# Tsunami: Science and Safety

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South-West suburb of Banda Aceh, Indonesia after the 2004 tsunami.

*On December 26th, 2004, Tom and Arlette Stuip were vacationing in Thailand. While eating breakfast on a terrace overlooking the beach and the Andaman Sea, Tom "noticed the waiters were all pointing at the sea which was receding rapidly. It was a fascinating sight. People got their cameras out and walked towards the dry seabed. The beach was full of sunbathing tourists." Tom was puzzled. While living along the beach in California, He had never observed the ocean behaving like this. "Then it clicked: the brambling he heard earlier was an earthquake. The receding water was the prelude to a tsunami." Arlette recalled, "Tom grabbed my hand and screamed, "Run!". At that same moment, he saw a high wall of water come crashing over the reef towards us at a speed of 40-50 mph. We ran uphill fast. The water was right behind us. The noise was deafening." When they returned to the hotel, destruction was everywhere. Many people were badly injured and many more were dead.*

## About the author

Sarah Glancy is a lecturer at the University of Hawaiʻi – West Oʻahu in the Math, Natural and Health Sciences Department. She teaches earth sciences classes and labs, primarily Introductory Geology, Geological Hazards, and Climate. She is passionate about teaching both science and non-science majors why hazards, such as tsunami, occur and what we can do about these natural phenomena.

Sarah received a Bachelor's of Science degree from the University of Puget Sound and a Master's degree in Geology and Geophysics from the University of Hawaiʻi at Mānoa. Sarah has been recognized for her excellence in teaching at the University of Hawaiʻi – West Oʻahu, having been awarded the Associated Students of the University of Hawaiʻi – West Oʻahu Senate's Appreciation Medal (2020) and the Open Educator Award (2019).

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This chapter is meant to teach a broad audience about tsunami and could be used in a variety of classes. If you feel that this chapter would be useful in your class, you are welcome to share it with your students. If you would like to modify or make additions to this chapter and require a Microsoft Word Document version, please contact the author. (Copyright information is provided below.) Also, feel free to contact the author if you have any questions or comments about this chapter. The author can be reached at: sglancy@hawaii.edu Thanks for reading!

## What is a tsunami?

As seen by this couple's experience, a tsunami can be extremely dangerous and damaging. But what is a tsunami? What does a tsunami look like? What causes a tsunami? And is there anything we can do about them?

A tsunami is a series of waves created when the ocean receives a large amount of energy. The most common causes are underwater earthquakes, volcanic eruptions, and landslides. Over 80% of tsunami are generated by earthquakes. Tsunami are not caused by the tides, so scientists do not consider them "tidal waves."

While people often visualize a tsunami as a large crashing wave, a tsunami does not always look that way. Sometimes a tsunami looks like a quickly rising tide. Some people mistakenly and dangerously think that a tsunami is only one wave and are not prepared for multiple waves. Tsunami waves are much wider than normal ocean waves and can last for a long time. The first wave may not be the largest or the most damaging. Tsunami waves can wrap around islands or land, so not just the coastline immediately facing the tsunami's source is at risk.

"Tsunami" is a Japanese word. Some people use the term "tsunami" as both a singular and plural noun. Others say "tsunami" for a singular noun and "tsunamis" as a plural noun. You will often see these terms used either way. In this chapter, "tsunami" will be used as both a singular and plural noun.

## Comparison of typical ocean waves and tsunami waves

How do regular ocean waves compare to tsunami waves? Ocean waves are caused by wind blowing over the ocean. Energy is transferred from the wind to the top of the water column. In contrast, a tsunami wave is created by a major event such as an undersea earthquake, a landslide, or a volcanic eruption. A large amount of energy is transferred from the event to the water. Instead of just affecting the top of the water column, the energy in a tsunami can move through much or all of the water column.

In order to understand a tsunami, it is helpful to know some wave properties. These are properties that all waves, including tsunami waves, share. Waves have a peak or crest (the highest point) and a trough (the lowest point). The vertical distance from the trough to the peak is the wave height. Half of the wave height is called the amplitude of the wave. The horizontal distance from peak to peak or from trough to trough is called the wavelength. These properties can be viewed in Figure 1.

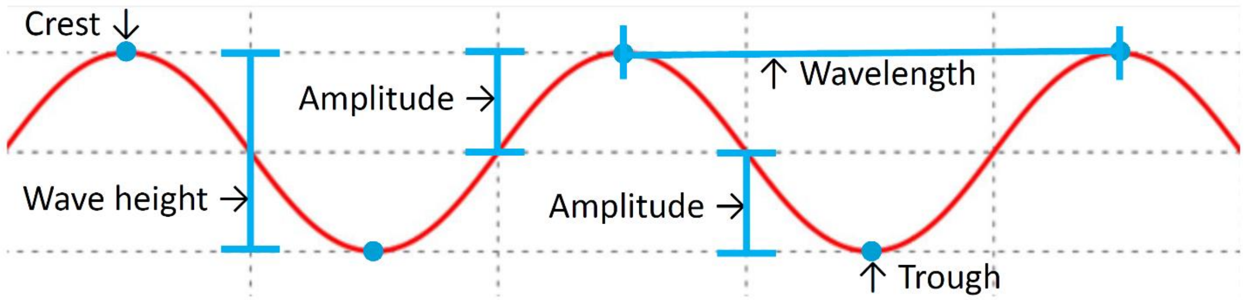



*Figure 1. Diagram of wave properties*

The frequency of waves is the number of waves that pass a point in a given period of time. How can you calculate wave frequency? Imagine floating in the ocean farther away from shore, where no waves are breaking. You will feel yourself float up with each wave crest and down with each trough. Count how many wave crests pass you in an amount of time that you choose, such as a few minutes or an hour. Now, divide the number of wave crests by the amount of time that you chose to calculate the wave frequency. For example, let's say that you count 12 wave crests in one minute (60 seconds). The wave frequency would be 12/60 = 0.2 waves per second, which is one wave crest every five seconds.

Wave period is how long it takes to complete one cycle of a wave. Again, imagine floating in the ocean where no waves are breaking. You feel a wave peak arrive. Now time how long it takes for the next peak to arrive. This amount of time is the wave period. You could alternately use the wave trough to determine the wave period.

Tsunami waves are long wavelength waves. This means that there is more distance between wave crests than normal ocean waves. The wavelength of an average ocean wave is 300-600 feet while the wavelength of a tsunami measures 60-300 miles! Since there is more distance between wave crests, there is more time between waves than for normal ocean waves. In other words, the frequency is lower. If the wave frequency is lower, than the period must be longer. A typical ocean wave's period is 5-20 seconds while a tsunami wave's period can range from 5 minutes to 2 hours.

The lower frequency and longer periods of tsunami waves mean that you will usually observe more ocean waves than tsunami waves in a given period of time. When you are on the beach, how often do you see waves crashing in the same location? Most likely, you will see waves crashing several times a minute. However, it might be two hours between tsunami waves arriving on shore. This can be dangerous for people who are not knowledgeable about tsunami waves. If someone does not know that there can be more than one large tsunami wave and that there can be minutes to hours between waves, they may think that the tsunami event is over after the first wave if they do not see another wave immediately approaching shore.

To illustrate these concepts, look at Figure 2. On May 23rd, 1960 Hilo Bay in Hawaiʻi was hit by a tsunami that originated from an earthquake in Chile. This figure shows water level measurements from Wailuku River Bridge, located near the river's entrance to Hilo Bay. These measurements were taken during the first few hours of the tsunami. Look at the left hand side of the figure, which shows the wave height in feet above or below normal low tide level (zero feet). (You can find the same information in meters on the righthand side of the graph). The first wave is labeled on the figure. You can see that the wave height at this time is displayed as higher than the normal low tide level. The first wave receded approximately 15 minutes later, causing the water level to drop to almost four feet below normal low tide level. But this was not the end of the 1960 tsunami event in Hilo. Approximately thirty minutes after the arrival of the first wave, another large wave arrived. You will notice that after this, water level continued to fluctuate dramatically, raising to about 14 feet above normal low tide at one point, and falling to more than six feet below low tide level at other points. Each high point represents the maximum height that an individual tsunami wave reached. These fluctuations mean that as the tsunami waves came onshore and went back out to sea, the water level in the bay would have been much higher than normal at certain times (tsunami waves could inundate land) and much lower than normal at other times. You will notice that there are multiple fluctuations (tsunami waves). The wave that devastated part of the town of Hilo is labeled on the figure. It is important to note that this was not the first nor the last wave. Additionally, the waves varied in size before and after the largest wave. Look at the time of the waves (shown at the top of the figure). You will notice that there are multiple minutes between the waves. The waves do not always occur at regular intervals. You will also notice that this figure shows over two hours of measurements. Multiple waves occurred during this period of time. The tsunami event was not over after the first wave and lasted for over two hours.

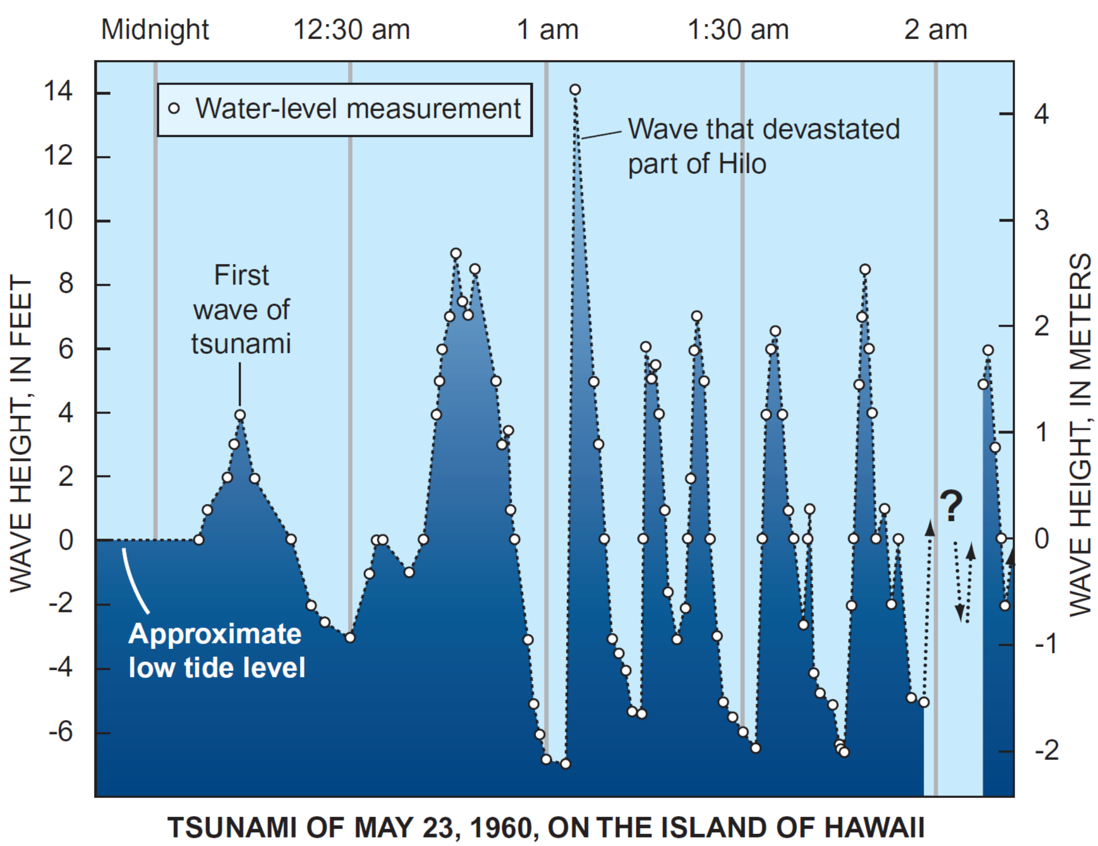



*Figure 2. Measurements of water height at Wailuku River Bridge, Hilo, Hawai'i during the night of May 23rd, 1960. These measurements document the arrival of multiple tsunami waves, which originated from an earthquake in Chile. These measurements were taken by Jerry Eaton and colleagues.*

## What causes a tsunami?

A tsunami starts when a large amount of energy is transferred to the water suddenly, for example, during an earthquake.

To explain what this means, let's use an example. Visualize diving into a pool of perfectly still water. When you dive into the pool, your sudden entry causes water to move. The force and energy from your dive now transfers to the water in the pool. You will notice concentric rings of ripples moving away from your point of entry. These ripples show the location of the energy and the movement of energy throughout the pool.

Now, let's use the example of an underwater earthquake. Similarly, when an earthquake happens on or below the ocean floor, water is suddenly moved or displaced. The energy from that displacement is transferred to the water. This energy then ripples out in all directions.

Tsunami waves are energy moving through the water. This means that rather than individual water molecules moving all the way from far out in the ocean to shore, energy is moving from the tsunami source to shore through the water. An analogy is people in a stadium doing "the wave." When people do "the wave" in a stadium, it is not one group of people walking though the stadium waving that makes it look like there is a wave going through the stadium. Instead, it is one group standing up and waving, and then the next group standing up and waving, and so on. The "energy" has moved through the stadium even though the original group of people have not walked away from their seats.

A large transfer of energy through the water allows tsunami waves to move very quickly through the open ocean. They can travel at the speed of a commercial jet in deep water (at over 500 miles per hour). Close to shore, they slow down to about the speed of a car in a residential neighborhood (20 or 30 miles per hour).

## What happens as a tsunami wave moves inland?

When the tsunami moves farther from the source, the energy spreads out and starts to dissipate. As the tsunami comes to shore, friction with the ocean bottom causes the waves to slow down. When tsunami waves slow down, their wave heights increase, often dramatically. The same amount of energy is now concentrated in less water. The tsunami wave is still powerful.

Even though energy dissipates as the tsunami moves further away from the source, it is important to realize that a tsunami can still be dangerous and deadly, even far from the source of the tsunami. For example, on May 22$^{nd}$, 1960, Chile was hit by a magnitude 9.5 earthquake, the largest earthquake ever recorded. 15 hours later, a 35-foot wave hit Hilo Bay in Hawaiʻi, killing sixty-one people.

The height of the tsunami wave above sea level is called the tsunami's runup. Inundation is how far inland the tsunami waves travel. Inundation will vary from place to place, even on one island, because it is dependent on the shape of the ocean floor and the land. In a very flat area, the tsunami can move farther inland than in a steep area. Therefore, even if the runup is the same in two areas, the inundation may be different.

## Tsunami and plate tectonics

Why do tsunami occur more frequently in some areas than in others? The answer: Earthquakes are distributed unequally throughout the world due to plate tectonics.

What is plate tectonics? Plate tectonics is the underlying cause of many hazards on Earth, including earthquakes and tsunami. The outer layer of the Earth is broken into pieces, called plates, that move. Plates can converge (move towards each other), diverge (move away from each other), or slide past each other. Interactions between these moving tectonic plates can cause earthquakes, which in turn, can cause tsunami waves to form. Figure 3 shows where different plates are located around the world, with the different colored areas representing different tectonic plates.

Now, we will explore the relationship between plate tectonics and a tsunami. Look at Figure 4, which shows the source locations for world-wide tsunami that occurred between 1610 B. C. to 2017 A.D. The different symbols represent different causes: volcanic eruptions, landslides, earthquakes, and unknown causes. Earthquakes (circles) are the most common cause. This figure illustrates that some areas of the world produce more tsunami than others.

Now, to illustrate the relationship between plate tectonics and tsunami compare Figure 3 and Figure 4. Look at the Pacific Ocean. In Figure 3, you will notice that the middle of the Pacific Ocean is on the Pacific Plate, with plate boundaries surrounding the Pacific Ocean. We will now compare the two figures, using the Aleutian Islands in Alaska as a starting point. Look at the northernmost part of the Pacific Plate. Where it borders the North American Plate, you will find the Aleutian Islands on the North American Plate. Now, find the Aleutian Islands on Figure 4. You will notice that this area has been the source for many tsunami.

Look for other plate boundaries in the Pacific Ocean. You will see that most of the western coasts of North and South America are plate boundaries and have produced numerous tsunami. Compare this to an area with no plate boundaries, such as the East Coast of the United States. You will notice that far fewer tsunami started in areas with no plate boundaries than areas on a plate boundary.

Finally, look at Antarctica. You will notice that it sits on the Antarctic Plate (blue in Figure 3). Follow the boundary between the Antarctic and Pacific Plate on both Figure 3 and Figure 4. You will notice that few to no tsunami formed here during this time period. While tsunami tend to start at plate boundaries, not all plate boundaries have the same number of tsunami-producing events associated with them. Why? The answer is that there are different types of plate boundaries. Recall that plates can converge, diverge, or slide past each other. Different types of plate motion will create different types of plate boundaries.

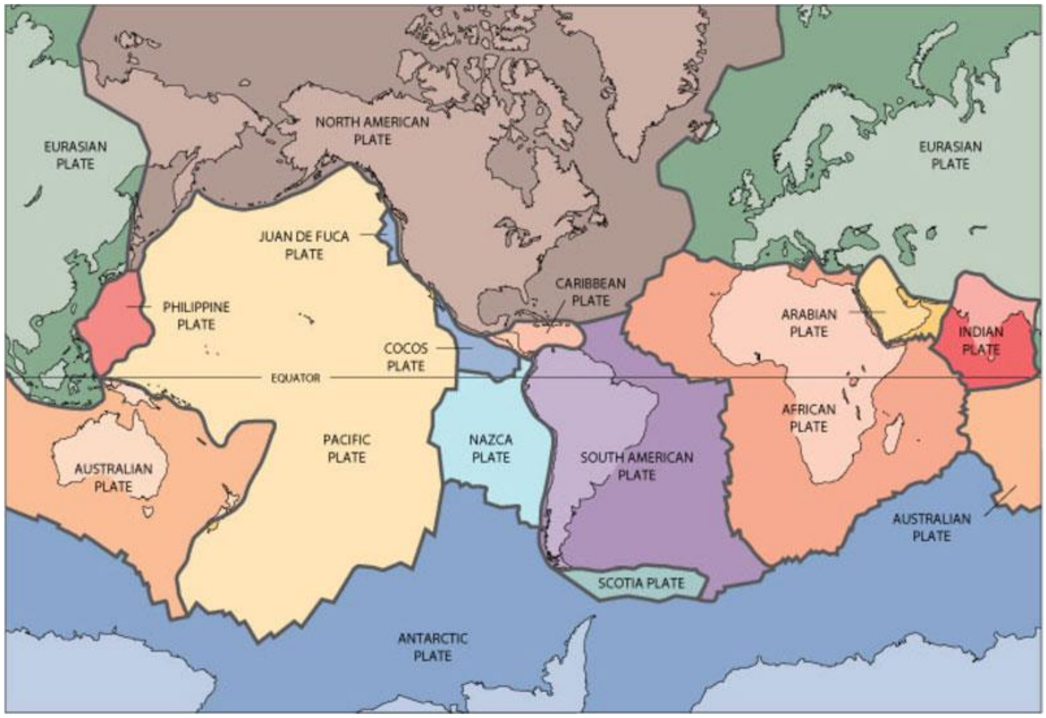



*Figure 3. Earth's tectonic plates*

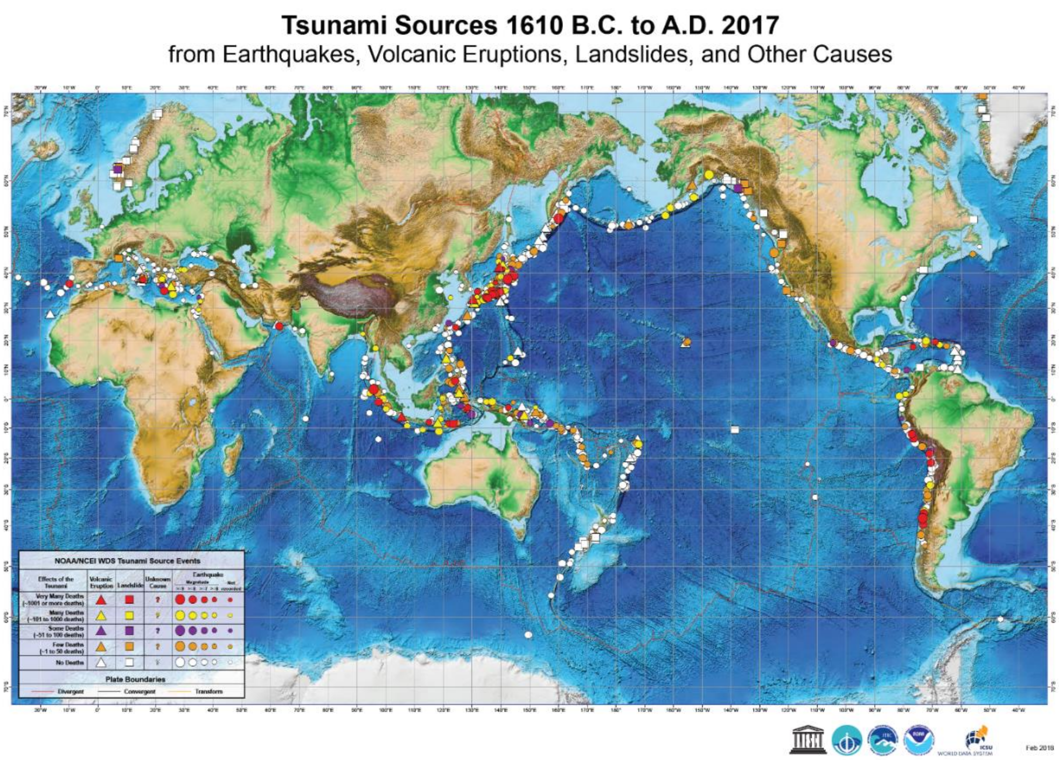
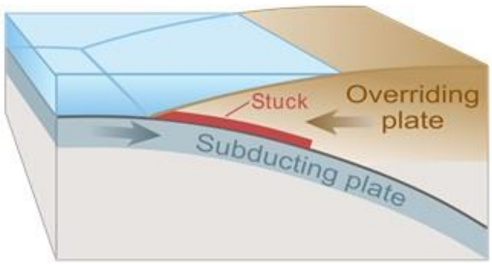



*Figure 4. Locations where tsunami were generated throughout the world from 1610 B.C. to 2017 A.D. Different symbols represent different tsunami causes. Note that most of the tsunami were caused by earthquakes (circles).*

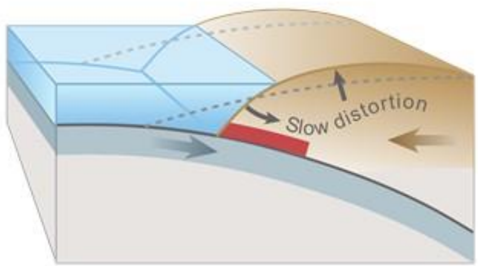
We will now examine subduction zones, a type of plate boundary that can create very large earthquakes and very powerful tsunami. Where the plates converge, one plate may subduct (be forced down) under another one. This type of plate boundary is called a subduction zone. The plates do not slide smoothly past each other. Instead, friction between the plates can cause them to become "stuck." More and more pressure builds up as the plates try to move and the overriding (upper) plate deforms. Eventually, the pressure is too great, the plates move, and an earthquake occurs. The overriding plate (the plate above the subducting plate) tries to snap back to its previous position and in the process displaces the water above it, imparting energy into the water and producing tsunami waves. Figure 5 illustrates and describes this process.

Globally, more than 80% of tsunami are generated in this way. Extremely large earthquakes can be generated at subduction zones. Subduction zone generated earthquakes can cause some of the most dangerous tsunami waves in the world. A very large earthquake from a subduction zone can travel across entire ocean basins, causing damage on coastlines surrounding that ocean. One example is the 2004 Indian Ocean Tsunami. While the tsunami was generated by an earthquake in a subduction zone near Sumatra, Indonesia, the tsunami was not limited to Indonesia. Countries around the Indian Ocean were devastated.

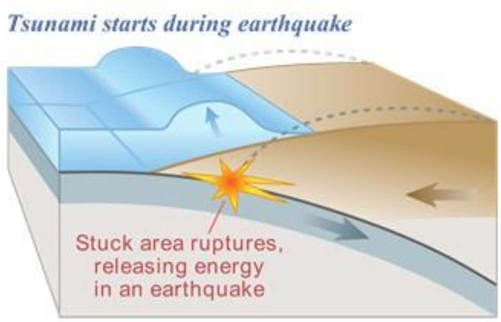
Another hazard found at subduction zones are volcanoes. Volcanoes can also trigger tsunami.



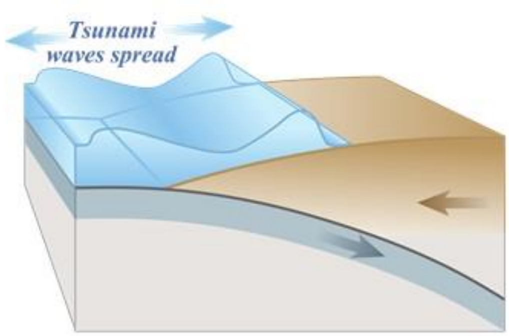

**Converging plates at a subduction zone become stuck.**
When two tectonic plates converge, one plate can subduct (be forced down) under the other one. The plates do not always move smoothly. The subducting plate and the overriding (upper) plate can become stuck (red area). The arrows represent the direction of plate motion.




**The overriding plate is deformed.**
If the two plates become stuck (red area), stress will build up. The overriding plate will be deformed (bent). The leading edge of the overriding plate will be pulled downwards with the subducting plate. The area behind it will bend upwards. This will occur slowly over time.




**An earthquake occurs and a tsunami begins.**
Eventually the stress becomes too great and the stuck area ruptures (breaks). Energy is released. When this energy reaches earth's surface, it causes the ground to shake, an earthquake. The leading edge of the overriding plate springs upwards, pushing the seafloor and water above it up and imparting energy to the water. A tsunami begins.




**Tsunami waves spread through the ocean.**
Tsunami waves can travel in all directions away from their source. Depending on the amount of energy involved, they can affect areas all around an ocean.

*Figure 5. A series of illustrations showing how tsunami can form in subduction zones.*

One region that is of particular interest when studying tsunami events is the “Ring of Fire.” The “Ring of Fire,” is a zone in the Pacific Ocean where tectonic plates interact to create volcanoes, earthquakes, and therefore tsunami waves. To see the location of the “Ring of Fire,” look at Figure 6, which is a map of the Pacific Ocean with the “Ring of Fire” indicated. You will notice that the “Ring of Fire” mostly circles the Pacific Ocean. Why? Let’s look at the “Ring of Fire” in more detail.

Look at Figure 3 and focus on the Pacific Plate (light yellow). You will notice that most of the Pacific Ocean is located on the Pacific Plate. Compare Figure 3 to Figure 4 and Figure 6. You will notice that the shape of the Pacific Plate mostly matches the shape of the “Ring of Fire,” as drawn on Figure 6. You will also notice that the “Ring of Fire” was the source of many tsunami between 1610 B.C. and 2017 A.D.

Why? Remember that the type of interaction between the tectonic plates governs what hazards occur at those locations. Look at Figure 6, which also shows where major subduction zones are located throughout the Pacific Ocean. You will notice that many of the plate boundaries around the Pacific are subduction zones, meaning that this region is at risk for large tsunami waves.

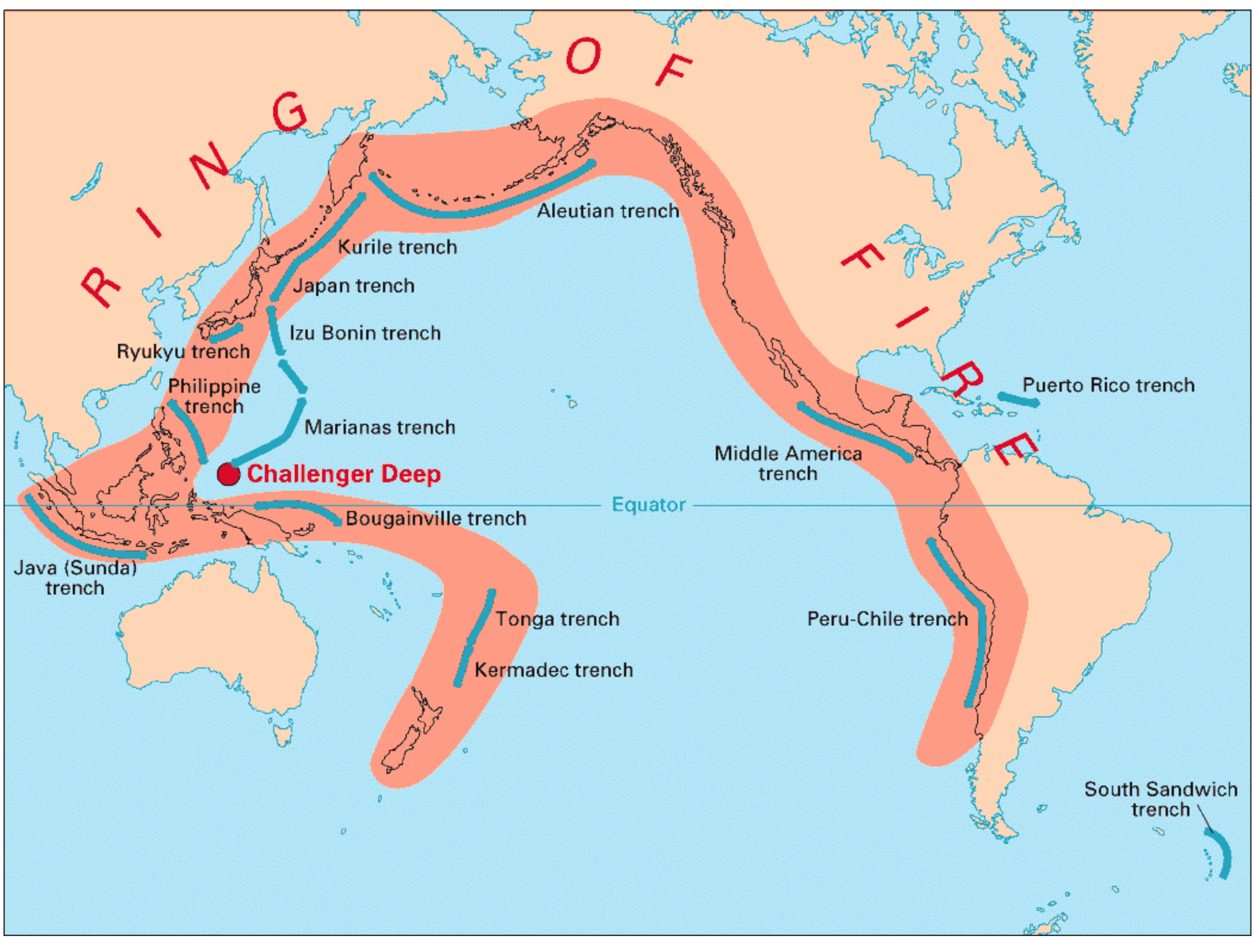



*Figure 6. Map of the “Ring of Fire.” Blue lines are subduction zones. Notice how many subduction zones there are around the Pacific Ocean.*

## Tsunami warning system in the United States

On April 1st, 1946, a large earthquake struck Alaska. Near the earthquake, the tsunami waves were as high as 138 feet or 42 meters. About five hours later, a 45 foot (13.7 meter) tsunami hit Hilo Bay in Hawaiʻi, killing 159 people. If those 159 people had received a warning, many or all of them could have survived. As a result, in 1949, the United States started a tsunami warning system.

There are now two tsunami warning centers in the United States: The National Tsunami Warning Center in Palmer, Alaska and The Pacific Tsunami Warning Center in Honolulu, Hawaiʻi. Both operate 24 hours a day and seven days a week, year-round. Figure 7 shows a scientist monitoring for a tsunami.


*Figure 7. A scientist monitors for tsunami.*

How can these centers forecast a tsunami? Remember that most tsunami waves are caused by earthquakes. Therefore, the tsunami warning centers monitor and analyze earthquakes.

When an earthquake occurs, scientists must first determine where the earthquake occurred. If the earthquake occurred underwater, there may be a tsunami risk. They also measure the magnitude of the earthquake, as a larger magnitude earthquake tends to be more likely to cause a tsunami. Lastly, they estimate how deep in the Earth the earthquake was. Shallow earthquakes are more likely to cause a tsunami.

If an earthquake occurs that scientists think may cause a tsunami, they then turn to sea level gauges to look for evidence of a tsunami. Is the water level higher than normal? DART buoys located at sea are useful tools to detect a tsunami. Figure 8 shows a diagram of what the DART system looks like. Sea level gauges (Figure 9) at harbors and other coastal areas are also useful in detecting any unusual changes in the level of the sea.

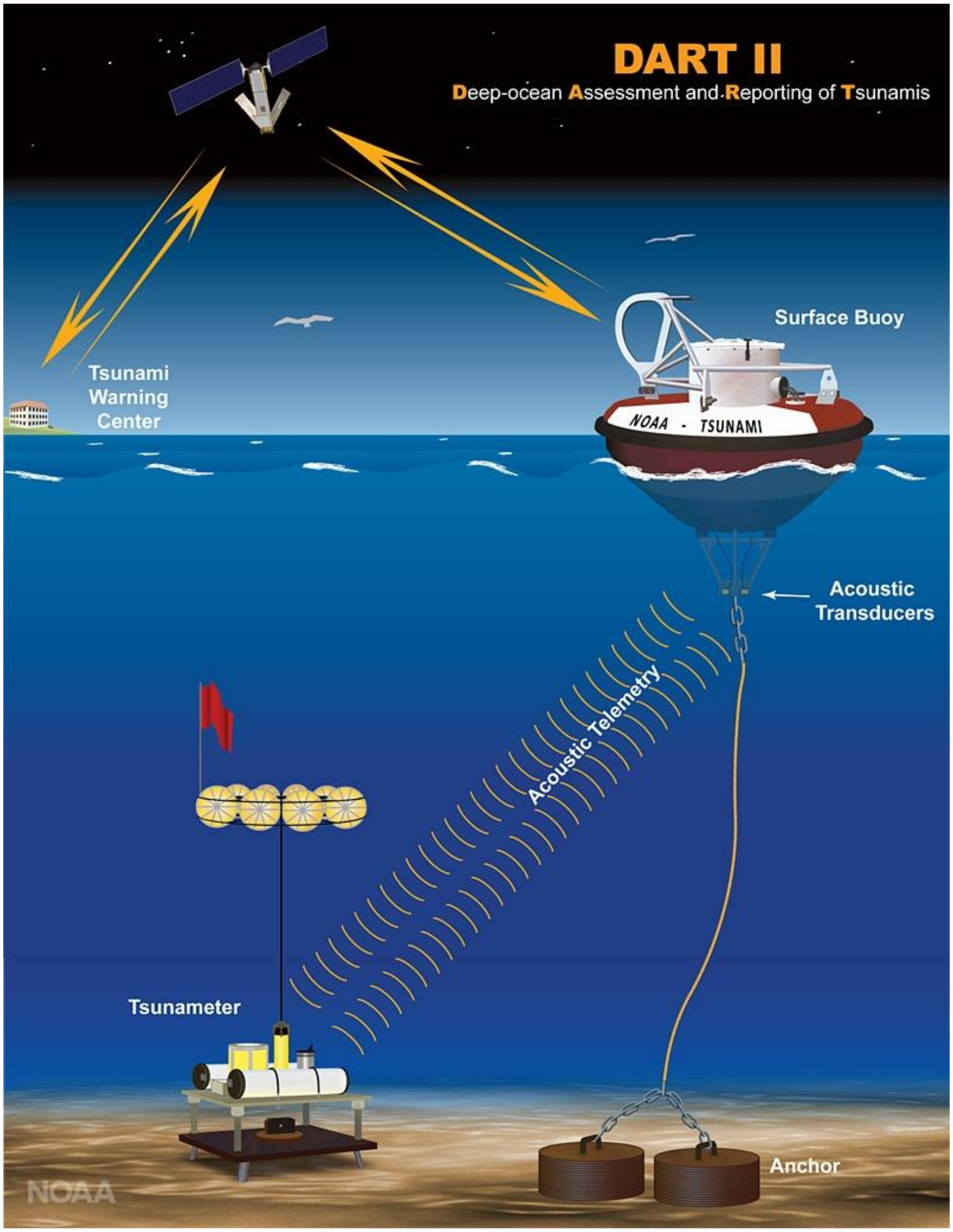



*Figure 8. Diagram of the DART system*


*Figure 9. Image of a coastal water-level station*

If information about the earthquake and data from sea level gauges indicate that a tsunami may occur, scientists must then forecast tsunami behavior and what areas are likely to be impacted by the tsunami.  Tsunami behavior is dependent on several factors.  The first factor is the nature of the earthquake.  For example, how deep in the Earth was the earthquake?  What was the magnitude of the earthquake?  How did the seafloor move (vertically or horizontally and by how much)?   Another factor is the shape of the sea floor.  The speed that the tsunami travels is dependent on the water depth.  The deeper the water, the faster the tsunami can move.  Using maps of seafloor depth, scientists can predict how long it will take for the tsunami to arrive at different locations around the world.

Once scientists have determined that a tsunami is likely, they must forecast the potential runup of the tsunami at different locations around the world.  To do so, they use computer models that predict tsunami behavior as a tsunami travels across the ocean and as it nears land.

After scientists have studied the earthquake, determined if a tsunami is likely, and forecasted the runup of any potential tsunami, they can then advise the public by issuing a message.  Here are the messages that you will hear from a warning center:

- If there is no predicted tsunami hazard, scientists will issue an **Information Statement**.
- If there is a risk of a tsunami, scientists can issue one of three messages:
    - A **Tsunami Watch** warns citizens and emergency managers that a tsunami threat is possible in the near future. Citizens should stay tuned for more information.
    - A **Tsunami Advisory** tells the public and emergency managers that there is a marine threat and/or a near-shore threat. An advisory is issued when the tsunami runup is forecasted to be 1-3 feet. Beaches will be cleared and people will be asked to stay out of the ocean and away from the water, but a large evacuation will not be mandated
    - A **Tsunami Warning** is issued when there is a risk that the tsunami will impact farther inland than the shoreline. A warning is issued if the runup is forecasted to be greater than three feet. In this case, people in tsunami evacuation zones will be asked to evacuate.

Figure 10 summarizes tsunami messages from warning centers.

When the tsunami's runup no longer meets these thresholds, the Tsunami Warning Center will issue a Cancellation. However, this does not necessarily mean that it is safe to return to the areas that were impacted by the tsunami. These areas may be covered in potentially hazardous debris and there may be dangerous ocean and shoreline conditions well after the main tsunami threat has passed. Local emergency managers and officials decide when to lift the evacuation order and when it is safe for people to return to their homes and businesses.

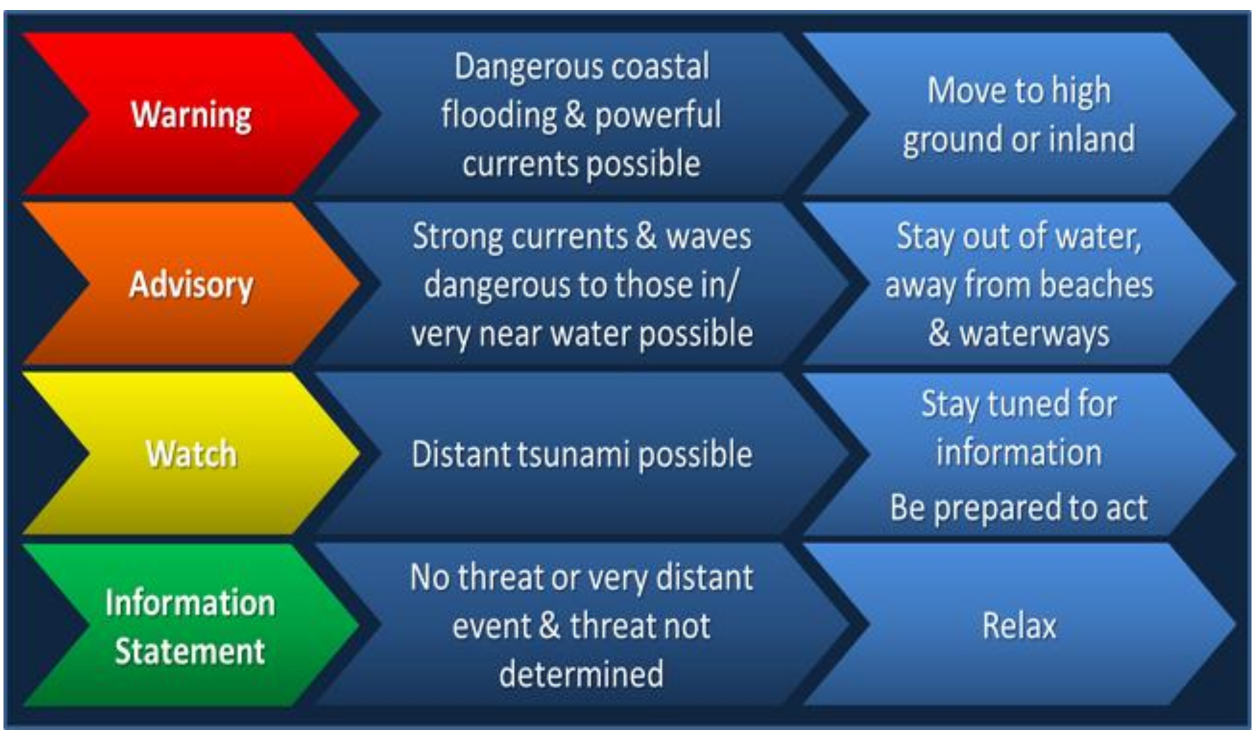



*Figure 10. Tsunami messages from Tsunami Warning Centers in the United States*

## How do you know if there is a threat of a tsunami?

Unfortunately, as tsunami waves are caused by powerful forces of nature, such as earthquakes, that we cannot control, we cannot prevent a tsunami from forming. All we can do is be prepared.

In the United States, there is a tsunami warning system in place to forecast tsunami events and inform local officials. In some places, such as Oʻahu, Hawaiʻi, a siren system is designed to alert the public about a tsunami warning. The Tsunami Warning Centers post information statements, watches, advisories, and warnings on their websites. Some other places around the world also have tsunami warning systems. If you live by the water or plan to travel somewhere by the water, it is good to do some research and learn if that area has a tsunami warning system.

If you are really close to the source of a tsunami, there might not be time for a tsunami warning system to inform you of the risk of a tsunami. Furthermore, not everywhere in the world along a coastline has a tsunami warning system, or the warning system may be damaged or destroyed due to the earthquake that caused the tsunami. Therefore, it is important to know some of the natural warning signs of a tsunami. This knowledge can save your life. If you experience any one of these natural warning signs, do not wait for a siren or an official warning. Move to higher ground immediately.

Some natural warning signs of a tsunami are:

- You may feel an earthquake. If you are near the water and feel an earthquake, it is important to get to higher ground immediately. The earthquake may have triggered a tsunami.
- If the trough of the wave arrives first, the ocean will recede like an extremely low tide and areas that are normally underwater will be exposed. Note: The sea does not always recede before a tsunami arrives.
- If the crest of the wave arrives first, the ocean will surge onto the beach. It can look like a rapidly rising tide, but it does not stop.
- You may see a bore, a wall of water.
- You may hear a loud roar from the ocean.

Note: You may not observe all of these signs before a tsunami arrives.

One person's knowledge of the natural signs of a tsunami saved many lives during the 2004 Indian Ocean Tsunami in Thailand. While on vacation in Thailand with her family, 10 year old Tilly Smith noticed that the sea was high on the beach. Waves were coming in but not leaving. The water looked "frothy and fizzy". She noticed a log that kept spinning around in the water. Then, she realized what was happening: a tsunami was approaching. Just two weeks earlier, in her geography class, she had learned about tsunami waves and watched a video of a tsunami in Hawaiʻi. Incredibly, she remembered and recognized the natural signs of a tsunami and urged her family and others to run away from the beach and move to higher ground. Her father alerted a security guard who then yelled for people to evacuate. Tilly then saw a wall of water approaching. Tilly, her family, hotel employees, and guests took shelter on an upper floor of the hotel. After the initial wave, she warned the people that more waves could arrive and that they should remain in the upper floors of the hotel. Luckily, no one on their beach died in the tsunami that killed almost 230,000 people.

## What should you do in the case of a tsunami?

Knowledge about tsunami safety is important for everyone. Even if you do not currently live by the ocean, you may one day live or vacation there, so it is important to understand what to do in the case of a tsunami.

If you are in an area that is at risk of being flooded during a tsunami, it is important to get to higher ground as soon as possible. This may mean traveling inland. In many areas of the world, if you are able to walk inland towards higher ground, that may be a better choice than driving because traffic jams can occur when many people attempt to evacuate at once. If there is not time to move inland and there are sturdy buildings in the area with at least four levels, you may need to "vertically evacuate." Buildings with an open floor plan are best. Go to one of those tall buildings and climb the stairs to at least the 4$^{th}$ floor. Because there may be many other people on the stairs behind you that are also trying to evacuate, it is advisable to keep climbing if possible. Note that not all buildings are built to withstand a tsunami.

How do you know if the area you are in is at risk if a tsunami arrives? In some area of the world, scientists, community leaders, and emergency managers have developed evacuation plans. To do so, scientists prepare maps that predict the risk of inundation from different sizes of tsunami. In order to prepare these maps, they study past tsunami events and earthquakes and use models to understand what may occur in the future. Emergency managers then use these maps to create evacuation plans for the region. These plans include evacuation maps, evacuation routes, and designated evacuation shelters. It is important to familiarize yourself with the evacuation plan in the area where you are living or are visiting.

Let us look at the island of Oʻahu, Hawaiʻi as an example. There are two evacuation zones on Oʻahu: 1. The Tsunami Evacuation Zone and 2. The Extreme Tsunami Evacuation Zone. If you are in one of these two evacuation zones when a tsunami occurs, you may need to evacuate. During a tsunami evacuation, you will need to either move inland to a safe zone or practice vertical evacuation.

The map below shows the Waikīkī area of Oʻahu (Figure 11). The red zone is the Tsunami Evacuation Zone. It is the zone closest to the ocean and people in this zone must evacuate in the case of any tsunami warning. People in the yellow zone, the Extreme Tsunami Evacuation Zone, evacuate only in the case of a larger tsunami. People in the Safe Zone (green) do not have to evacuate. When a tsunami threatens, emergency managers tell citizens which zone(s) must evacuate. A series of detailed evacuation maps has been made for all coastal areas on Oʻahu.

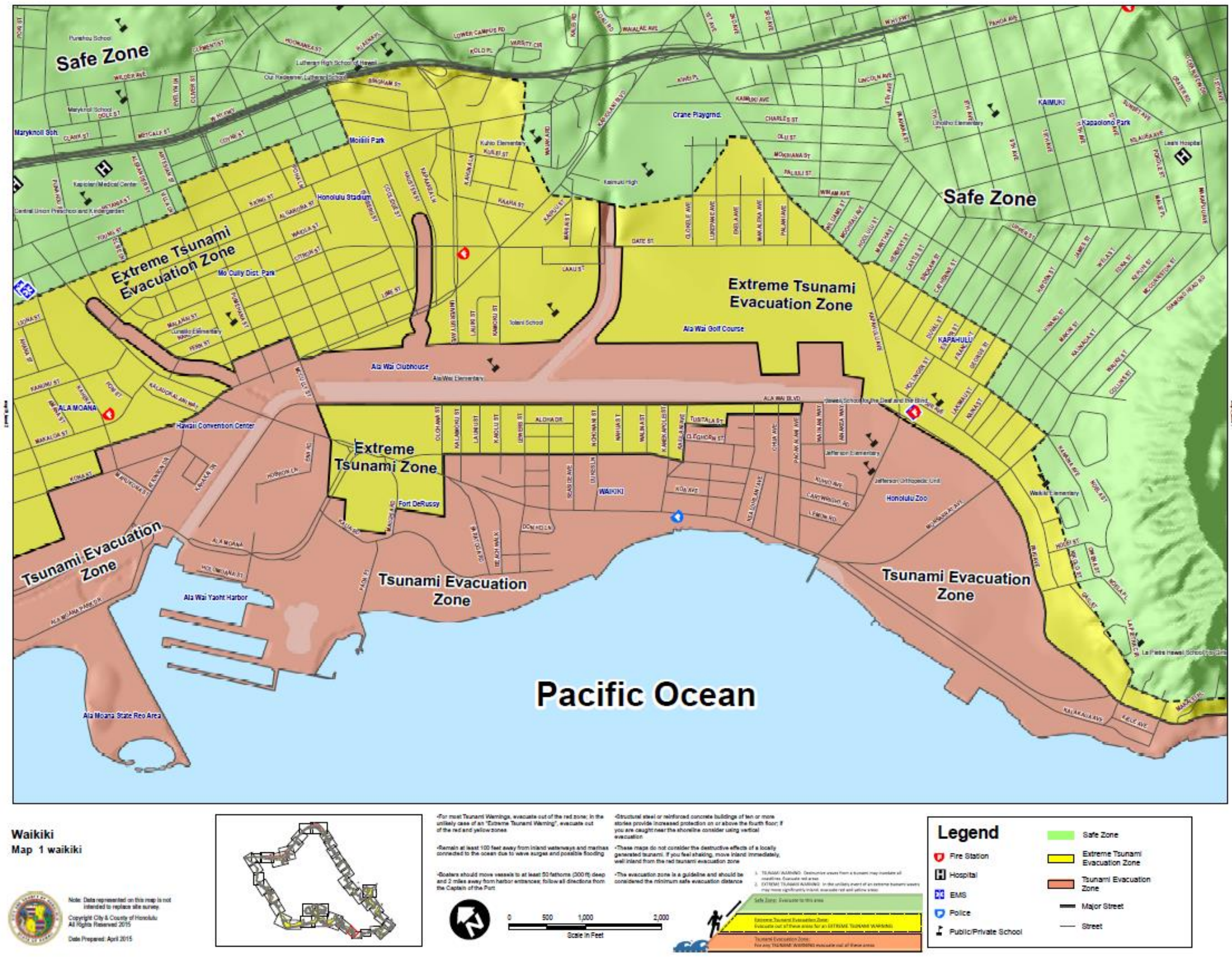



*Figure 11. Tsunami evacuation map for Waikīkī, Hawai'i*

If you live by the ocean, familiarize yourself with the evacuation zone(s), evacuation plans, evacuation routes, and the evacuation shelters for your community. Do you live, work, shop, or go to school in an evacuation zone? Think about what you would do during a tsunami. Would you be required to leave your work, home, or school? If so, where would you go?

If you are vacationing in an area near an ocean, read the tsunami safety and evacuation plans so you will know what to do and where to go in the case of a tsunami.

## Paleotsunami research and indigenous knowledge aid tsunami understanding and emergency preparedness

How can we predict future tsunami strength and risk? To do this, scientists examine multiple types of records throughout the world.

Written records can provide detailed information about past tsunami events. Scientists can use these records to determine when a tsunami occurred and the damage it caused. While these records can be very detailed and useful to scientists, they often do not extend back far into time.

In many places around the world, information about past tsunami events and tsunami safety are recorded in oral traditions. These stories and legends tell scientists where a tsunami occurred in the past. For example, local Native Americans shared stories about the 1700 Cascadia earthquake and tsunami, which originated in what is now the states of Oregon, Washington and Northern California, plus Vancouver Island in Canada.

Oral traditions containing information about tsunami safety can save lives. For example, on December 26th, 2004, a tsunami in the Indian Ocean killed almost 230,000 people. Although Simeulue Island was close to the epicenter of the earthquake which triggered the tsunami, only seven of 75,000 people living on the island died. Why? Many people survived because of oral traditions passed down over generations. These oral traditions warned Simeulue Island residents that feeling an earthquake and observing receding water were signs that a tsunami would quickly arrive and to move immediately to higher ground.

Scientists also use paleotsunami studies of rock, sediment, and/or soil layers to better understand tsunami threats. Scientists examine the layers for signs of tsunami deposits, such as the presence of sand or large grain size and/or rock debris in areas where such deposits would not normally occur. For example, scientists might find many layers of mud and then a layer of sand and rock debris. The layer of sand and rock debris could be a tsunami deposit, which has brought in larger particles than typically found in the area of study.

For surface or near surface deposits, geologists dig pits or trenches to look at sediment layers. Figure 12Figure 12 is an image of such a trench where tsunami and non-tsunami layers can be seen. For deeply buried sediment or rock, geologists drill into the ground and pull out sediment or rock cores. Cores are cylinders of sediment or rock that contain layers deposited over time. These layers sometimes contain tsunami deposits. Figure 13 is an image of a sediment core from Japan showing two tsunami deposits, as well as non-tsunami related layers.

If geologists discover tsunami deposits, they trace the extent of the tsunami by looking for the same deposit in many nearby areas. Geologists can then determine how far inland the tsunami went. In some cases, the damage caused by a tsunami is still present. In Washington and Oregon, a tsunami caused by the large 1700 Cascadia earthquake caused the ground near the ocean to fall five feet. The ensuing tsunami waters rushed inland, killing large cedar trees. These “ghost trees” are visible today. If a similar event were to occur today, the damage would be catastrophic.

Geologists age date the tsunami layers to determine when the tsunami occurred.  If multiple layers of tsunami deposits exist, geologists then count the number of tsunami events over the period of time represented by the rock or soil layers to determine the recurrence interval.

The recurrence interval is a measure of how often a tsunami occurs.  If the recurrence interval of a tsunami with a 10-foot runup is 100 years, this means that a tsunami with a runup of 10 feet occurs on average every 100 years.  Note that the recurrence interval gives the average amount of time between tsunami events, not the exact amount of time.  In other words, it cannot be used to predict the exact timing of a future tsunami event.  In the example, if a tsunami with a 10-foot runup occurred in 2010, that does not mean that there will not be a tsunami with a 10-foot runup until 2110.  A tsunami could happen this year or it could happen after the year 2110.


*Figure 12. Image of a trench that scientists have dug into sediment layers to look for tsunami deposits.  The dark grey squares represent locations where sediment samples were collected for further analysis.*


*Figure 13. A sediment core from Arahama, Japan showing two tsunami deposits, as well as non-tsunami related sediment layers.*

# Conclusion

A tsunami is a powerful and dangerous event, where a series of large waves can inundate the shoreline and sometimes far inland. Waves can flood the land for a long period of time and the first wave is not always the largest. Tsunami waves are most frequently generated by underwater earthquakes, volcanic eruptions or landslides, with earthquakes being the most common cause. While tsunami cannot be prevented or predicted days, months, or years in advance, there are steps that we as a society can take to try to minimize the impacts of tsunami. Scientists can use paleotsunami research and modeling to understand what can happen in an area in the future and create maps of areas that are at the most risk. Emergency managers and community leaders can use this information to make evacuation maps and plans. In some locations, oral traditions and traditional knowledge of tsunami safety are being revitalized. After an underwater earthquake occurs, scientists can forecast if, when, and where a tsunami may occur. In the United States, two tsunami warning centers study tsunami and make these forecasts. Emergency managers and community leaders can then use this information to order evacuations, if necessary.

There are steps that everyone can take to help keep themselves, their family, friends, and community safer. Study the tsunami evacuation maps of the area where you live or vacation and know what you would need to do if a tsunami occurs. Realize that it is not always possible for an official warning to reach you before the first tsunami wave arrives in an area if that area is close to the source of the tsunami. Furthermore, some areas may not have warning systems in place. Therefore, it is important to know the possible warning signs of a tsunami and to be alert for these signs while at the beach.

## Some further reading

- Information from The **National Oceanic and Atmospheric Administration's Tsunami Program** can be found at the following link: https://www.tsunami.noaa.gov/
- Information from The National Oceanic and Atmospheric Administration / National Weather Service's **U.S. Tsunami Warning System** can be found at the following link: https://www.tsunami.gov/
- Information from The **International Tsunami Information Center** can be found at the following link: http://itic.ioc-unesco.org/index.php
- Information from The **Pacific Tsunami Museum** can be found at the following link: http://tsunami.org/
- Information from The **Intergovernmental Oceanic Commission Tsunami Programme** can be found at the following link: http://ioc-tsunami.org
- A list of **International Tsunami Information Centers** can be found at the following link: http://itic.ioc-unesco.org/index.php?option=com_content&view=category&layout=blog&id=2006&Itemid=2006

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