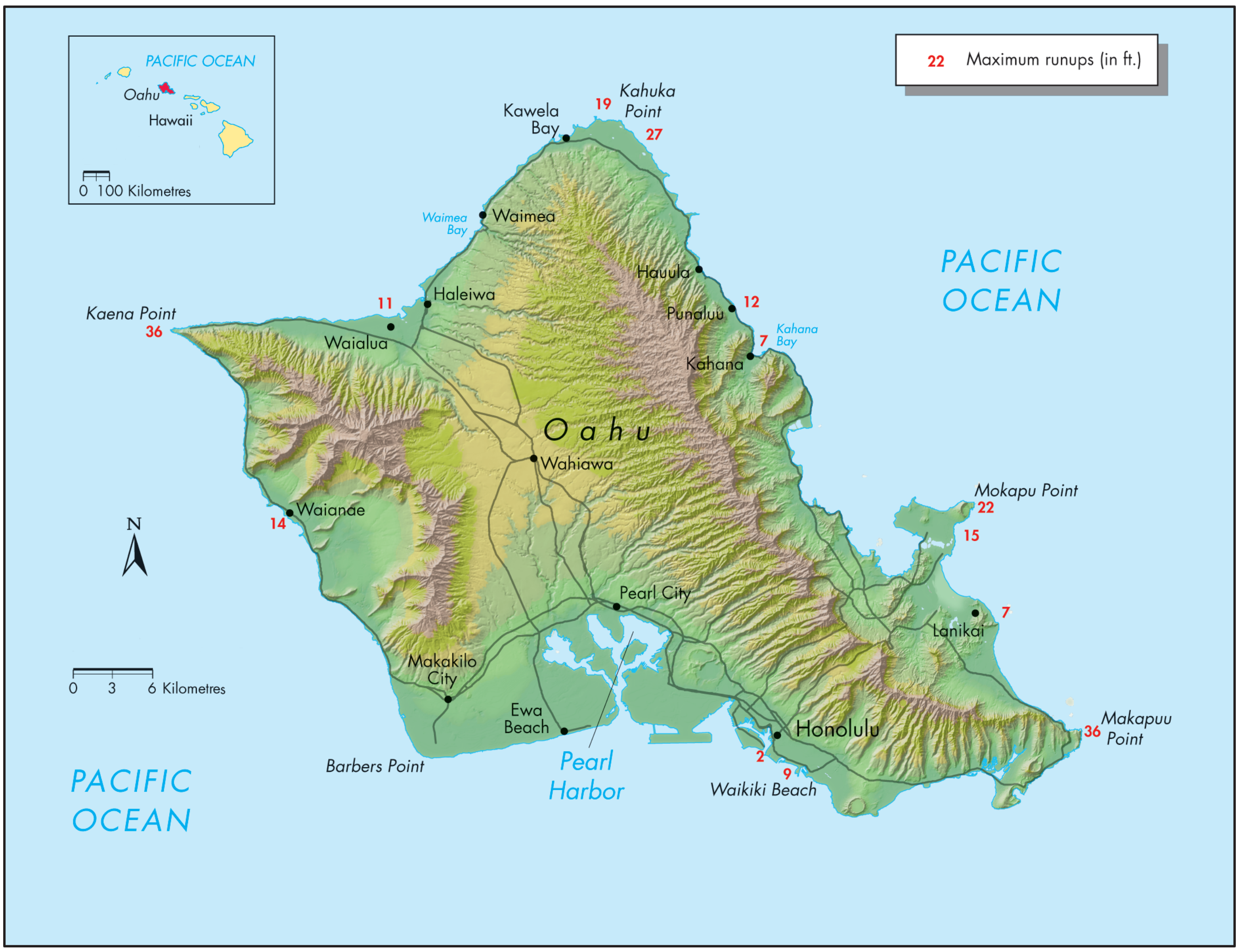
FIGURE 3.12 TSUNAMI WARNING SYSTEM IN THE PACIFIC (a) A bottom sensor detects a tsunami and a tethered buoy transmits the information to a tsunami warning system. (b) The Pacific Tsunami Warning Center in Hawaii acquires information from three sources: a network of seismographs, more than 100 tide gauges, and 30 DART ocean-bottom pressure sensors linked to surface buoys. The dashed lines show the time it would take a tsunami to reach Hawaii from locations in the Pacific Ocean. *(Modified after NOAA National Weather Service)*

When the source of the tsunami is less than about 100 km away, there generally is insufficient time to warn and safely evacuate people, and no warning is possible when a local landslide triggers a tsunami. People close to the source, however, will probably feel the earthquake and can immediately move to higher ground. Certainly, if one observes the water receding, it is a sign to run inland or to higher ground if possible. Some coastal communities in British Columbia, Hawaii, Alaska, Washington, Oregon, California, Japan, New Zealand, and elsewhere also have warning sirens to alert people that a tsunami may soon arrive.

Structural Control

Tsunami that are even a metre or two high have such power that houses and small buildings are unable to withstand their impact.[7] However, larger structures, such as high-rise hotels and critical facilities, can be engineered to greatly reduce or minimize the impact. For example, the cities of Hilo and Honolulu in Hawaii have special requirements for construction of buildings in the tsunami run-up zone. Elevation of buildings and other types of flood proofing (for example, installing seals for basement windows and bolting houses to their foundations) provide protection where water depths are 1 m or less and currents are not strong. Structures can be elevated to higher levels to provide greater protection, but the cost may be prohibitive. Some houses near the coast on the Hawaiian Islands have been built on pilings, their floors elevated 2 m to 3 m above ground level to allow water to move freely beneath them. However, the current building codes and guidelines in most jurisdictions exposed to tsunami do not adequately address the effects of tsunami on buildings and other structures.[29]

Dykes and walls can be constructed to prevent waves from reaching threatened residential and commercial areas. However, these barriers are expensive and should be built to the highest possible elevation that can be reached by a tsunami.[21] In some cases, offshore barriers can deflect tsunami waves or lessen their energy before they reach the shore. Again, these are expensive structures and may provide only limited protection. They are economically feasible only



▲ **FIGURE 3.13 TSUNAMI RUN-UP ON OAHU** Map of Oahu, Hawaii, showing vertical run-up of the 1946 tsunami that originated from an earthquake in the Aleutian Islands, Alaska. Values are in feet. *(Modified after Walker, D. "1994.Tsunami facts." SOEST Technical Report 94-03. School of Ocean and Earth Science and Technology)*

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where large populations are at risk and where the threatened shoreline is at the head of a bay or inlet. Japan has constructed offshore breakwaters and onshore concrete walls to protect many of its coastal towns and cities from tsunami.

Tsunami Inundation Maps

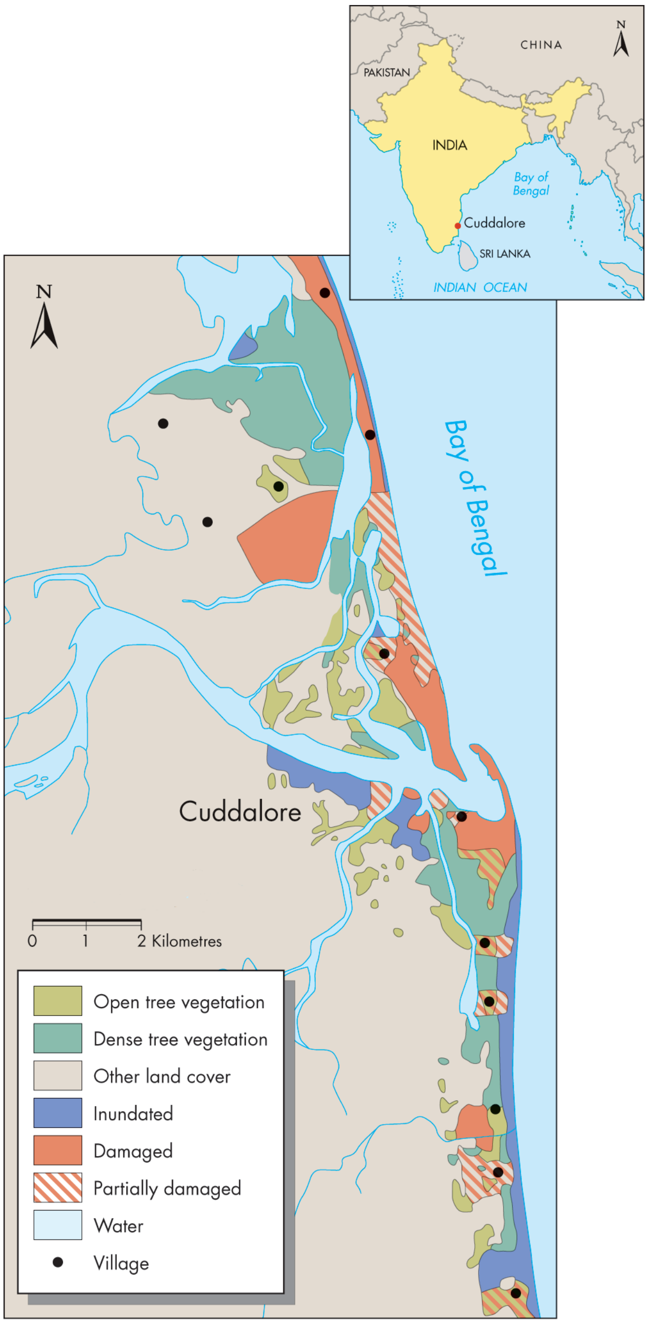
It is a fairly straightforward procedure to produce a run-up or inundation map after a damaging tsunami. Such a map was prepared for the island of Oahu, Hawaii, following the 1946 Aleutian tsunami (Figure 3.13). It illustrates the tremendous variability of run-up height in a typical tsunami—from 0.6 m in Honolulu to 11 m at Kaena Point and Makapuu Point at the northwest and southeast corners of the island.

Risk to coastal communities can be assessed by determining the frequency and size of past tsunami from historical records and geological data. Maximum tsunami heights along a reach of the coast are estimated using computer-generated models and from the distribution of historic and prehistoric tsunami deposits. Maps can then be produced showing areas likely to be inundated by tsunami of different sizes. The maps may be used to guide or restrict development in tsunami-prone areas and to educate people living in these areas about the risk they face. Computer models also provide estimates of tsunami arrival times, currents, and forces on structures. The maps can be produced by communities to show areas that are likely to be inundated by tsunami of different sizes as an aid in emergency planning. Many American and Canadian communities, for example Ucluelet and Port Alberni on Vancouver Island, have such maps.

Land Use

Following the 2004 Indian Ocean tsunami, scientists discovered that tropical vegetation played a role in determining tsunami damage. The destruction along shorelines that experienced the highest waves was near total (Figure 3.14). Damage in areas where the waves were smaller, however, was

◀ **FIGURE 3.14 TSUNAMI DAMAGE TO TREES** IKONOS satellite images of a low-lying coastal area (a) before and (b) after the 2004 Indian Ocean tsunami. Note the near-total loss of vegetation by the tsunami. *(KRONOS satellite images courtesy of Centre for Remote Images, Sensing and Processing (CRISP) and GeoEye. Copyright 2007. All rights reserved)*



▲ **FIGURE 3.15 TREES PROVIDE SOME PROTECTION FROM TSUNAMI** This map shows vegetation cover prior to the 2004 tsunami and post-tsunami damage to the land and villages in the Cuddalore District of India. *(Modified after 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)*

more variable—some coastal villages were destroyed, whereas others suffered much less damage. Many villages that were spared were protected from the energy of the tsunami by either coastal mangroves or several rows of plantation trees.[30] Land-use and land-cover studies have documented the advantages of locating villages inland from a protective buffer of coastal vegetation (Figure 3.15). Yet coastal mangroves are commonly not valued and are removed and replaced by homes, tourist hotels, and other buildings. These structures are generally located close to the beach and thus are vulnerable to tsunami attack. Although it may not be practical to move tourist areas inland, protective vegetation could be retained or planted between the development and the ocean to provide protection from at least small tsunami.

Probability Analysis

The risk of a particular event can be defined as the product of the probability of the event and its consequences, should it occur. Thus determining the likelihood or probability of a tsunami is an important component of risk analysis. A hazard analysis may rely on evidence from past tsunami rather than attempt to calculate the probability of a future event. This aim of this approach is simply to derive a tsunami inundation map for use in identifying evacuation routes. In contrast, probability analysis provides information not only on the likelihood of a tsunami, but its location, the extent of the run-up, and the possible severity of damage. The approach taken in a probabilistic analysis of tsunami hazard involves:

- Identification and specification of potential earthquake sources and their associated uncertainties.
- Specification of factors that will attenuate or reduce tsunami waves as they travel from the source area.
- Statistical analysis of past tsunami, their sources, attenuation, and other factors, similar to what is done in an earthquake hazard analysis.

The probabilistic approach to tsunami hazard assessment is still being refined and improved. One difficulty is that tsunami at a particular location are generally rare events. If past events are too rare to develop a robust frequency–magnitude relation, a statistical technique known as Monte Carlo simulation can be used. The objective of the simulation is to determine tsunami return periods and probabilities for both distant and local sources. The technique selects a random sample of earthquakes of different magnitudes and determines the tsunami that would be propagated by each of these quakes. A mathematical model is then constructed based on the simulated events to estimate tsunami amplitude or run-up along a particular coast. The analysis must be done for each of the potential seismic sources for that particular coastline.[31]

Education

Even the most reliable tsunami warning system is unlikely to be effective if people do not respond in orderly and intelligent ways. Because tsunami are infrequent, people's recollections, as with any rare natural phenomenon, fade with time, leading some communities into a false sense of security. Education is therefore essential if communities are to become more resilient (see Professional Profile).

PROFESSIONAL PROFILE

Jose Borrero—Tsunami Scientist

Tsunami scientist Jose Borrero has witnessed firsthand the combined powers of land and sea unleashed (Figure 3.16). As a researcher with the University of Southern California Tsunami Research Center, he has travelled to areas hit by some of the most massive natural disasters in recent decades.

When a 10 m tsunami killed 2100 people in New Guinea in 1998, Borrero and his colleagues were there a week later to study the extent of the wave damage.

▲ **FIGURE 3.16** **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. *(© USC Tsunami Research Group)*

"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 says.

The researchers travelled 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 an earthquake had created 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 waves had pushed boats onto balconies and stripped trees off the side of a mountain 25 m up.

Borrero and colleagues used their data to develop a report about the risk Sumatra faces from future earthquakes and tsunami along the next segment of 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 says.

Tsunami education, Borrero says, is critical for coastal areas located directly on top of earthquake faults that produce tsunami. "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 where 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

A public education program must provide tsunami information at regular intervals, perhaps annually, and must include instructions on how to get information during an alert, where to go, and what things to take. Educational initiatives should be included in school curricula to ensure that future generations understand the hazards and potential impacts of tsunami. Education about tsunami should not be limited only to those living on or near the coast but should be extended to all communities, because people from inland regions often travel to tsunami-prone areas.

A range of educational initiatives can be undertaken in coastal communities. Activity sheets containing graphics, pictures, data, questions, and other relevant information can be used in schools to educate students about tsunami hazards. Evacuation routes can be publicized and marked by signs. Citizens should be consulted about land use in the tsunami inundation zone before decisions are made about siting or relocating critical facilities such as hospitals and police stations, schools and other high-occupancy buildings, and petroleum-storage tank farms. Tsunami information can be printed in newspapers and telephone books, along with phone numbers of local emergency service offices. Citizens should also be regularly informed about local warning systems.

It is important to educate coastal residents and visitors that there is a difference between a **tsunami watch**, which is a notification that an earthquake that could cause a tsunami has occurred, and a **tsunami warning** indicating that a tsunami has been detected and is moving across the ocean toward their area. For a distant tsunami, several hours may pass between the time a warning is issued and when the waves arrive. In a local tsunami, there may be very little lead time, so attention must be given to nature's warning signs, such as earthquake shaking or recession of water from a shoreline. People must also be educated that tsunami are a train of waves and that the second and third waves may be larger than the first. Finally, people must be told that that the water returning to the sea once a wave has reached its inland limit can be just as dangerous as the incoming wave.

Tsunami Readiness

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

- Have an emergency operation centre with 24-hour capability.
- Have ways to receive tsunami warnings from the Canadian Meteorological Service, National Weather Service, Coast Guard, or responsible provincial and state agencies.
- Have ways to alert the public.
- Develop a tsunami preparedness plan that includes emergency drills.
- Promote community awareness of tsunami hazards through educational programs.

The educational component is of particular importance. Most people don't even know when a tsunami watch or warning has been issued. If they do, they may not be aware of the appropriate response. For example, in 2005, there was an earthquake in the Pacific Ocean far from the city of Santa Barbara, which has been certified a tsunami-ready community. As it turned out, a tsunami did not occur, but a tsunami watch was instituted for the California coast. Nothing was said about the size of the possible tsunami, so on hearing the notice some people drove to the top of a nearby mountain pass more than a kilometre above sea level. The pass was great for a view, but people certainly did not need to drive that far or that high to evacuate the potential danger zone. The media reported that some people were perched on a sea cliff at night, while others climbed palm trees to see if the waves were coming. This experience suggests that coastal communities, even "tsunami-ready" ones, are not adequately prepared.

3.6 Perception and Personal Adjustment to Tsunami Hazard

The above 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. If a warning is issued, a person can take the following actions:

- If you are at the beach and experience a strong earthquake, leave the beach and low-lying coastal area immediately.
- If the trough of a tsunami wave arrives first, the ocean will recede from the shoreline. This recession is nature's warning sign that a large wave is on the way and you should run from the beach.
- Although a tsunami may be relatively small at one location, it may be much larger nearby.
- Most tsunami consist of a series of waves, and there can be up to an hour between waves. It is therefore important to stay out of dangerous areas until authorities issue a notice that all is clear.
- If you hear a tsunami siren in a coastal community, move away from the beach to higher ground (at least 20 m above sea level) and listen to a radio for emergency information.
- If you are aware that a tsunami warning has been issued, do not go down to the beach to watch the tsunami. If you can see the wave, you may be too close to escape. Remember that these waves move fast and can be deadly. A 2-m tall person is very small compared to a 15 m tsunami wave.

Summary

The devastating tsunami in the Indian Ocean in 2004 was an international wake-up call that we are not yet prepared for tsunami and that we need effective warning systems in the world's major ocean basins. These systems must be designed to reach both coastal residents and visitors, and they must be coupled with an effective education program so that people are more aware of the hazard.

A tsunami is produced by the sudden vertical displacement of water in the sea or a lake. Processes that can produce tsunami include large earthquakes, landslides, explosive volcanic eruptions, and impacts of extraterrestrial objects. The largest and most damaging tsunami over the past few millennia have been caused by giant earthquakes associated with Earth's major subduction zones.

Distant tsunami can travel thousands of kilometres across the ocean to strike a remote shoreline. In contrast, a local tsunami travels a much shorter distance to a nearby coast and can strike with little warning.

Tsunami effects are both primary and secondary. The primary effects are related to the direct impact, inundation, and erosion by the tsunami as it moves inland from the shore. Virtually nothing at the shore can survive a large tsunami. In 2004 in Indonesia, concrete buildings were flattened by the force of the waves. Secondary effects include possible water pollution, fires in urban areas, and disease.

Tsunami are linked to the earthquakes that cause them, and tsunami inundation may directly follow the ground shaking and land-level change produced by quakes. Both earthquakes and tsunami may cause fires. A tsunami may also change the coastline through erosion and deposition of sediment. Following a large earthquake and tsunami, parts of the coast may scarcely resemble what they looked like prior to the event.

Many strategies are available to minimize tsunami hazard. These include detection and warning, structural control, construction of tsunami run-up maps, land-use practices, probability analysis, education, and tsunami readiness. We are able to detect distant tsunami in the open ocean and accurately estimate their arrival time to within a few minutes. It is more difficult to provide adequate warning of a local tsunami because it arrives at the shore soon after an earthquake. In this case, ground shaking or a sudden withdrawal of water from the coast may signal that a tsunami may soon arrive. In addition, warning sirens may alert people in a community to move inland or to nearby higher ground.

Without adequate education, tsunami watches and warnings are ineffective because many people do not know the appropriate action to take to save themselves and others. Through education, people will learn the natural warning signs of an approaching tsunami. Further, they will understand that tsunami are a series of waves and the second or third wave may be the largest. The water returning to the ocean following tsunami inundation can cause as much damage as the incoming water.

Most communities along coasts exposed to significant tsunami are not adequately prepared for this underestimated natural hazard. Adequate preparation includes improved perception of hazards and risk, preparation and implementation of a tsunami preparedness plan, and promotion of community awareness and education.

Key Terms

distant tsunami (p. 78)
local tsunami (p. 78)
run-up (p. 78)
tsunami (p. 72)
tsunami-ready (p. 90)
tsunami warning (p. 90)
tsunami watch (p. 90)

Review Questions

1. What is a tsunami?
2. What natural processes cause a tsunami? What is the main cause?
3. What is the difference between a distant and a local tsunami?
4. What are the major effects of a tsunami?
5. Explain the relationship between plate tectonics and tsunami.
6. How are tsunami detected in the open ocean?
7. What is the difference between a tsunami watch and a tsunami warning?
8. What are the primary and secondary effects of tsunami?
9. Describe the methods used to minimize the tsunami hazard.
10. What is meant by *tsunami-ready*?

Critical Thinking Questions

1. You are in charge of developing an education program aimed at raising a community's understanding of tsunami. What sort of program would you develop and what would it be based on?
2. What do you think should be the role of the media in helping make people more aware of the tsunami hazard? How should scientists be involved in increasing awareness?
3. You live in a coastal area that experiences large but infrequent tsunami. You are working with the planning department of your community to improve its tsunami readiness. What issues do you think are most important for achieving this goal and how would you convince the community that it is necessary or in their best interest to be tsunami-ready?

Selected Web Resources

Tsunami!
www.ess.washington.edu/tsunami General information about tsunami, their causes, history, and safety from the University of Washington Department of Earth and Space Sciences

Tsunami
www.tsunami.noaa.gov Information on tsunami basics, warning, preparedness, hazard assessment, education, and animations from the National Oceanic and Atmospheric Administration

Tsunami in Canada
http://atlas.nrcan.gc.ca/auth/english/maps/environment/naturalhazards/tsunami A catalogue of major tsunami that have struck Canada, from Natural Resources Canada

www.pac.dfo-mpo.gc.ca/sci/OSAP/projects/tsunami/default_e.htm Information on tsunami research, the physics of tsunami, tsunami models, and potential tsunami in the Cascadia subduction zone from the Fisheries and Oceans Canada

International Tsunami Information Centre
http://ioc3.unesco.org/itic Information about tsunami, warnings, and international tsunami programs from UNESCO

Pacific Tsunami Warning Center
www.weather.gov/ptwc A wide range of information from the Pacific Tsunami Warning Center

Surviving a Tsunami—Lessons from Chile, Hawaii, and Japan
http://pubs.usgs.gov/circ/c1187/index.html Updated U.S. Geological Survey Circular 1187 about tsunami safety and the 1960 tsunami in Chile, Hawaii, and Japan

Tsunami and Earthquake Research at the U.S. Geological Survey
http://walrus.wr.usgs.gov/tsunami Information from the U.S. Geological Survey about tsunami research and links to panoramas and animations of tsunami behavior

Life of a Tsunami
http://walrus.wr.usgs.gov/tsunami/basics.html Illustrated description from the U.S. Geological Survey of how a tsunami forms, moves, and comes ashore

National Tsunami Hazard Mitigation Program
http://nthmp.tsunami.gov Information about tsunami hazard assessment, warning, and mitigation from the Executive Office of the President of the United States

About Tsunami
www.abuhrc.org/research/tsunami/Pages/index.aspx Follow the link "Project Pages" to webpages with information about mega-tsunami and the 2004 Indian Ocean tsunami from the Benfield Hazard Research Centre at University College London

Preparing for Tsunami
www.pep.bc.ca/hazard_preparedness/Tsunami_Brochure/Prepare_for_Tsunami.html Information from the British Columbia Provincial Emergency Program on how you can protect yourself from tsunami

On the Companion Website

Test your knowledge in Hazard City. Analyze data and evaluate risk. This book has its own Companion Website where you will find Hazard City assignments which challenge you to make assessments and offer recommendations. You will also find animations on the Companion Website and additional resources, including reference material on minerals, rocks, maps, and geologic time.