

EENS 2040	Natural Disasters
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<b>Tsunami</b>	

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Up until December of 2004, the phenomena of tsunami was not on the minds of most of the world's population. That changed on the morning of December 24, 2004 when an earthquake of moment magnitude 9.1 occurred along the oceanic trench off the coast of Sumatra in Indonesia. This large earthquake resulted in vertical displacement of the sea floor and generated a tsunami that eventually killed about 230,000 people and affected the lives of several million people. Although people living on the coastline near the epicenter of the earthquake had little time or warning of the approaching tsunami, those living farther away along the coasts of Thailand, Sri Lanka, India, and East Africa had plenty of time to move higher ground to escape. But, there was no tsunami warning system in place in the Indian Ocean, and although other tsunami warning centers attempted to provide a warning, there was no effective communication system in place. Unfortunately, it has taken a disaster of great magnitude to point out the failings of the world's scientific community and to educate almost every person on the planet about tsunami.

Even with heightened world awareness of tsunami, disasters still occur. On September 29, 2009, earthquakes in the Samoa region of the southwest Pacific Ocean killed nearly 200 people, and as a result of the Chilean earthquake of February, 2010, at least 50 casualties resulted from a tsunami triggered by a moment magnitude 8.8 earthquake.

On March 11, 2011 a Moment Magnitude 9.0 earthquake struck off the northern Coast of Japan. The Earthquake generated a tsunami that rose up to 135 feet above sea level and killed over 20,000 people. Because of Japan's familiarity with earthquakes and enforcement of earthquake resistant building codes, there was only minor destruction from the earthquake itself. But, despite that fact that a tsunami warning system was in place, the earthquake was so close to the coast, that little time was available for people to react.

Besides that high death toll, the tsunami caused one of the worst nuclear disasters in history. The Fukushima nuclear power plant, located on the coast was hit by a 49 ft. tsunami wave that overtopped the tsunami protection walls that were only 19 feet high, and flooded the backup generators for the plant that were somehow placed on the first floor in a known tsunami zone!

We will first exam videos of the Japanese tsunami, (see also - <http://www.pbs.org/wgbh/nova/earth/japan-killer-quake.html>) then discuss some important points about tsunami, followed by a PBS video concerning the 2004 Indonesian Tsunami which killed over 230,000 people (see <http://www.pbs.org/wgbh/nova/tsunami/>).

The lecture notes below cover the essential points discussed in class and provide more details.

### **What is a Tsunami**

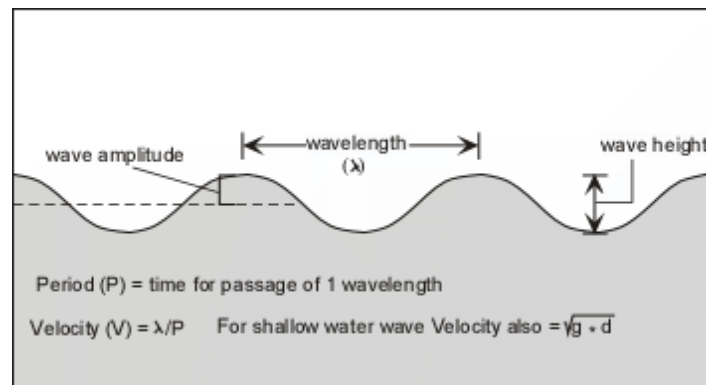
A tsunami is a very long-wavelength wave of water that is generated by sudden displacement

of the seafloor or disruption of any body of standing water. Tsunami are sometimes called "seismic sea waves", although they can be generated by mechanisms other than earthquakes. Tsunami have also been called "tidal waves", but this term should not be used because they are not in any way related to the tides of the Earth. Because tsunamis occur suddenly, often without warning, they are extremely dangerous to coastal communities.

### Physical Characteristics of Tsunami

All types of waves, including tsunamis, have a wavelength, a wave height, an amplitude, a frequency or period, and a velocity.

- **Wavelength** is defined as the distance between two identical points on a wave (i.e. between wave crests or wave troughs). Normal ocean waves have wavelengths of about 100 meters. Tsunami have much longer wavelengths, usually measured in kilometers and up to 500 kilometers.



- **Wave height** refers to the distance between the trough of the wave and the crest or peak of the wave.
- **Wave amplitude** - refers to the height of the wave above the still water line, usually this is equal to 1/2 the wave height. Tsunami can have variable wave height and amplitude that depends on water depth as we shall see in a moment
- **Wave frequency or period** - is the amount of time it takes for one full wavelength to pass a stationary point.
- **Wave velocity** is the speed of the wave. Velocities of normal ocean waves are about 90 km/hr while tsunamis have velocities up to 950 km/hr (about as fast as jet airplanes), and thus move much more rapidly across ocean basins. The velocity of any wave is equal to the wavelength divided by the wave period.

$$V = \lambda/P$$

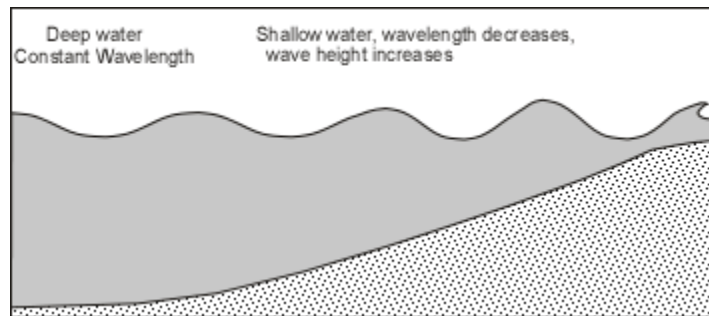
Tsunami are characterized as shallow-water waves. These are different from the waves most of us have observed on a the beach, which are caused by the wind blowing across the ocean's surface. Wind-generated waves usually have period (time between two successive waves) of five to twenty seconds and a wavelength of 100 to 200 meters. A tsunami can have a period in

the range of ten minutes to two hours and wavelengths greater than 500 km. A wave is characterized as a shallow-water wave when the ratio of the water depth and wavelength is very small. The velocity of a shallow-water wave is also equal to the square root of the product of the acceleration of gravity,  $g$ , ( $10\text{m/sec}^2$ ) and the depth of the water,  $d$ .

$$V = \sqrt{g * d}$$

The rate at which a wave loses its energy is inversely related to its wavelength. Since a tsunami has a very large wavelength, it will lose little energy as it propagates. Thus, in very deep water, a tsunami will travel at high speeds with little loss of energy. For example, when the ocean is 6100 m deep, a tsunami will travel about 890 km/hr, and thus can travel across the Pacific Ocean in less than one day.

As a tsunami leaves the deep water of the open sea and arrives at the shallow waters near the coast, it undergoes a transformation. Since the velocity of the tsunami is also related to the water depth, as the depth of the water decreases, the velocity of the tsunami decreases. The change of total energy of the tsunami, however, remains constant.



Furthermore, the period of the wave remains the same, and thus more water is forced between the wave crests causing the height of the wave to increase. Because of this "shoaling" effect, a tsunami that was imperceptible in deep water may grow to have wave heights of several meters or more.

If the trough of the tsunami wave reaches the coast first, this causes a phenomenon called **drawdown**, where it appears that sea level has dropped considerably. Drawdown is followed immediately by the crest of the wave which can catch people observing the drawdown off guard. When the crest of the wave hits, sea level rises (called **run-up**). Run-up is usually expressed in meters above normal high tide. Run-ups from the same tsunami can be variable because of the influence of the shapes of coastlines. One coastal area may see no damaging wave activity while in another area destructive waves can be large and violent. The flooding of an area can extend inland by 300 m or more, covering large areas of land with water and debris. Flooding tsunami waves tend to carry loose objects and people out to sea when they retreat. Tsunami may reach a maximum vertical height onshore above sea level, called a run-up height, of 30 meters. A notable exception is the landslide generated tsunami in Lituya Bay, Alaska in 1958 which produced a 60 meter high wave.

Because the wavelengths and velocities of tsunami are so large, the period of such waves is also large, and larger than normal ocean waves. Thus it may take several hours for successive crests to reach the shore. (For a tsunami with a wavelength of 200 km traveling at 750 km/hr, the wave period is about 16 minutes). Thus people are not safe after the passage of the first large wave, but must wait several hours for all waves to pass. The first wave may not be the largest in the series of waves. For example, in several different recent tsunami the first, third,

and fifth waves were the largest.

### **How Tsunami are Generated**

There is an average of two destructive tsunami per year in the Pacific basin. Pacific wide tsunami are a rare phenomenon, occurring every 10 - 12 years on the average. Most of these tsunami are generated by earthquakes that cause displacement of the seafloor, but, as we shall see, tsunami can be generated by volcanic eruptions, landslides, underwater explosions, and meteorite impacts.

### **Earthquakes**

Earthquakes cause tsunami by causing a disturbance of the seafloor. Thus, earthquakes that occur along coastlines or anywhere beneath the oceans can generate tsunami. The size of the tsunami is usually related to the size of the earthquake, with larger tsunami generated by larger earthquakes. But the sense of displacement is also important. Tsunami are generally only formed when an earthquake causes vertical displacement of the seafloor. The 1906 earthquake near San Francisco California had a Richter Magnitude of about 7.1, yet no tsunami was generated because the motion on the fault was strike-slip motion with no vertical displacement. Thus, tsunami only occur if the fault generating the earthquake has normal or reverse displacement. Because of this, most tsunami are generated by earthquakes that occur along the subduction boundaries of plates, along the oceanic trenches. Since the Pacific Ocean is surrounded by plate boundaries of this type, tsunami are frequently generated by earthquakes around the margins of the Pacific Ocean.

### **Examples of Tsunami generated by Earthquakes**

Although the December 2004 Indian Ocean tsunami is by far the best well known and most deadly (and will be featured in a video in class), we here discuss other disastrous tsunami generated by earthquakes.

- April 1, 1946 - A magnitude 7.3 earthquake occurred near Unimak Island in the Aleutian Islands west of Alaska, near the Alaska Trench. Sediment accumulating in the trench slumped into the trench and generated a tsunami. A lighthouse at Scotch Gap built of steel reinforced concrete was located on shore at an elevation of 14 m above mean low water. The first wave of the tsunami hit the Scotch Gap area 20 minutes after the earthquake, had a run-up 30 m and completely destroyed the lighthouse. 4.5 hours later the same tsunami reached the Hawaiian Islands after traveling at an average speed of 659 km/hr. As it approached the city of Hilo on the Big Island, it slowed to about 47 km/hr (note that even the fastest human cannot run faster than about 35 km/hr) and had a run-up of 18 m above normal high tide. It killed 159 people (90 in Hilo) and caused \$25 million in property damage.
- May 22, 1960 - A moment magnitude 9.5 earthquake occurred along the subduction zone off South America. Because the population of Chile is familiar with earthquakes and potential tsunami, most people along the coast moved to higher ground. 15 minutes after the earthquake, a tsunami with a run-up of 4.5 m hit the coast. The first wave then retreated, dragging broken houses and boats back into the ocean. Many people saw this smooth retreat of the sea as a sign they could ride their boats out to sea and recover some of the property swept away by the first wave. But, about 1 hour later, the second wave traveling at a velocity of 166 km/hr crashed in with a run-up of 8 m. This wave crushed

boats along the coast and destroyed coastal buildings. This was followed by a third wave traveling at only 83 km/hr that crashed in later with a run-up of 11 m, destroying all that was left of coastal villages. The resulting casualties listed 909 dead with 834 missing. In Hawaii, a tsunami warning system was in place and the tsunami was expected to arrive at 9:57 AM. It hit at 9:58 AM and 61 people died, mostly sightseers that wanted to watch the wave roll in at close range (obviously they were too close). The tsunami continued across the Pacific Ocean, eventually reaching Japan where it killed an additional 185 people.

- March 27, 1964 - The Good Friday Earthquake in Alaska had a moment magnitude of 9.2. This earthquake also occurred along the subduction zone, and as we saw in our study of earthquakes, caused deformation of the crust where huge blocks were dropped down as much as 2.3 m. Because the coastline of Alaska is sparsely populated, only 122 people died from the tsunami in Alaska. With a tsunami warning system in place in Crescent City, California, all the townspeople moved to higher ground. After watching four successive waves destroy their town, many people returned to the low lying areas to assess the damage to their property. The fifth wave had the largest run-up of 6.3 m and killed 12 people.
- September 2, 1992 - A magnitude 7 earthquake off the coast of Nicaragua in Central America occurred along the subduction zone below the Middle America Trench. The earthquake was barely felt by the residents of Nicaragua and was somewhat unusual. A 100 km-long segment of the oceanic lithosphere moved 1 m further below the over riding plate over a period of two minutes. Much energy was released but the ground did not shake very much. Seawater apparently absorbed some of the energy and sent a tsunami onto the coast. Residents had little warning, 150 people died and 13,000 people were left homeless.

## Volcanic Eruptions

Volcanoes that occur along coastal zones, like in Japan and island arcs throughout the world, can cause several effects that might generate a tsunami. Explosive eruptions can rapidly emplace pyroclastic flows into the water, landslides and debris avalanches produced by eruptions can rapidly move into water, and collapse of volcanoes to form calderas can suddenly displace the water.

The eruption of Krakatau in the Straights of Sunda, between Java and Sumatra, in 1883 generated at least three tsunami that killed 36,417 people. It is still uncertain exactly what caused the tsunami, but it is known that several events that occurred during the eruption could have caused such tsunami.

- A large Plinian eruption column blasted pumice and ash up to 40 km into the atmosphere. This Plinian eruption column likely collapsed several times to produce pyroclastic flows, any of which could have generated a tsunami.
- A loud explosive blast was heard as far away as Australia. This blast was likely caused by a phreatic explosion that occurred as a result of seawater coming in contact with the magma. The explosion could have generated at least one of the tsunami.
- At some point during the eruption a caldera formed by collapse of the volcanic island. Areas that were once more than 300 m above sea level were found 300 m below sea level after the eruption. The sudden collapse of the volcano to form this caldera could have

caused one or more tsunamis.

- Earthquakes were felt throughout the eruption. Any one of these submarine earthquakes could have caused a tsunami.

One of the tsunamis had a run-up of about 40 m above normal sea level. A large block of coral weighing about 600 tons was ripped off the seafloor and deposited 100 m inland. One ship was carried 2.5 km inland and was left 24 meters above sea level, with all of its crew swept into the ocean.

## **Landslides**

Landslides moving into oceans, bays, or lakes can also generate tsunamis. Most such landslides are generated by earthquakes or volcanic eruptions. As previously mentioned, a large landslide or debris avalanche fell into Lituya Bay, Alaska in 1958 causing a wave with a run-up of about 60 m as measured by a zone completely stripped of vegetation.

## **Underwater Explosions**

Nuclear testing by the United States in the Marshall Islands in the 1940s and 1950s generated tsunamis.

## **Meteorite Impacts**

While no historic examples of meteorite impacts are known to have produced a tsunami, the apparent impact of a meteorite at the end of the Cretaceous Period, about 65 million years ago near the tip of what is now the Yucatan Peninsula of Mexico, produced a tsunami that left deposits all along the Gulf coast of Mexico and the United States.

## **Mitigation of Risks and Hazards**

The main damage from tsunamis comes from the destructive nature of the waves themselves. Secondary effects include the debris acting as projectiles which then run into other objects, erosion that can undermine the foundations of structures built along coastlines, and fires that result from disruption of gas and electrical lines. Tertiary effects include loss of crops and water and electrical systems which can lead to famine and disease.

Within the last century, up until the December 2004 tsunami, there were 94 destructive tsunamis which resulted in 51,000 deaths. Despite the fact that tsunami warning systems have been in place in the Pacific Ocean basin since 1950, deaths still result from tsunamis, especially when the source of the earthquake is so close to a coast that there is little time for a warning, or when people do not heed the warning or follow instructions associated with the warning. These factors point out the inadequacy of the world in not having a tsunami warning system in place in the Indian Ocean, where in one event, the death toll from tsunami was increased by a factor of 5 over all previous events.

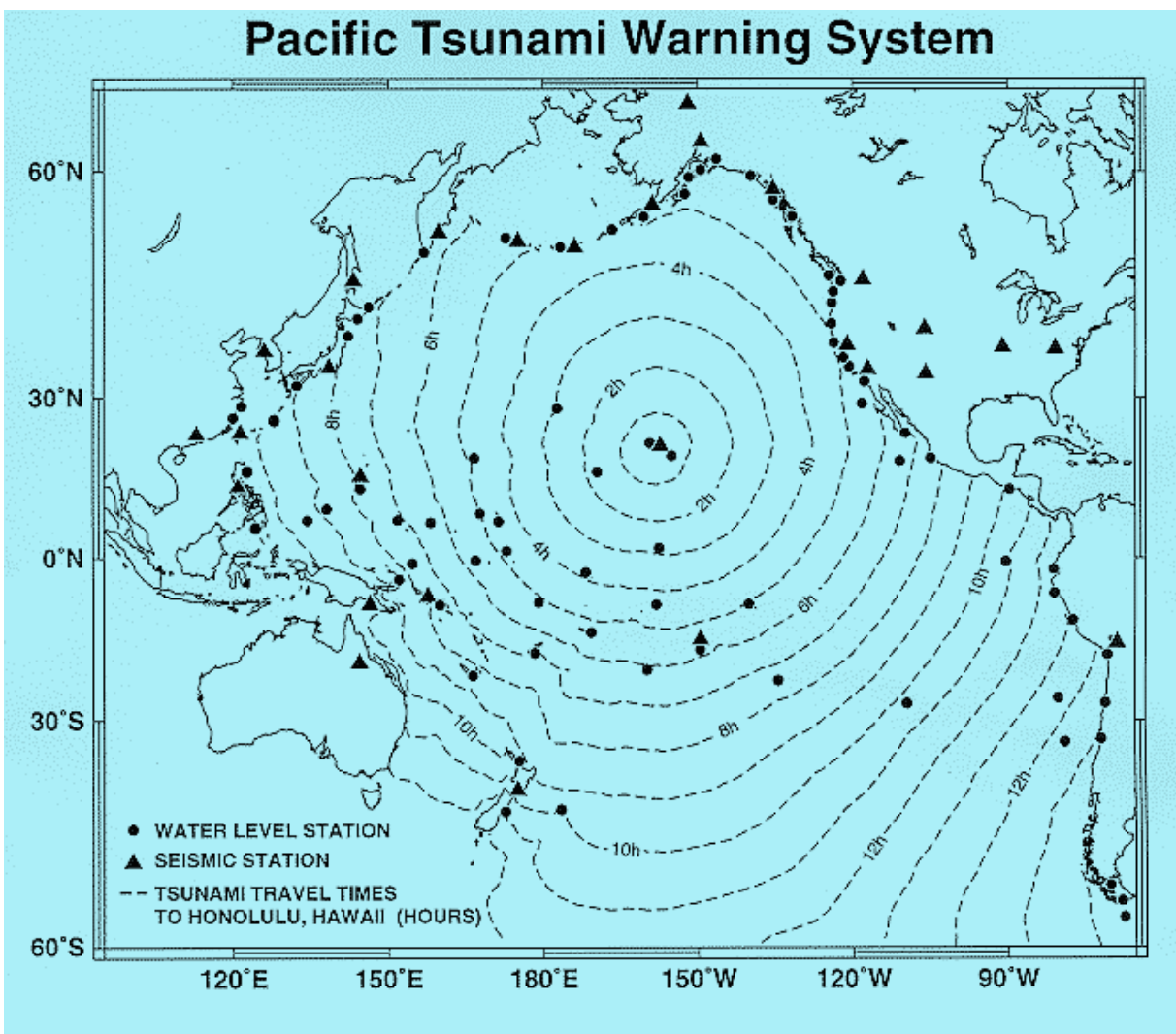
## **Prediction and Early Warning**

For areas located at great distances from earthquakes that could potentially generate a tsunami there is usually plenty of time for warnings to be sent and coastal areas evacuated, even though tsunamis travel at high velocities across the oceans. Hawaii is a good example of an area located

far from most of the sources of tsunami, where early warning is possible and has saved lives. For earthquakes occurring anywhere on the subduction margins of the Pacific Ocean there is a minimum of 4 hours of warning before a tsunami would strike any of the Hawaiian Islands.

The National Oceanic and Atmospheric Administration (NOAA) has set up a Pacific warning system for areas in the Pacific Ocean, called the Pacific Tsunami Warning Center. It consists of an international network of seismographic stations, and tidal stations around the Pacific basin that can all send information via satellite to the Center located in Hawaii. When an earthquake occurs somewhere in the region, the Center immediately begins to analyze the data looking for signs that the earthquake could have generated a tsunami. The tidal stations are also monitored, and if a tsunami is detected, a warning is sent out to all areas on the Pacific coast. It takes at least 1 hour to assimilate all of the information and issue a warning. Thus for an average velocity of a tsunami of 750 km/hr, the regional system can provide a warning sufficient for adequate evacuation of coastal areas within 750 km of the earthquake.

In order to be able to issue warnings about tsunami generated within 100 to 750 km of an earthquake, several regional warning centers have been set up in areas prone to tsunami generating earthquakes. These include centers in Japan, Kamchatka, Alaska, Hawaii, French Polynesia, and Chile.



These systems have been very successful at saving lives. For example, before the Japanese warning system was established, 14 tsunami killed over 6000 people in Japan. Since the establishment of the warning system, up until March 2011, 20 tsunami have killed 215 people in Japan.

Like all warning systems, the effectiveness of tsunami early warning depends strongly on local authority's ability to determine that there is a danger, their ability to disseminate the information to those potentially affected, and on the education of the public to heed the warnings and remove themselves from the area.

## **Tsunami Safety Rules**

In case you are ever in an area where there is a threat of tsunami, I have downloaded the following tsunami safety rules from the West Coast & Alaska Tsunami Warning Center Home Page: <http://wcatwc.arh.noaa.gov/safety.htm>

- A strong earthquake felt in a low-lying coastal area is a natural warning of possible, immediate danger. Keep calm and quickly move to higher ground away from the coast.
- All large earthquakes do not cause tsunami, but many do. If the quake is located near or directly under the ocean, the probability of a tsunami increases. When you hear that an earthquake has occurred in the ocean or coastline regions, prepare for a tsunami emergency.
- Tsunami can occur at any time, day or night. They can travel up rivers and streams that lead to the ocean.
- A tsunami is not a single wave, but a series of waves. Stay out of danger until an "ALL CLEAR" is issued by a competent authority.
- Approaching tsunami are sometimes heralded by noticeable rise or fall of coastal waters. This is nature's tsunami warning and should be heeded.
- A small tsunami at one beach can be a giant a few miles away. Do not let modest size of one make you lose respect for all.
- Sooner or later, tsunami visit every coastline in the Pacific. All tsunami - like hurricanes - are potentially dangerous even though they may not damage every coastline they strike.
- Never go down to the beach to watch for a tsunami! **WHEN YOU CAN SEE THE WAVE YOU ARE TOO CLOSE TO ESCAPE.** Tsunami can move faster than a person can run!
- During a tsunami emergency, your local emergency management office, police, fire and other emergency organizations will try to save your life. Give them your fullest cooperation.
- Homes and other buildings located in low lying coastal areas are not safe. Do **NOT** stay in such buildings if there is a tsunami warning.
- The upper floors of high, multi-story, reinforced concrete hotels can provide refuge if

there is no time to quickly move inland or to higher ground.

- If you are on a boat or ship and there is time, move your vessel to deeper water (at least 100 fathoms). If it is the case that there is concurrent severe weather, it may be safer to leave the boat at the pier and physically move to higher ground.
- Damaging wave activity and unpredictable currents can affect harbor conditions for a period of time after the tsunami's initial impact. Be sure conditions are safe before you return your boat or ship to the harbor.
- Stay tuned to your local radio, marine radio, NOAA Weather Radio, or television stations during a tsunami emergency - bulletins issued through your local emergency management office and National Weather Service offices can save your life.

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### Questions on this material that could be asked on an exam

Note that answers to some of these questions will come from the video

1. Discuss 5 ways that a tsunami can be generated.
2. Compare and contrast tsunami waves with normal wind-driven ocean waves in terms of their wavelength, period, velocity, and amplitude.
3. Is a tsunami a single wave or numerous waves? If a tsunami has multiple waves, is there any pattern as to which will be the highest and most destructive?
4. What are the best ways to mitigate against casualties and damage from tsunami?
5. If you are on the beach, what signs of an impending tsunami are observable, and what action(s) should you take to avoid death or injury?

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