1

Introduction

INTRODUCTION

A tsunami is a wave, or series of waves in a wave train, generated by the sudden, vertical displacement of a column of water. This displacement can be due to seismic activity, explosive volcanism, a landslide above or below water, an asteroid impact, or certain meteorological phenomena. These waves can be generated in oceans, bays, lakes, rivers, or reservoirs. The term *tsunami* is Japanese and means harbor (*tsu*) wave (*nami*), because such waves often develop as resonant phenomena in harbors after offshore earthquakes. Both the singular and plural of the word in Japanese are the same. Many English writers write the plural of tsunami by adding an s to the end of the singular form. The Japanese usage will be adhered to throughout this text.

Before 1990, the public perceived tsunami as originating primarily from large, distant, underwater earthquakes—mainly in the Pacific Ocean. The fear of tsunami was allayed by the knowledge that an early warning system existed to prevent loss of life. In the 1990s, 14 major tsunami events struck the world's coastlines. While other disasters over this period have caused more deaths and greater economic destruction, these tsunami events have made scientists aware that the tsunami hazard is pervasive. The tsunami occurred as near-coastal events—generated by small earthquakes or even submarine landslides—and in many cases with minimal warning to local inhabitants. These perceptions suffered a major shock on December 26, 2004 when one of the largest earthquakes ever recorded, centered off the coast of northern Indonesia, generated a tsunami that swept across the northern Indian Ocean and killed hundreds of thousands of unsuspecting people. Big tsunami can occur without warning in a world where technology is supposed to save everyone. Nothing imaginable could be worse. However, evidence for mega-tsunami more than ten times larger than the Indian Ocean event has been discovered along the apparently aseismic and protected coastline of eastern Australia. These tsunami have run-up heights exceeding the largest earthquake-generated tsunami documented anywhere in the world over the past 5,000 years. These events have not only been repetitive, but also recent. They appear novel because they occurred in a country without a long, scientifically based, written history or record of tsunami. Aboriginal legends, however, orally record their occurrence. Ongoing research indicates that such mega-tsunami are more widespread. Their signature not only dominates the Australian coast, but also that of New Zealand and eastern Scotland. The generation of these mega-tsunami is contentious but most likely due to either great submarine landslides or the impact of asteroids and comets with the Earth's oceans.

These recent occurrences and discoveries have serious implications when it is realized that Western civilization is unique in its settlement of the shoreline and its development of great coastal cities. If a submarine landslide generated a near-coastal tsunami off the coasts of Sydney, Los Angeles, Tokyo, Honolulu, Chennai (formerly Madras), or any of a dozen other large cities, the death toll would be in the tens of thousands. A geological clock is also ticking away that eventually will see the occurrence of a tsunami as large as the Indian Ocean event of 2004 off the coast of Portugal, the northwest coast of the United States, or the Caribbean. This book describes tsunami as an underrated hazard and summarizes some of these recent discoveries. It presents a comprehensive coverage of the tsunami threat to the world's coastline.

FIVE STORIES

1 An Aboriginal legend

(Peck, 1938; Parker, 1978)

It was a stifling hot day, and all the Burragorang people lay prostrate around their camp unable to eat. As night approached, no one could sleep because of the heat and the mosquitoes. The Sun set blood red and the Moon rose full in the east through the haze. With just a remnant of red in the western sky, the sky suddenly heaved, billowed, tumbled, and then tottered before crumbling. The Moon rocked, the stars clattered, and the Milky Way split. Many of the stars—loosened from their places—began to fall flashing to the ground. Then a huge ball of burning blue fire shot through the sky at enormous speed. A hissing sound filled the air, and the whole sky lit like day. Then the star hit the Earth. The ground heaved and split open. Stones flew up accompanied by masses of earth followed by a deafening roar that echoed through the hills before filling the world with complete noise. A million pieces of molten fire showered the ground. Everyone was awestruck and frozen in fear. The sky was falling. Smaller stars continued to fall throughout the night with great clamoring and smoke. The next morning when all was quiet again only the bravest hunters explored beyond the campsite. Great holes were burnt into the ground. Wherever one of the larger molten pieces had hit, it had piled up large mounds of soil. Many of these holes were still burning with flames belching out. Down by the sea, they were amazed. Fresh caves lined the cliffs.

Soon stories reached them from neighboring tribes that not only had the sky fallen, but also the ocean. These neighbors began talking about a great ancestor who had left the Earth and gone into the sky, and who had traveled so fast that he had shot through the sky. The hole he had made had closed up. This ancestor had tried to get back through the sky by beating on top of it, but it had loosened and plummeted to the Earth, along with the ocean. Before anyone could discuss this story, it began to rain—rain unlike anything anyone had seen before. It rained all day and all night, and the rivers reached their banks and then crept out across the floodplains. Still the rain came down, and the people and all the animals fled into the hills. When the water rose into the hills, the people fled to the highest peaks. Water covered the whole land from horizon to horizon unlike anything anyone had ever seen before. It took weeks for the water to go down, everyone got very hungry, and many people died. Nothing was the same after the night that the sky fell. Now, whenever the sea grows rough and the wind blows, people know that the ocean is angry and impatient because the ancestor still refuses to let it go back whence it came. When the storm waves break on the beach, people know that it is just the great ancestor beating the ocean down again.

2 The Kwenaitchechat Legend, Pacific Northwest

(Heaton and Snavely, 1985; Satake *et al.*, 1996; Geist, 1997a)

It was a cold winter's night along the Cape Flattery coast of the Pacific Northwest. At Neeah Bay, the Kwenaitchechat people had eaten and settled into sleep. Then the ground began to shake violently. The land rolled from west to east and jerked upward, leaving the beach exposed higher above the high-tide line than anyone had seen it before. Everyone ran out into the moonless night and down to the beach, where there was less chance in the dark of being flung into trees or the sides of huts by the shaking. As they fled onto the beach, the adults began to sink into the sand as if it were water. The old people were the last to get to the beach, and when they did, they were yelling frantically for everyone to run to higher ground. The young men laughed at them, saying that it was safer in the open. Suddenly the water in the bay began to recede, far beyond the limit of the lowest tide, farther than anyone had seen it go. Everyone paused and stared at the ocean as if for eternity. Then the water began to come back. There was no sound except for the loud rushing of water swallowing everything in the bay. As one, all the tribespeople turned and began to run back to the village—to the canoes. Few got back. Those that did flung themselves, children, and anything else they could grab in the dark into the canoes. Then they were all picked up and swept north into the Straits of Juan de Fuca and into the forests. The water covered everything on the cape with only the hills sticking out. When the waters finally receded, many had drowned. Some canoes were stuck in the trees of the forest and were destroyed. Some people without any means of paddling the canoes were swept onto Vancouver Island beyond Nootka. In the light of day, all trace of the village in Neeah Bay was gone. So were all the neighboring villages. No sign of life remained except for the few survivors scattered along the coast and the animals that had managed to flee into the hills.

On the other side of the Pacific Ocean, in Japan, 10 hours later, the residents of villages along the coast at Miyako, Otsucki, and Tanabe had finished their work for the day and had gone to sleep. It was cloudy but calm along the coast. Then at around nine in the evening, without any preceding earthquake, the long waves started coming in—3 m high at Miyako, 2 m at Tanabe. All along the coast, the sea suddenly surged over the shore without warning into the low-lying commercial areas of the towns and into the rice paddies scattered along the coastal plains. The merchants, fishermen, and farmers had seen such things before—the small waves that came in like tsunami but without any earthquake. They were lucky, because if there had been an earthquake, many people would have died. Instead, only a few lost their possessions. The events of that night were just a nuisance thing, of no great consequence.

3 Krakatau, August 27, 1883

(Myles, 1985; Bryant, 2005)

Van Guest was sweating profusely as he climbed through the dense jungle above the town of Anjer Lor. He stopped to gasp for breath, not because he was slightly out of shape, but because the sulfurous fumes burned his lungs. He looked down at the partially ruined town. There was no sign of life although it was nearly 10 o'clock. His head pounded at the excitement of the scene and the strain of the trek sped blood through his temples. He did not know if he felt the thumping of blood in his head or the distant rumbling. Sometimes both were synchronous, and it made him smile. This was the chance of a lifetime. No one was paid to do what he did or had remotely thought to climb to the top of one of the hills to get the best view. Besides, most of the townspeople had fled into the jungle after the waves had come through yesterday and again in the early morning. As he neared the top of the hill he looked for a spot with a clearing to the west, reached it, and turned. Beyond laid purgatory on Earth, the incredible hell of Krakatau in full eruption.

As a volcanologist for the Dutch colonial government, Van Guest was aware of the many eruptions that continually threatened Dutch interests in the East Indies. Tambora in 1815 was the worst. No one thought that anything else could be bigger. He had seen Galunggung go up the previous year with over a hundred villages wiped out. Krakatau had had an earthquake then, and when it began to erupt in May, the governor in Batavia had ordered him to investigate. He had come to this side of the Sunda Strait because he thought he would be safe 40 km from the eruption. Van Guest tied his handkerchief over his nose and mouth, slipped on the goggles to keep the sting from his eyes, and peered through his telescope across the strait, hoping to catch a glimpse of the volcano itself through the ash and smoke. Suddenly the view cleared as if a strong wind had blown the sky clean. He could see the ocean frothing and churning chaotically. Only the Rakata peak remained, and it was glowing red. The smallest peak, Perboewatan, had blown up at 5:30 that morning. Danan, which was 450 m high, had gone just over an hour later. Each had sent out a tsunami striking the coastline of Java and Sumatra in the dark. That is what had cleared out the town in the early hours.

As he glanced down at the abandoned boats in the bay, Van Guest noticed that they were all lining up toward the volcano. Then they drifted quickly out to sea and disappeared in the maelstrom. Suddenly, a bolt of yellow opened in the ocean running across the strait to the northwest and all the waters in the strait flooded in. Instantly, a cloud of steam rose to the top of the sky. As Van Guest stood upright, awestruck, a blast of air flattened him to the ground and an incredible noise deafened him. The largest explosion ever heard by humans had just swept over him. The pressure wave would circle the globe seven times. When he gained his feet, Van Guest thought he was blind. The whole sky was as black as night. He stumbled down the slope back toward the town. It took him nearly 30 minutes to get down to the edge of the town through the murk. Just as he approached the outskirts of Anjer Lor, he could see the telegraph master, panic stricken, racing up the hill toward him, silhouetted against the sea—or what Van Guest thought was the sea. It was hilly and moving fast toward him. The sea slowly reared up into an incredible wave over 15 m high and smashed through the remains of buildings next to the shoreline. Within seconds it had splintered through the rest of the houses in the town and was closing fast. The pace of the telegraph master slowed noticeably as he climbed the hill. The wave crashed through the coconut palms and jungle at the edge of the town. Tossing debris into the air, it sloshed up the hill. The telegraph master kept running or stumbling toward Van Guest, then collapsed into his arms with only meters to spare between him and the wave. It had finally stopped. Both men had just witnessed one of the biggest volcanic eruptions and tsunami ever recorded.

4 Burin Peninsula, Newfoundland, November 18, 1929

(Cox, 1994; Whelan, 1994; Dawson *et al.*, 1996)

It was just after five in the afternoon on a cold autumn evening when the residents of outports along the Burin Peninsula of Newfoundland felt the tremors. Windowpanes rattled and plates fell out of sideboards. It was so unusual that one by one people poked their heads out of their pastel clapboard houses to see if anyone else had noticed—fishermen and their families at Taylors Bay, Point au Gaul, Lamaline, Lord's Cove, and 35 other communities nestled into the narrow coves along one of the most isolated coasts in North America. Isaac Hillier—who was just 18 at the time—went outside and saw an elderly French man gesturing excitedly to a group of his neighbors. When the man stooped and put his ear to the ground, Isaac's curiosity got the better of him and he went closer to hear what was going on. The old man began to wave his arms and shout that the water would come. Those gathered around him turned to each other and asked, "How would he know that?" One by one they went back to their evening chores before the storm set in. Isaac, although curious, did likewise.

The young children were put to bed upstairs in the wood houses shortly after their evening meals. At Lord's Cove, 3-year-old Margaret Rennie was one such child. The excitement of the earthquake was beyond her comprehension, and she only wanted to get into bed to keep warm. Toward 7:30 PM, 7-year-old Norah Hillier could hardly keep awake any more. Her father had come back with the news that the

Figure 1.1. "All the sheep!" Child's impression of a large tsunami breaking on a rocky coast at night. © Kate Bryant, 1998.

telegraph line to St. John's was broken. He had gone out again to see if he could do anything before it got colder. Norah heard a loud roar and glanced out the window to the sea only a few meters away. "Oh!" she cried out, "All the sheep!" All she could see were thousands of white sheep riding a mountain of water that was getting higher and higher, and louder (Figure 1.1). Within seconds, the foaming water was in the house. Her oldest sister bolted for the door and pushed against it. They were up to their waists in water, and the house began to move.

Lou Etchegary had never seen cars before, but with beams of moonlight breaking through the cloud and shining on its crest, the tsunami looked like a car with its headlights on—driving fast up the harbor. Within seconds, a wall of water 3 m high was smashing crates off the wharf and lifting fishing dories and schooners 5 m high as if they were matchsticks. Anchors snapped, and all the boats either surged on the crest of the wave or raced belly-up to the pebble beach at the back of the cove. No one had a clue in the dark what was happening. At Taylors Bay, Robert Bonnell heard the wave coming and, grabbing his two children, raced for the hills. He tripped in the dark, fell down, and watched helplessly as the water dragged his children back into the maelstrom. Margaret Rennie slept as her house was swept into the pond out back. Rescuers raced to the house in the dark and smashed in the windows to get into the rooms. Margaret was found unconscious and still lying on her bed. Her mother, Sarah, and three brothers and sisters were found drowned downstairs in the kitchen. Norah Hillier's dad raced back to the house as soon as he saw water flooding his house. The only thing he could think of was to grab his soaking wet girls and drag them through the peat bog to the hills. He could already see a number of bonfires being lit by his neighbors who lived farther inland.

Isaac Hillier stood in disbelief. How did that old man know that the water would come? Before he could think further, another wave flooded in. It picked up the remaining boats and pieces of houses, and thrashed them across the beach. Isaac could also see the barrels of flour, molasses, and salted fish, stored on the wharves for the coming winter, floating in the mess. Before it was over, two more waves smashed into the debris stacking it 2 m high in places. Not only was there no food or shelter, their lifeline to St. John's—the boats—was also gone. Stunned, Isaac froze in shock as shivers swept up and down his spine. Stumbling toward the bonfires, he became acutely aware of the shouts of rescuers and the crying, and then of the snow and the bitter cold.

5 Papua New Guinea, July 17, 1998

It was a perfect tropical evening along the Aitape coast of Papua New Guinea. Here on the narrow sand barrier that ran for 3 km in front of Sissano lagoon, life was paradise—sago trees, coconut groves, white beaches, and the ever-present emerald waters of the Bismarck Sea. It was the dry season, and as the Sun set, people in the villages were busying themselves preparing their evening meals. The men had had a good day fishing in the ocean; the women, good returns from their nets set in Sissano lagoon. Children and young people, many who had come home from Port Moresby for the school holidays, played along the beach. Ita glanced at her watch. It was ten to seven—still plenty of time before the sing-sing. She glanced at her two babies who were lying beside her and smiled. These holiday periods when all the children were home were the happiest of times.

She bent over to check her cooking, and that is when she first noticed the earthquake. The water in the pot began to shimmer. Then the ground began to roll. It came in from the north, from the sea. Everyone in the village froze in their tracks. The region often experienced earthquakes but they were always small. How big was this one going to be? Ten seconds, 30 seconds, a minute, two. Then the shaking stopped. Ita looked around. She lived at the back of the lagoon, only 75 m from the ocean. She saw some of the older people gathering around a cluster of buildings closer to the sea. They were talking frantically. She would never forget the look on their faces; it was one of sheer panic. Some of the younger men joined the group. One old man began pointing at the ocean. He was yelling, and Ita could just catch his words. He talked about "leaving the village," "the wave was coming," and "everyone must run." She thought how foolish. The village was on a barrier between the ocean and the lagoon. There was nowhere to run. One of the young men in the group put his arm around the old man's shoulders, smiled, and then began to laugh—not at him, not with him, but in that reassuring way that went with the nonchalant attitude of a people comfortable with a relaxed, carefree lifestyle.

Ita heard a rumbling like thunder, and as she glanced through the trees to the ocean, she noticed that the tide was going out, farther than she could remember. By now, some of the children had run up from the beach. One of them said that they had seen the ocean splash tens of meters into the air on the horizon just after the ground shock. They were now asking their parents to come down to the beach. It was full of cracks. Within minutes, everyone was talking about the earthquake. It had not been a big one. The houses built on stilts were still standing. Some people had wandered down to the beach; but the older people were more distraught than ever. Then someone yelled, "Look," and pointed to the ocean. Ita strained to view the horizon in the twilight. A thousand lights from phosphorescence began to sparkle in the water, which had now retreated several hundred meters from shore. Then she noticed that the horizon was moving; it was getting higher and higher. Abruptly a second earthquake jolted her. This time it rolled in from the southeast. As she turned and looked east along the coast, she saw a large wave breaking—not really breaking, but frothing and sparkling. Everyone instantaneously began yelling "Run," but the roar of the wave cut off the shouts. Like a jet plane landing, it engulfed the night. Ita turned, grabbed her two babies beside her, raced the few steps to the canoe, and jumped in. Before the wave hit with a thud, a blast of air knocked her flat to the bottom. The canoe was tossed several meters into the air and then flung like a surfboard into the lagoon and across to the swamp on the other side. At Sissano, Warapu, Malol, Arop, and half a dozen villages all along the Aitape coast, the scene was the same. A 10 m to 15 m high tsunami swamped the coast. At some places the wave raced along the shore; at others it just reared from the ocean and ran straight inland through buildings faster than people could run. Everywhere, people were knocked into trees behind the beach or flushed into the lagoon.

It was now night. One could only hear the noise of the wave as it crossed Sissano lagoon and the screams of people as they gasped for air or tried to swim in the turbulent water. A putrid odor filled the air. In all, three waves swept one on top of the other across the coast. From the beginning of the first earthquake to the last wave, it was all over within half an hour. The villages were gone; debris was everywhere. As a surreal mist rose from the lagoon and crept into the silent swamps, the feeble cries of survivors, grunts of foraging pigs, and isolated barks from hungry dogs looking for an evening meal were the only sounds of songs to be heard along the Aitape coast that night.

In all 2,202 people died, 1,000 were injured, and 10,000 were made homeless. Many of the dead died from their injuries as they clung to trees in the impenetrable mangrove forest on the other side of the lagoon, waiting days for rescue, on a remote coastline thousands of kilometers from nowhere. Ita? She survived. Her canoe was caught in the mangrove. After two days she was rescued with her two babies and reunited with an overjoyed husband.

SCIENTIFIC FACT OR LEGENDS?

All of these stories have elements of truth, yet only two are reliable—those of Krakatau and the Burin Peninsula. The description of the tsunami generated by the eruption of Krakatau in 1883 is based upon historical scientific records—mainly the diary of Van Guest, the colonial volcanologist. The Burin Peninsula story is linked to the Grand Banks earthquake and tsunami of 1929. This event is known more for the breaking of telegraph cables on the seabed between New York and Europe than for the deadly tsunami that struck the southeast coast of Newfoundland. Both stories also have elements of fabrication. While the individual experiences of Van Guest and the telegraph master are true, the descriptions of their feelings and eventual meeting at the end have been embellished to produce a more colorful story. The Krakatau eruption and tsunami are probably some of the best-documented tsunami events in the scientific literature. At least four articles about it have been written in *Nature* and two in *Science*. However, there is still scientific debate whether or not the largest tsunami that reached Anjer Lor and other locations in the Sunda Strait was the result of the eruptions in the early morning or the one at 9:58 AM. If witnesses had not been wiped out by the earlier tsunami, they more than likely did not see the last one because they had fled inland to safety. Thick ash also obscured the last event—turning day into night. Field surveys afterwards could not discern the run-up of individual waves, but only the highest run-up elevation of the biggest wave.

Readers may also be willing to accept the story from Papua New Guinea because it, like the Newfoundland one, is based upon interviews with eyewitnesses. Scientists have cobbled the story together from newspaper reports and interviews. Unfortunately, both stories are unreliable because interviewers, unless they apply structured qualitative methodology, can be prone to exaggeration. In essence, both the Papuan New Guinea and Newfoundland stories represent the early phases of an oral tradition or folklore about a tsunami event that is being passed on by word of mouth, or in the 20th century supported by written documentation. When there are no witnesses to a notable event left alive and no written records, then all these stories become legends. Legends have an element of truth, but often the exact circumstances of the story cannot be verified. The tsunami story by the Kwenaitchechat native people is a legend. However, when the most likely source of a documented tsunami in Japan on January 26, 1700 was evaluated—using computer modeling—as being a giant earthquake off the coast of Washington State, the legend suddenly took on scientific acceptability and received front-page coverage in *Nature*.

The Aboriginal story incorporates numerous published legends in the southeast part of Australia. One story actually uses the colloquial word *tidal wave* for tsunami. Scientific investigations along the southeast coast of Australia now indicate that the Aboriginal stories are not myths, but legends of one or more actual events. While no Aborigine at the time thought of writing up a description of any of these tsunami events and publishing it as a scientific paper in *Nature* or *Science*, the legends are just as believable as any newspaper article or scientific paper. They are just briefer and less specific. The sky may have fallen in the form of an asteroid or meteorite shower with large enough objects to generate tsunami tens of meters high. There is geomorphic evidence along the southeast coast of New South Wales, the northeast coast of Queensland, and the northwest coast of Western Australia for mega-tsunami. Certainly the coastal features are so different in size from what historical tsunami have produced anywhere in the world in the past 200 years that a comet or asteroid impact with the ocean must be invoked. The subsequent floods also have veracity. Asteroid impacts with the ocean put enormous quantities of water into the atmosphere as either splash or vaporized water from the heat of the impact. That heated vapor condenses and falls as rain because it is not in equilibrium with the pre-existing temperature of the atmosphere. Research is beginning to indicate that rivers and waterfalls across Australia have flooded beyond maximum probable rainfalls—the theoretical highest rainfall that can occur under existing rain-forming processes. Asteroid impacts with the ocean may explain not only some of the evidence for mega-tsunami, but also this mega-flooding.

The single thread running through all five stories is tsunami. The stories have been deliberately selected to represent the different causes of tsunami. The Aboriginal legend refers to the impact of an asteroid and the associated airburst. The historically accurate Krakatau story recounts a volcano-induced tsunami, while the Kwenaitchechat legend undoubtedly refers to a tsunami generated by an earthquake of magnitude 9.0 along the Cascadia subduction zone of the western United States in January 1700. The Newfoundland tale refers to the Grand Banks earthquake and submarine landslide of 1929—the only well-documented tsunami to affect the east coast of North America. Finally, and more worrisome, the origin of the Papua New Guinea event is still being debated. The event is worrisome because the wave was too big for the size of the earthquake involved. The combination of downfaulting close to shore and slumping of offshore sediments on a steep, offshore slope may have caused the exceptionally large tsunami. Many countries have coastlines like this. The event is also disconcerting because our present scientific perception and warning system—especially in the Pacific Ocean—is geared to earthquake-induced waves from distant shores. Certainly very few countries, except Chile and Japan, have developed a warning system for nearshore tsunami. The stories deliberately cover this range of sources to highlight the fact that, while earthquakes are commonly thought of as the cause of tsunami, tsunami can have many sources. Our present knowledge is biased, even after the shock of the Indian Ocean Tsunami of 2004. Tsunami are very much an underrated, widespread hazard. Any coast is at risk.

CAUSES OF TSUNAMI

(Wiegel, 1964; Iida, 1963; Bryant, 2005)

Most tsunami originate from submarine seismic disturbances. The displacement of the Earth's crust by several meters during underwater earthquakes may cover tens of thousands of square kilometers and impart tremendous potential energy to the overlying water. Tsunami are rare events, in that most submarine earthquakes do not generate one. Between 1861 and 1948, as few as 124 tsunami were recorded from 15,000 earthquakes. Along the west coast of South America, 1,098 offshore earthquakes have generated only 20 tsunami. This low frequency of occurrence may simply reflect the fact that most tsunami are small in amplitude—and go unnoticed—or the fact that most earthquake-induced tsunami require a shallow focus seismic event with a surface wave magnitude, M_s, greater than 6.5. Earthquakes as a cause of tsunami will be discussed in fuller detail in Chapter 5.

Submarine earthquakes have the potential to generate landslides along the steep continental slope that flanks most coastlines. In addition, steep slopes exist on the sides of ocean trenches and around the thousands of ocean volcanoes, seamounts, atolls, and guyots on the seabed. Because such events are difficult to detect, submarine landslides are considered a minor cause of tsunami. The July 17, 1998 Papua New Guinea event renewed interest in this potential mechanism. A large submarine landslide or even the coalescence of many smaller slides has the potential to displace a large volume of water. Geologically, submarine slides involving up to 20,000 km^3 of material have been mapped. Tsunami arising from these events would be much larger than earthquake-induced waves. Only in the last 40 years has coastal evidence for these mega-tsunami been uncovered. Submarine landslides as a cause of tsunami and mega-tsunami will be discussed in Chapter 6.

Tsunami can also have a volcanic origin. Of 92 documentable cases of tsunami generated by volcanoes, 16.5% resulted from tectonic earthquakes associated with the eruption, 20% from pyroclastic (ash) flows or surges hitting the ocean, 14% from submarine eruptions, and 7% from the collapse of the volcano. A volcanic eruption rarely produces a large tsunami, mainly because the volcano must lie in the ocean. For example, the largest explosive eruption of the past millennium was Tambora in 1815. It only produced a local tsunami 2 m–4 m high because the volcano lay 15 km inland. In contrast, the August 27, 1883 eruption of Krakatau, situated in the Sunda Strait of Indonesia, produced a tsunami with nearby run-up heights exceeding 40 m above sea level. The wave was detected at the Cape of Good Hope in South Africa 6,000 km away. The atmospheric pressure pulse generated water oscillations that were measured in the English Channel 37 hours later, on the other side of the Pacific Ocean at Panama and in San Francisco Bay, and in Lake Taupo in the center of the North Island of New Zealand. Probably the most devastating event was the Santorini Island eruption around 1470 BC, which generated a tsunami that must have destroyed all coastal towns in the eastern Mediterranean. The Santorini crater is five times larger in volume than that of Krakatau, and twice as deep. On adjacent islands, there is evidence of pumice stranded at elevations up to 50 m above sea level. The initial tsunami waves may have been 90 m in height as they spread out from Santorini. Volcanoes as a cause of tsunami will be discussed in Chapter 7.

There has been no known historical occurrence of tsunami produced by an asteroid impact with the ocean. However, this does not mean that they are an inconsequential threat. Stony asteroids as small as 300 m in diameter can generate tsunami over 2 m in height that can devastate coastlines within a 1,000 km radius of the impact site. The probability of such an event occurring in the next 50 years is just under 1%. One of the largest impact-induced tsunami occurred at Chicxulub, Mexico, 65 million years ago at the Cretaceous–Tertiary boundary. While the impact was responsible for the extinction of the dinosaurs, the resulting tsunami swept hundreds of kilometers inland around the shore of the early Gulf of Mexico. Impact events are ongoing. Astronomers have compiled evidence that a large comet encroached upon the inner solar system and broke up within the last 14,000 years. The Earth has repetitively intersected debris and fragments from this comet. However, these encounters have been clustered in time. Earlier civilizations in the

Middle East were possibly destroyed by one such impact around 2350 BC. The last rendezvous occurred as recently as AD 1500; however, it occurred in the Southern Hemisphere where historical records did not exist at the time. Only in the last decade has evidence become available to show that the Australian coastline preserves the signature of mega-tsunami from this latest impact event. One of the main themes of this book is the exposition of this evidence. The geomorphic signatures of tsunami will be presented in Chapters 3 and 4, while asteroids as a cause of mega-tsunami will be discussed in detail in Chapter 8.

Finally, meteorological events can generate tsunami. These tsunami are common at temperate latitudes where variations in atmospheric pressure over time are greatest. Such phenomena tend to occur in lakes and embayments where resonance of wave motion is possible. Resonance and the features of meteorological tsunami will be described in Chapter 2.

DISTRIBUTION AND FATALITIES

Accounts of tsunami extend back almost 4,000 years in China, 2,000 years in the Mediterranean—where the first tsunami was described in 479 BC—and about 1,300 years in Japan. However, many important tsunamigenic regions have much shorter documentation. For example, the Chile–Peru coastline, which is an important source of Pacific-wide tsunami, has records going back only 400 years to 1562, while those from Alaska have only been documented since 1788. Tsunami records in Hawaii, which is a sentinel for events in the Pacific Ocean, exist only from 1813 onward. Few records exist along the west coast of Canada and the contiguous United States. The southwest Pacific Ocean records are sporadic and almost anecdotal in reliability. Only in the last 20 years have records been compiled from Australia and New Zealand, with historical documentation extending back no further than 150 years.

The regional distribution of major tsunami is tabulated in Table 1.1. Only the South Atlantic appears to be immune from tsunami. The North Atlantic coastline also is virtually devoid of tsunami. However, the Lisbon earthquake of November 1, 1755, which is possibly the largest earthquake known, generated a 15 m high tsunami that destroyed the port at Lisbon. It also sent a wall of water across the Atlantic Ocean that raised tide levels 3 m–4 m above normal in Barbados and Antigua in the West Indies. Tsunami also ran up and down the west coast of Europe, and along the Atlantic coast of Morocco. The Spanish port of Cádiz and Madeira in the Azores were also hit by waves 15 m high, while a 3 m to 4 m high wave sunk ships along the English Channel. The continental slope off Newfoundland, Canada, is seismically active and has produced tsunami that have swept onto that coastline. The Burin Peninsula tsunami described earlier reached Boston, where it registered a height of 0.4 m. By far the most susceptible ocean to tsunami is the Pacific Ocean region, accounting for 52.9% of all events. The following sections describe some of the more noted oceans or seas that have experienced tsunami.

Table 1.1. Percentage distribution of tsunami in the world's oceans and seas.

Location	*Percentage*
Atlantic east coast	1.6
Mediterranean	10.1
Bay of Bengal	0.8
East Indies	20.3
Pacific Ocean	25.4
Japan–Russia	18.6
Pacific east coast	8.9
Caribbean	13.8
Atlantic west coast	0.4

Source: From Bryant (2005).

Mediterranean Sea

(Kuran and Yalçiner, 1993; Tinti and Maramai, 1999)

The Mediterranean Sea has one of the longest records of tsunami. Over 300 events have been recorded since 1300 BC. Large tsunami originate in the eastern Mediterranean, the Straits of Messina of southern Italy, or southwest of Portugal. About 7% of known earthquakes in this region have produced damaging or disastrous tsunami. Around Greece, 30% of all earthquakes produce a measurable seismic wave, and 70 major tsunami have been recorded. Around Italy, there have been 67 reliably reported tsunami over the past 2,000 years. The majority of these have occurred in the last 500 years, as records have become more complete. Of these, 46 were caused by earthquakes and 12 by volcanoes. By far the most destructive tsunami followed an earthquake on December 28, 1908 in the Messina Strait region. A small proportion of the 60,000 people killed during this event were drowned by the tsunami, which flooded numerous coastal villages and reached a maximum run-up exceeding 10 m in elevation.

Caribbean Sea

(National Geophysical Data Center and World Data Center A for Solid Earth Geophysics, 1984; Lander and Lockridge, 1989; Schubert, 1994)

The Caribbean—including the south coast of the United States—is particularly prone to tsunami as the Caribbean Plate slides eastward relative to the North American Plate at a rate of $2\,\mathrm{cm\,yr^{-1}}$, producing strong seismic activity in the Puerto Rico

Trench. Unfortunately, the threat here has been overshadowed by the more frequent occurrence of tropical cyclones or hurricanes. The record of tsunami is one of the longest in North America, beginning on April 16, 1690, with an event near St. Thomas in the Virgin Islands. Here the sea dropped 16 m–18 m. The devastating Port Royal, Jamaica, tsunami, which drowned 3,000 people, followed this event two years later in June 1692. An earthquake that sent much of the city sliding into the sea triggered the tsunami. Ships standing in the harbor were flung inland over two-story buildings. An earthquake in the Anegada trough between St. Croix and St. Thomas produced another significant tsunami on November 18, 1867. The resulting tsunami reached 7 m–9 m at St. Croix, 4 m–6 m high at St. Thomas, 3 m at Antigua, and 1 m–6 m in Puerto Rico. Run-ups of 1.2 m–1.5 m were common elsewhere throughout the southern Caribbean. Other notable events have occurred in 1842, 1907, 1918, and 1946. Of these, two bear mention—the tsunami of October 25, 1918 and August 4, 1946. The former event had a maximum run-up height of 7 m at Frederiksted, St. Croix, and was recorded at Galveston, Texas. The latter event followed a magnitude 8.1 earthquake off the northeast coast of the Dominican Republic. Locally, the tsunami penetrated several kilometers inland and drowned about 1,800 people. It also was observed at Daytona Beach, Florida.

Pacific Ocean Region (including Indonesia)

(Cornell, 1976; Iida, 1983, 1985; National Geophysical Data Center and World Data Center A for Solid Earth Geophysics, 1984, 1989; Lockridge, 1988b; Gusiakov and Osipova, 1993; Howorth, 1999; Intergovernmental Oceanographic Commission, 1999)

Figure 1.2a plots the distribution of 1,274 observations of tsunami reported along the coastlines of the Pacific Ocean region since 47 BC. The size of the circles is proportional to the number of observations per degree square of latitude and longitude. The data are biased in that the same event can be recorded at more than one location. The map excludes 217 observations that cannot be precisely located. The distribution of all observations is tabulated by region in Table 1.2. Because some countries have better observation networks than others, smaller events are overemphasized. This is true of the west coast of North America, which is overrepresented in the modern record, despite having records of tsunami for only the last 200 years. Some countries are underrepresented in Figure 1.2a. For example, over a hundred observations from Australia are not included. The coastline of Japan has the longest historical record of tsunami, with 22.1% of all events originating here. Two other regions also stand out as having a high preponderance of tsunami—the coast of South America with 18.6% of events and Indonesia with 12.3%. A few small areas are highly prone to tsunami. These areas include Northern California, Hawaii, southwest Chile, and the Chile–Peru border region. Destructive tsunami have inundated the Chilean coast at roughly 30-year intervals in recorded history.

Tsunamigenic earthquakes with surface wave magnitudes greater than 8.2 affect the entire Pacific Ocean once every 25 years. Figure 1.2b plots the source region of ocean-wide events. Major events are also listed in Table 1.3. Significant events have

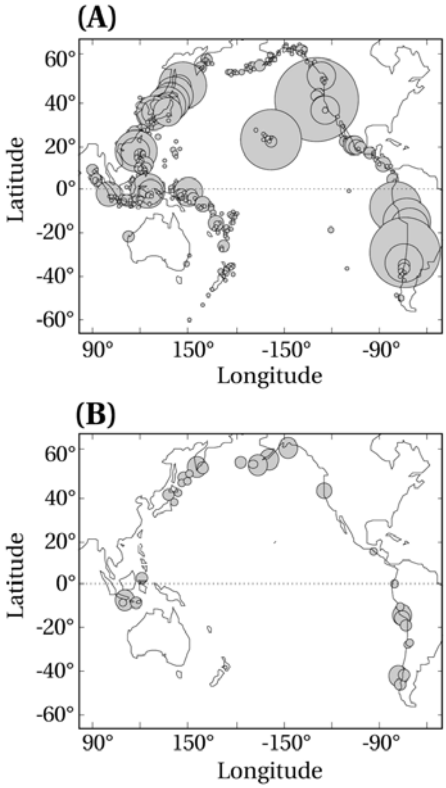

Figure 1.2. Location of tsunami in the Pacific Ocean region: (A) Location of 1,274 tsunami since 47 BC. Size of circle increases proportional to number of events per degree square of latitude and longitude. (B) Source of significant distant (teleseismic) tsunami. Size of circle increases proportional to area affected and magnitude of the event. Based upon Lockridge (1985), (1988b); Intergovernmental Oceanographic Commission (1999).

increased in frequency in the 20th century. Earthquakes in southern Chile, Alaska, and the Kamchatka Peninsula have the greatest chance of generating ocean-wide tsunami in the Pacific. The west coast of the United States provides a fourth source; however, the last Pacific-wide event originating here occurred 300 years ago, before European settlement, on January 26, 1700. The May 22, 1960 Chilean event is the most significant historical tsunami. This event will be described in detail in Chapter 5. It is a benchmark for tsunami in the 20th century. A series of tsunami waves spread across the Pacific over a period of 24 hours, taking over 2,500 lives. The tsunami significantly affected such diverse places as Hawaii, Pitcairn Island, New Guinea, New Zealand, Japan, Okinawa, and the Philippines.

The most tsunamigenic coastline in the world is that of the Kamchatka Peninsula, Russia. Between 1737 and 1990, the region experienced almost 8,000 earthquakes of which 96 generated localized tsunami. Volcanic eruptions here have also produced six tsunami, while four events have an unknown source. During the

Table 1.2. Origin of tsunami by region around the Pacific Ocean.

Region	*Number of tsunami generated*	*Percentage*
Japan	329	22.10
South America	278	18.60
Indonesia	184	12.30
New Guinea–Solomon Islands	129	8.70
Philippines	128	8.60
Kamchatka–Kuril Islands	95	6.40
New Zealand–Tonga	82	5.50
North America	78	5.20
Alaska–Aleutian Islands	77	5.20
Central America	72	4.80
Hawaii	39	2.60
Total	*1,491*	*100.00*

Source: Based on Intergovernmental Oceanographic Commission (1999).

same period, the region was subject to 15 tsunami from distant sources. A significant tsunami floods alluvium plains along the peninsula every 12.3 years. The most destructive tsunami, penetrating up to 10 km inland, occurred in 1737, 1841, 1923, 1937, 1952, and 1969. The largest event followed the Great Kamchatka Earthquake of October 17, 1737. Tsunami run-up heights reached 60 m above sea level in the North Kurile Islands. The second largest event occurred on November 4, 1952, with run-up heights of 20 m in the same area. This latter tsunami was also a Pacific-wide event.

Local tsunami are also common on the islands of the South Pacific; however, no significantly sized, earthquake-induced tsunami has propagated outside this region. Because many islands drop off into deep water, locally generated tsunami can travel at their maximum velocity, up to 1,000 km h^{-1}, and reach the adjacent shore in 5–10 minutes. The Papua New Guinea–Solomon Islands region has experienced 78 tsunami in the period between 1768 and 1983. Volcanism has caused one-eighth of all tsunami. The largest event occurred on March 13, 1888, when the Ritter Island volcano off the north coast of Papua New Guinea collapsed, generating a 15 m high tsunami. The most recent event of significance occurred in the early evening of July 17, 1998 along the Sissano–Aitape coast of northern Papua New Guinea. One of the stories earlier referred to this event. It will be described in more detail in Chapter 5. Eleven tsunami have struck Fiji in the 100-year period 1877–1977, averaging one

Table 1.3. Occurrence of significant tsunami in the Pacific region documented snce 47 BC.

Date	*Source*	$H_{r\max}$ (m)	*Distant areas affected*
January 26, 1700	Washington State	Unknown	Japan
July 8, 1730	Concepción (Chile)	Unknown	Japan
November 7, 1837	S. Chile	8.0	Hawaii
July 9, 1854	N. Kuril Islands	Unknown	Japan
August 13, 1868	Arica (Chile)	21.0	Peru, Japan, Hawaii, New Zealand, Australia, Fiji, U.S.A
January 20, 1878	Aleutian Islands	3.0	Hawaii
May 10, 1877	Arica (Chile)	24.0	Peru, Hawaii, California, New Zealand, Australia
August 27, 1883	Krakatau, Sunda Straits	42.0	India, Australia
January 31, 1906	Ecuador	5.0	California, Hawaii
August 17, 1906	Chile	3.6	Hawaii, Japan, California
August 15, 1918	Celebes Sea	12.0	Indonesia, Philippines
September 7, 1918	S. Kuril Islands	12.0	Japan, Hawaii
November 11, 1922	Atacama (Chile)	12.0	Samoa, Hawaii, Colombia, Japan, New Zealand
February 3, 1923	Kamchatka Peninsula	8.0	Hawaii
March 2, 1933	Sanriku, Japan	29.3	Hawaii
August 1, 1940	West Hokkaido (Japan)	3.5	Russia, Korea
April 1, 1946	Unimak Island (Alaska)	35.0	Hawaii, California, Samoa, Peru, Chile
November 4, 1952	Kamchatka Peninsula	20.0	Hawaii, Sanriku (Japan)
March 9, 1957	Aleutian Islands	16.2	Hokkaido (Japan), California, Hawaii, El Salvador
November 6, 1958	S. Kuril Islands	5.0	Japan

(*continued*)

Table 1.3—(*continued*)

Date	*Source*	$H_{r\max}$ (m)	*Distant areas affected*
May 22, 1960	S. Chile	25.0	South America, Central America, North America, Hawaii, Japan, Marquesas Islands, Pitcairn Island, Samoa, Easter Island, Kuril Islands, Johnston Atoll, Christmas Island, Taiwan, Fiji, New Zealand, Australia
November 20, 1960	Peru	9.0	Japan
March 28, 1964	Alaska	67.1	U.S. west coast, Canada, Hawaii, Japan
February 4, 1965	Aleutian Islands	10.7	Japan, Hawaii
August 11, 1968	SE Hokkaido (Japan)	5.0	Former U.S.S.R.
June 10, 1975	Kuril Islands	5.5	Hokkaido (Japan)
August 19, 1977	S. Sumbawa	15.0	Australia
March 3, 1985	Central Chile	3.5	Hawaii, Alaska, Japan, Ecuador
June 2, 1994	Java	13.9	Australia

Note: One event may be recorded at more than one location.
Sourxe: Based on Lockridge (1988b), and the Intergovernmental Oceanographic Commission (1999).

tsunami every ten years. Tsunami are a more frequent hazard here than tropical cyclones. Many small islands in the South Pacific are vulnerable to tsunami because populations are concentrated around coastlines and perceive the hazard as being rare.

Over the past 2,000 years there have been 692,464 deaths attributed to tsunami in the Pacific region. Of these deaths, 95.4% occurred in events that killed more than a thousand people each. The number of deaths are tabulated in Table 1.4 for each of the main causes of tsunami, while the events with the largest death tolls—including the Indian Ocean event of 2004—are presented in Table 1.5. Tectonically generated tsunami account for the greatest death toll, 89.7%, with volcanic eruptions accounting for 7.5%—mainly during two events, the Krakatau eruption of August 26–27, 1883 (36,417 deaths) and the Unzen, Japan, eruption of May 21, 1792 (14,524 deaths). Before the Indian Ocean tsunami, the number of fatalities was decreasing over time and was concentrated in Southeastern Asia, including Japan. The biggest tsunami of the 20th century occurred in Moro Gulf, Philippines, on August 16, 1976, where 8,000 people died. The largest, total death toll is concentrated in Indonesia

Table 1.4. Causes of tsunami in the Pacific Ocean region over the last 2,000 years.

Cause	*Number of events*	*Percentage of events*	*Number of deaths*	*Percentage of deaths*
Landslides	65	4.6	14,661	2.1
Earthquakes	1,172	82.4	620,796	89.7
Volcanic	65	4.6	51,643	7.5
Unknown	121	8.5	5,364	0.8
Total	*1,423*	*100.0*	*692,464*	*100.0*

Source: Intergovernmental Oceanograhic Commission (1999), United Nations (2006), National Geophysical Data Center and World Data Center A for Solid Earth Geophysics (2007).

Table 1.5. Largest death tolls from tsunami in the Pacific and Indian Oceans over the last 2,000 years.

Date	*Fatalities*	*Location*
December 26, 2004	228,432	Indonesia–Indian Ocean
May 22, 1782	50,000	Taiwan
August 27, 1883	36,417	Krakatau (Indonesia)
October 28, 1707	30,000	Nankaido (Japan)
June 15, 1896	27,122	Sanriku (Japan)
September 20, 1498	26,000	Nankaido (Japan)
August 13, 1868	25,674	Arica (Chile)
May 27, 1293	23,024	Sagami Bay (Japan)
February 4, 1976	22,778	Guatemala
October 29, 1746	18,000	Lima (Peru)
January 21, 1917	15,000	Bali (Indonesia)
May 21, 1792	14,524	Unzen, Ariake Sea, Japan
April 24, 1771	13,486	Ryukyu Archipelago
November 22, 1815	10,253	Bali (Indonesia)
May 1765	10,000	Guanzhou, South China Sea
August 16, 1976	8,000	Moro Gulf (Philippines)

Source: Intergovernmental Oceanographic Commission (1999) and National Geophysical Data Center and World Data Center A for Solid Earth Geophysics (2007), where 237,156 deaths have occurred, the two largest events being the Indian Ocean tsunami of 2004 (167,736 deaths) and the eruption of Krakatau (36,000 fatalities). This location is followed closely by the Japanese Islands where 211,300 fatalities have occurred. Two events affected the Nankaido region of Japan on October 28,1707 and September 20, 1498, killing 30,000 and 26,000 people, respectively. The Sanriku coast of Japan has the misfortune of being the heaviest populated tsunami-prone coast in the world. About once per century, killer tsunami have swept this coastline, with two events striking within a 40-year timespan between 1896 and 1933. On June 15, 1896 a small earthquake on the ocean floor, 120 km southeast of the city of Kamaishi, sent a 30 m wall of water crashing into the coastline, killing 27,122 people. The same tsunami event was measured 10.5 hours later in San Francisco on the other side of the Pacific Ocean. On March 3, 1933, disaster struck again when a similarly positioned earthquake sent ashore a wave that killed 3,000 inhabitants. Deadly tsunami also characterize the South China Sea. Here, recorded tsunami have killed 77,105 people, mainly in two events in 1762 and 1782.

New Zealand and Australia

(de Lange and Healy, 1986; Bryant and Nott, 2001)

Australia and New Zealand are not well represented in any global tsunami database. This is surprising for New Zealand, because it is subject to considerable local tectonic activity and lies exposed to Pacific-wide events. At least 32 tsunami have been recorded in this latter country since 1840. The largest event occurred on January 23, 1855 following the Wellington earthquake. The run-up was 9 m–10 m high within Cook Strait and 3 m high at New Plymouth, 300 km away along the open west coast. However, the highest recorded tsunami occurred following the Napier earthquake of February 2, 1931. The earthquake triggered a rotational slump in the Waikare estuary that swept water 15.2 m above sea level. The most extensive tsunami followed the August 13, 1868 Arica earthquake in northern Chile. Run-up heights of 1.2 m–1.8 m were typical along the complete east coast of the islands. At several locations, water levels dropped 4.5 m before rising an equivalent amount. Subsequent earthquakes in Chile in 1877 and 1960 also produced widespread effects. New Zealand has the distinction of recording two tsunami generated by submarine mud volcanism associated with diapiric intrusions. These occurred near Poverty Bay on the east coast of North Island. The largest wave had a run-up of 10 m elevation.

In Australia, 45 tsunami events have been recorded, beginning with the 1868 Arica, Chilean event. The closest sources for earthquake-generated tsunami lie along the Tonga–New Hebrides trench, the Alpine Fault on the west coast of the South Island of New Zealand, and the Sunda Arc south of the Indonesian islands. The Alpine Fault is an unproven source because it last fractured around 1455, before European settlement. It has the potential to produce an earthquake with a surface wave magnitude, M_s, of at least 8.0, with any resulting tsunami reaching Sydney within two hours. The largest tsunami to be recorded on the Sydney tide gauge was 1.07 m following the Arica, Chile, earthquake of May 10, 1877. However, the Chilean tsunami of May 22, 1960 produced a run-up of 4.5 m above sea level. In Sydney and Newcastle harbors, this tsunami tore boats from their moorings and took several days to dissipate. The northwest coast is more vulnerable to tsunami because of the prevalence of large earthquakes along the Sunda Arc, south of Indonesia. The largest run-up measured in Australia is 6 m, recorded at Cape Leveque, Western Australia, on August 19, 1977 following an Indonesian earthquake. Waves of 1.5 m and 2.5 m height were measured on tide gauges at Port Hedland and Dampier, respectively. Another tsunami on June 3, 1994 produced a run-up of 4 m at the same location. The Krakatau eruption of 1883 generated a tsunami run-up in Geraldton, 1,500 km away, that obtained a height of 2.5 m. This tsunami moved boulders 2 m in diameter 100 m inland and more than 4 m above sea level opposite gaps in the Ningaloo Reef protecting the Northwest Cape. south of the Northwest Cape, tsunami heights decrease rapidly because the coastline bends away to the east. At present, Indonesia is the only known source for tsunami affecting Western Australia.

Bays, fjords, inland seas, and lakes

(Kuran and Yalçiner, 1993; Camfield, 1994; Ranguelov and Gospodinov, 1995; Altinok *et al.*, 1999; Bryant, 2005)

Tsunami are not restricted to the open ocean. They can occur in bays, fjords, inland seas, and lakes. The greatest tsunami run-up yet identified occurred at Lituya Bay, Alaska, on July 9, 1958. The steep slope on one side of the bay failed following an earthquake, sending 0.3 km^3 of material cascading into a narrow arm of the bay. A wall of water swept 524 m above sea level on the opposite shore, and a 30 m to 50-m high tsunami propagated down the bay, killing two people. Steep-sided fjords in both Alaska and Norway are also subject to similar slides. In Norway, seven tsunamigenic events have killed 210 people. The heights of these tsunami ranged between 5 m and 15 m, with run-ups surging up to 70 m above sea level.

Inland seas are also prone to tsunami. There have been 20 observations of tsunami in the Black Sea in historical records. In Bulgaria, maximum probable run-up heights of 10 m are possible. One of the earliest occurred in the first century BC at Karvarna. In AD 853, a tsunami at Varna swept 6.5 km inland over flat coastal plain and traveled 30 km up a river. On March 31, 1901, a 3 m high tsunami swept into the port of Balchik. Bulgarian tsunami originate from earthquakes on the Crimean Peninsula or from the eastern shore in Turkey. Submarine landslides are also likely sources because the Black Sea is over 2,000 m deep with steep slopes along its eastern and southern sides. The Anatolian Fault Zone that runs through northern Turkey and Greece has produced many tsunami in the Black Sea and the Sea of Marmara to the west. At least 90 tsunami have been recorded around the coast of Turkey since 1300 BC. A tsunami flooded Istanbul on September 14, 1509, over-topping seawalls up to 6 m high. At least 12 major tsunami have occurred historically in the Sea of Marmara, mainly in Izmit Bay. The most recent occurred on August 17, 1999. This tsunami appears to have been caused by submarine subsidence during an earthquake. Maximum run-up was 2.5 m along the northern coast of the bay and 1.0 m–2.0 m along the southern shore. Ten tsunami generated by earthquakes or landslides have been recorded in the Caspian Sea. Seven of these occurred on the west coast and three on the east coast. However, the risk is small, as run-ups for the 1 : 100 event do not exceed 1 m.

Finally, tsunami can be generated even in small lakes. The Krakatau eruption of August 27, 1883 sent out a substantial atmospheric shock wave that induced a 0.5 m high, 20-minute oscillation in Lake Taupo situated in the middle of the North Island of New Zealand. Burdur Lake in Turkey has had numerous reports of tsunami although the lake is only 15 km long. On January 1, 1837 an earthquake-generated tsunami swept its shores and killed many people. Tsunami have washed up to 300 m inland around this lake.

METEOROLOGICAL PHENOMENA, FREAK WAVES, AND STORM SURGES

(Wiegel, 1964; Rabinovich and Monserrat, 1996; Hamer, 1999; Bryant, 2005; Monserrat, Vilibi, and Rabinovich, 2006)

Meteorological or meteo-tsunami have the same periods, spatial scales, physical properties, and destructive impact as seismically generated tsunami. Meteorological tsunami are associated with the passage of typhoons, fronts, atmospheric pressure jumps, or atmospheric gravity waves; however, not all of the latter produce meteorological tsunami even at favorable locations. Other forcing mechanisms may be involved. For example, tidally generated internal waves play an essential role in the formation of seiches in the Philippines and Puerto Rico, while wind waves can generate seiching in many harbors. Meteorological tsunami occur when the atmospheric phenomenon generating any surface wave moves at the same speed as the wave. Hence storm surges can be classified as meteorological tsunami if the forward speed of the storm matches that of the surge. For example, during the Long Island Hurricane of 1938, people described the storm surge as a 13 m high wall of water approaching the coast at breakneck speed. This description is similar to some that have been made for 10 m to 15 m high tsunami approaching coastlines.

Meteorological tsunami take on various local names: *rissaga* in the Balearic Islands in the eastern Mediterranean, *abiki* or *yota* in bays in Japan, *marubbio* along the coast of Sicily, *stigazzi* in the Gulf of Fiume, and *Seebär* in the Baltic Sea. They also occur in the Adriatic Sea, the South Kuril Islands, Korea, China, the Great Lakes of North America, and numerous other lakes that can come under the influence of atmospheric activity. Meteorological tsunami can be significant recurrent phenomena. For example, the south end of Lake Michigan near Chicago has experienced many atmospheric events, with one of the largest generating a 3 m wave in 1954. In Nagasaki Bay, Japan, 18 *abiki* events have occurred between 1961 and 1979. The event of March 31, 1979 produced 35-minute oscillations having amplitudes of 2.8 m–4.8 m. In Longkou Harbor, China, 13 seiches have occurred between 1957 and 1980 with a maximum amplitude of 2.9 m. Finally, in the Mediterranean Sea, meteorological tsunami with heights up to 3 m have been recorded at numerous locations.

Meteorological tsunami can consist of single or multiple waves. For example, a meteorological tsunami was probably the cause of the single wave that swept Daytona Beach, Florida, late at night on July 3, 1992. The wave swamped hundreds of parked cars and injured 75 people. However, isolated occurrences and single waves are rare. The phenomenon often affects a particular inlet or bay along a coast because meteorological tsunami are also the product of resonance due to the geometry and topography of a specific section of coastline. Resonance explains why meteorological tsunami recur at specific locations, have constant periodicities, occur as a wave train, and have high-localized amplitudes. Harbors and bays are particularly vulnerable to resonant excitation of waves even where no wave is noticeable along the adjacent open coast. Friction and non-linear processes weaken the formation or propagation of meteorological tsunami so that they disappear in narrow or shallow inlets.

One of the most unusual phenomena to explain is the occurrence of freak waves arriving at a coastline on fine days. These waves are probably solitary waves that have a peak rising above mean water level, but no associated trough. Solitary waves may only have a height of several centimeters in deep water, but when they enter shallow water, their height can increase dramatically. For example, very fast boats such as catamaran ferries can produce a wake that behaves as a solitary wave. In shallow water, the wakes have reached heights of 5 m, overturning fishing boats, and swamping beaches under placid seas. Isolated freak waves can also be caused by the occurrence of a small, localized, submarine landslide—in some cases without an attendant earthquake. Such freak waves are usually treated as a novelty and consequently have not received much attention in the scientific literature. Unlike meteorological tsunami that occur repetitively at some spots, freak waves are a sporadic phenomenon. In the Bahamas, isolated sets of large waves occurring on fair-weather days are referred to as *rages*; however, distant storms cannot be ruled out as a source. In the southern UK, such freak events on clear days are known as *ghost storms*. In Hawaii, the threat of freak waves is certainly recognized and they are attributed to tsunami of an uncertain origin. One of the more unusual events took place on the island of Majuro in the Marshall Islands in 1979. On a clear calm day, a single 6 m high wave appeared from the northeast at low tide, crossed the reefs protecting the shoreline, and crashed through the residential and business districts in the town of Rita, washing away 144 homes. The next day at high tide the same thing happened again. After this second wave hit, the island was declared a natural disaster area by the U.S. government, which was administering the islands. Six days later, another series of waves up to 8 m high again swept the east coast of the island, destroying the hospital, communications center, and more houses. The waves cost $20 million and affected the livelihood of two-thirds of the island's 12,000 people. As recently as September 16, 1999, a 5 m to 6 m wave struck the coastline of Omoa Bay on the island of Fatu Hiva, south of the Marquesas in the central South Pacific Ocean, in the early afternoon on a quiet sunny day. Fortunately, the wave was preceded by a drop in sea level that was recognized as the imminent approach of a tsunami. While evacuations took place, the wave still hit a school, leaving some fleeing students hanging onto floating objects. Buildings close to the shore were destroyed, but no one was killed.

In Australia, two areas—Wollongong and Venus Bay—have reported freak waves. At Wollongong, 40 km south of Sydney on the New South Wales south coast, there have been two incidences of freak waves, both occurring under calm conditions. In the 1930s, water suddenly withdrew from a bathing beach and was followed less than a minute later by a single wave that washed above the high-tide line into the backing dunes. In January 1994, my son witnessed a lone wave that removed paraphernalia and sunbathers from a popular swimming beach, on a calm sunny day. At Venus Bay, which lies 60 km east of Melbourne, Victoria, single large waves often strike the coast on calm seas. The waves have been described as walls of water. One such wave took out a flock of sheep that were grazing near the shore, while another almost dunked a small fishing boat, which only survived because its owner cut the anchor and rode out the wave. Several fishing parties have disappeared along this coast on days when the sea was calm. None of these events can be linked to any tsunamigenic earthquake offshore in the Tasman Sea, Southern Ocean, or Pacific Ocean.

This chapter has presented stories on the human impact of tsunami and alluded to the numerous mechanisms that can generate this hazard. In doing so, terms such as wave height, run-up, and resonance have been used without any explanation about what they mean. The next chapter deals with the definition of these terms and the description of the features that make up tsunami.