Unit 5
Tsunami Hazards

In this unit, you will

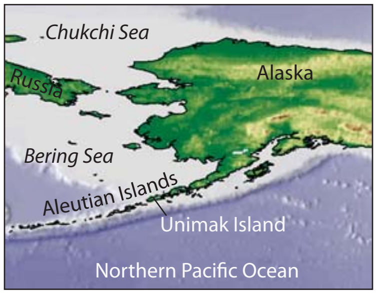
- ***Analyze two major tsunami events in detail.***
- ***Discover the effects tsunamis have on communities and how communities can prepare for them.***
- ***Examine tsunami trigger events and develop criteria for issuing tsunami warnings.***

NOAA/NGDC/Sunset Newspaper

A major earthquake off the coast of Chile on May 22, 1960 produced a tsunami that affected the entire Pacific Basin. In Hilo, Hawaii — 10,000 km from the earthquake — the tsunami caused 61 deaths and $24 million in property damage. Frame buildings were either crushed or floated off their foundations, and only buildings of reinforced concrete or structural steel remained standing.

Warm-up 5.1

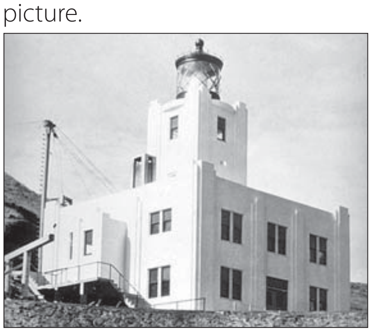
Location map



The Scotch Cap Lightstation, located on Unimak Island in Alaska, was a five-story, reinforced concrete structure built 10 meters (33 feet) above sea level. On April 1, 1946 a strong earthquake jolted the lightstation. Forty-five minutes later, a tsunami estimated at 35 meters (115 feet) high obliterated the lightstation.

The eyewitness account reprinted here is the actual report submitted by a petty officer stationed in the radio shack seen on the cliff above the lightstation in the bottom picture.

US Coast Guard



Before (above) and after (below) pictures of the Scotch Cap Lightstation.

Scotch Cap Lightstation

After reading the account of the tsunami that destroyed the Scotch Cap Lightstation in 1946 (pages 125 – 126), list and describe all of the tsunami-related hazards discussed. Feel free to add other hazards from your previous knowledge or experience with tsunamis.

Tsunami hazards

1.

2.

3.

4.

5.

6.

7.

8.

Tsunami hazard examples (optional)

If you have access to a computer, you can see examples of these and other tsunami hazards. Be sure to add any new hazards you find to your list.

- Launch ArcMap, and locate and open the **ddde_unit_5.mxd** file.

Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.

- In the Table of Contents, right-click the **Geological Hazards** data frame and choose Activate.

- Expand the **Geological Hazards** data frame.

To see examples of other earthquake hazards:

- Turn on the **Hazard Links** layer.
- Select the **Hazard Links** layer.
- Using the Hyperlink tool, click on each of the blue tsunami hazard symbols (blue waves) on the map.
- Read the caption for each picture (or watch the movie), then close its window. There may be more than one picture for each link.

Questions

1. Which of the hazards you listed on the previous page caused the greatest amount of damage and loss of life at the Scotch Cap Lightstation?

2. Do you think anything could have been done to protect the lightstation or its staff? Explain.

3. From the account, did the lightstation staff have warning signs of the coming wave? Explain.

4. Why do you think so much of the world's population lives close to the ocean?

5. Would you rebuild the lightstation in the same location? Explain.

Eyewitness account

Scotch Cap Lightstation

Memorandum kept by Chief Radio Electrician
Hoban B. Sanford, U. S. Coast Guard

At 0130 Xray, 1 April, 1946, at which time I was awake and reading, a severe earthquake was felt. The building (CG Unit 368 - Unimak A/F Station) creaked and groaned loudly. Objects were shaken from my locker shelves. Duration of the quake was approximately 30 to 35 seconds. The weather was clear and calm.

Knowing that the volcanoes to Northward of the building had been active at one time, I immediately looked in that direction for signs of renewed activity and upon seeing none made a round of the building to see what, if any, damage had been caused by the tremor. Inspection failed to reveal any damage other than objects shaken from locker shelves. The crew were all awakened by the quake.

Intending to call Scotch Cap Lightstation on the phone to ascertain if they had felt, or been damaged by, the quake, I went to the phone in Operations, but Pitts, RM2c, had already done so and he stated they had felt the tremor and that Pickering, MoMM2c, who was on watch at the lightstation, had said that he was "plenty scared" and was going to call Dutch Harbor Navy Radio to see what information that unit might have regarding the earthquake.

At 0157 Xray a second severe quake was felt. This one was shorter in duration, lasting approximately 15 to 20 seconds, but harder than at 0130 Xray. I again looked towards the mountains for any signs of volcanic activity, but still could see none. I made a second round of the building to see if any damages had resulted but none was apparent.

The crew was gathered in the Recreation Hall discussing the shocks, their probable cause and location, when a crew member stated he had talked with Scotch Cap Lightstation after the second shock, and they were attempting to contact Dutch Harbor Radio for any news of the quakes.

At 0218 Xray a terrible roaring sound was heard followed almost immediately by a very heavy blow against the side of the building and about 3 inches of water appeared in the galley, Recreation Hall and passageway. From the time the noise was heard until the sea struck was a matter of seconds. I should say between five and ten seconds at most. Ordering the crew to get to the higher ground of the DP D/F building immediately. I went to the control room and, after a couple of calls to Kodiak and Adak Net Control Stations, broadcast a priority message stating we had been struck by a tidal wave and might have to abandon the station, and that I believed Scotch Cap Lightstation was lost.

> (Message: - PPP NMJ NNA NNFV NNBT TIDAL WAVE MAY HAVE TO ABANDON THIS PLACE X BELIEVE NNHX LOST INT R INT R XXX)

Received no answer to calls or receipt for message and did not know until daylight that the receiving antennae had been carried away. Electric power was fluctuating badly, and starting for the generator room to ascertain the cause and extent of damage, I found that D'Agostino, ETMlc, and Campanaro, RM2c, had voluntarily remained behind to assist.

Water had struck the switchboards through a burst-in door and the voltage control regulator was burning on the back of the board. ETMlc D'Agostino used a CO_2 extinguisher while I shut down the generator. This placed the station in darkness.

Companaro found and lit a kerosene pressure lantern and we proceeded to make emergency repairs. The switchboards were shunted and the generator connected directly to the line. This restored lighting and some power circuits. Companaro was sent to call back some members of the crew to get more clothing and canned goods to be taken to the DP building in case of a second wave. While crew members were thus engaged, D'Agostino and myself made a rapid survey of damage. At 0345 I went to edge of hill above Scotch Cap Lightstation to observe conditions there. The way was littered with debris, and the lightstation had been completely destroyed. I returned to the DF Station and, with D'Agostino, continued cleaning up water and muck about generators. At 0550 had one generator running full power, at this time transmitted a dispatch to the DCGO, 17ND, via Kodiak re conditions. At 0700 went down to the site of the lightstation, the sea by this time having receded to its usual limits, and in company with several crew members searched among the debris for any signs of bodies of personnel. On top of hill behind the lightstation we found a human foot, amputated at the ankle, some small bits of intestine which were apparently from a human being, and what seemed to be a human knee cap. Nothing else was found. At 0725 was informed Sarichef Beacon heard. At 0800 sent out searching parties to attempt locate any trace of Scotch Cap personnel. Searching parties later returned and reported no trace of the lightstation crew. The crew of the lightstation was comprised of Petit, CBM, OinC; Pickering, MoMM2c; Dykstra, Slc; Ness, Slc; and Calvin, Flc.

Searching parties were out daily whenever weather permitted until 20 April when CBM Sievers of CGC *CLOVER*, which was establishing a temporary light on the site of the destroyed light, located a body which was identified as Paul J. Ness, Slc, a member of the lightstation crew. The body was viewed by several crew members and myself and all agreed that it was Ness, who had high cheek bones, slightly prominent upper incisor teeth and a small goatee. The pharmasist [*sic*] mate from Unit 368 had been observing the large toes on both feet of Ness and the nails were pared away from the sides. This condition, also existed on the feet of the body. The remains were wrapped in an old blanket and canvas and removed to above the high water mark, pending burial instructions from DCGO, 17ND. On 22 April at 1030 CBM Sievers, who was conducting a search to eastward, returned to Unit 368 and stated he had found another body. With several crew members I proceeded on to the location but was unable to identify the body. The body was decapitated, disemboweled, and in a poor state of preservation. A homemade monel ring on the right hand could not be identified by any member of the crew of Unit 368.

At 1100 crew members who had been searching to westward reported they had found the right thigh and foot of a man. The foot could not be identified. These remains were gathered in old mail sacks and placed in a rough coffin. The body of Ness was placed in an individual coffin.

At 1545, 23 April, the body of Ness was buried in an individual grave, the unidentified portions of bodies were buried in a common grave adjacent thereto. The graves are at the seaward edge of the western bank of the first ravine to the eastward of Scotch Cap Lightstation and are approximately 300 yards from the site of the light, near the graves of two Russian seamen. The graves are plainly marked with white wooden crosses with brass plates securely attached, and are well covered with rocks to discourage depredation by animals.

The area covered by searches was approximately 5 miles eastward, 4 miles westward from Scotch Cap Lightstation, and inland to the high water mark of the tidal wave.

Notes: Most of the abbreviations used in this account are U.S. Coast Guard occupations and ranks: RM2c - Radioman Second Class • MoMM2c - Motor Machinist's Mate Second Class • ETM1c - Electronic Technician's Mate First Class • S1c - Seaman First Class • F1c - Fireman First Class • CBM - Chief Boatswain's Mate • OinC - Officer In Charge. Other abbreviations include the following: DCGO - District Coast Guard Officer • CGC - Coast Guard Cutter. "Xray" is a designation for the time zone covering Unimak Island. It is UTC –11, which means it is 11 hours offset from Greenwich Mean Time. For comparison, the U.S. Eastern time zone is UTC – 5, Central is UTC – 6, Mountain is UTC – 7, and Pacific is UTC – 8. "0130 Xray" at Unimak Island is thus 7:30 in the morning on the East Coast and 4:30 in the morning on the West Coast.

Source: U.S. Coast Guard

Investigation 5.2

Deadly tsunamis

What does it mean?

The Japanese characters for tsunami translate literally as "harbor wave." Understanding tsunami behavior is important in Japan, where both lives and property have been destroyed by tsunamis throughout history.

津 tsu = *harbor* or *port*

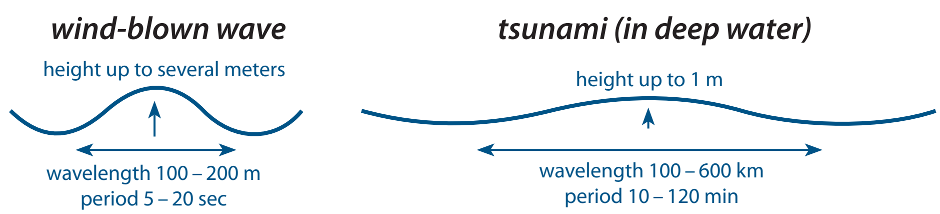
波 nami = *wave*

Tsunamis (soo-NAH-meez) are one of the most devastating geologic hazards facing coastal communities. Sometimes mistakenly called "tidal waves," tsunamis are not related to the ocean's tides. Rather, they are waves caused by the sudden movement of the seafloor or coastline due to geologic events such as earthquakes, volcanic eruptions, or landslides.

When the seafloor moves suddenly, it displaces the overlying water, forming a "hill" or "valley" on the surface. As gravity makes the ocean surface return to its normal level, the energy spreads out rapidly as a series of concentric waves, like ripples on a pond.

Tsunamis are not like wind-blown ocean waves. Wind-blown waves have amplitudes (height ÷ 2) up to a few meters and wavelengths (distance from crest to crest) of a few hundred meters. In the open ocean, tsunami amplitudes range from a few millimeters to about half a meter depending on the depth of the water, and the tsunamis have wavelengths of hundreds of kilometers.

Period [of a wave] — the time required for successive wave crests to pass a fixed point.



The great tsunami of 1960

Launch ArcMap, and locate and open the **ddde_unit_5.mxd** file.

Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.

In the Table of Contents, right-click the **1960 Chile Tsunami** data frame and choose Activate.

Expand the **1960 Chile Tsunami** data frame.

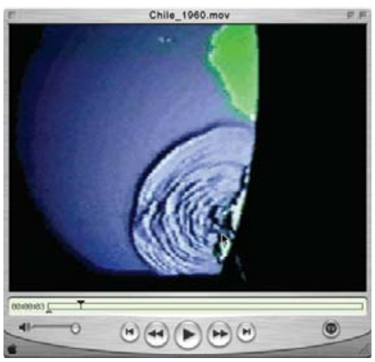
On May 22, 1960 a magnitude 9.6 earthquake, the strongest ever recorded, struck off the coast of Chile. The location of the quake is marked in this data frame with a red star symbol.

Turn on the **Plate Boundaries** layer.

1. At which type of plate boundary did the earthquake occur?

Turn off the **Plate Boundaries** layer.

The animation does not show the entire globe. The star on the illustration above marks the location of the earthquake that produced the tsunami.



Animation courtesy of Disaster Control Research Center, Tohoku University, and Obayashi Corporation, Japan.

The quake generated a huge tsunami that temporarily raised sea level by as much as 30 m and devastated communities along the Chilean coast. In all, more than 1200 people were killed. Unfortunately, the danger was not limited to the nearby coastline.

In the open ocean, tsunamis are difficult to detect and impossible to see. To study tsunami behavior, researchers build numerical models on computers. One of these models recreates the 1960 Chilean tsunami. The heights of the waves are greatly exaggerated to make them visible.

The model shows only part of the globe. Use the diagram at left to orient yourself before viewing the animation.

To view the 1960 Chilean tsunami model:

- Using the Hyperlink tool, click on the tsunami source off the coast of Chile (the red star). Be patient while the movie loads.
- Watch the movie several times. The waves travel a long distance, so the view rotates twice to show them passing Hawaii and reaching the far side of the Pacific.

After viewing the movie, answer the following questions.

2. How do tsunamis respond when they strike islands or coastlines?

3. By the time the waves reach Japan, how much energy do they appear to have lost? (All? Most? A little? None?)

- Close the Media Viewer window.

Tsunamis exhibit all of the properties of waves. In the animation, notice how tsunamis “slosh” back and forth in the ocean as they reflect off coastlines, islands, and shallow underwater landforms. They reflect (bounce) off obstacles, refract (change direction) as they change speed, and diffract (change direction) as they pass obstacles. As they slosh around the ocean basin, colliding waves may add together or cancel each other out, causing their amplitudes to be much higher or lower than expected.

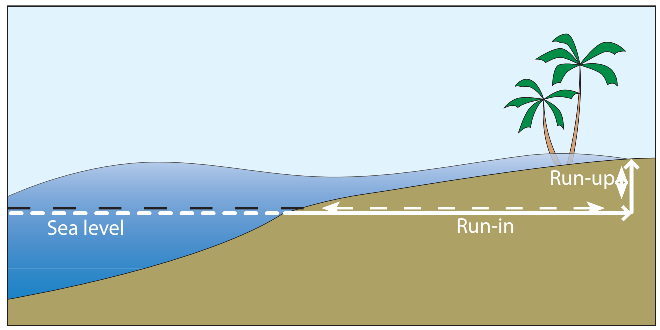
Measuring the effects of tsunamis

Often, the first indication of a tsunami is a rapidly falling water level, followed by a rapidly rising water level that inundates low-lying coastal areas. Major tsunamis can also have towering breaker waves. A tsunami's impact on these areas is usually described by two measurements:

- **run-up** — the maximum height of a tsunami above normal sea level.
- **run-in** — the distance the rising water reaches inland from the normal coastline.

Run-up and run-in

Tsunami run-up and run-in depend on many factors, including the size of the trigger event, the distance traveled, seafloor topography, tides, and the shape of the coastline.



- Turn on the **Maximum Run-up** layer.
- Select the **Maximum Run-up** layer.

This layer shows locations that recorded measurable run-up from the 1960 Chilean tsunami. As you saw in the animation, this tsunami affected the entire Pacific basin.

The color of the run-up symbols varies with the height of the run-up. As expected, sites near the source recorded the highest run-up, with the run-up generally decreasing with distance. Unusual circumstances, however, may produce a high run-up far from the source. Next, you will examine the effects of the tsunami on the islands of Hawaii and Japan.

Calculating the tsunami's speed

To calculate the Chilean tsunami's speed, you need to know the distance it traveled and the time it took to go that distance.

- Using the Measure tool, measure the distance from the tsunami source to Hawaii by clicking once on the source, dragging across to Hawaii, and double-clicking on Hawaii. The distance (Total) is displayed in the Status Bar in the lower left corner of the data frame window.

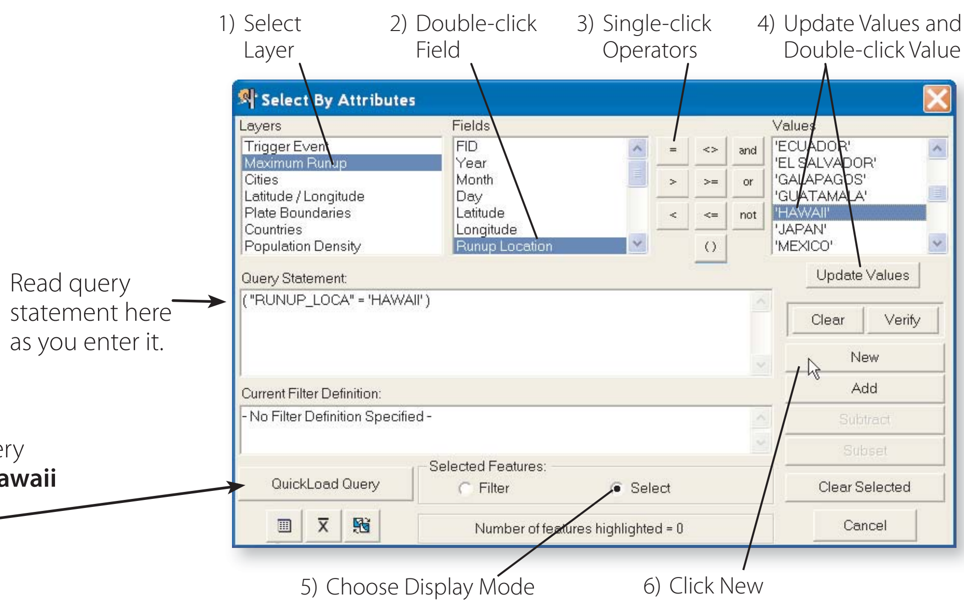
4. Record the distance from the trigger event to Hawaii in the **Distance** column of the table on the following page. The distance to Japan has already been recorded for you.

Location	Distance *km*	Shortest travel time *hours*	Speed *km/hr*	Highest run-up *m*
data source:	*measured*	*from table*	*calculated*	*from table*
Hawaii				
Japan	17,000			

Next you will find the shortest time required for the tsunami's leading wave to reach Hawaii.

- Click the Select By Attributes button .
- To display run-up sites in Hawaii, query the **Maximum Run-up** layer for **("Run-up Location" = 'HAWAII')** as shown in steps 1-6. Your query will actually read:

("RUNUP_LOCA" = 'HAWAII')



QuickLoad Query

- Click the QuickLoad Query button and select the **Hawaii Run-up** query.
- Click **OK**.
- Click **New**.

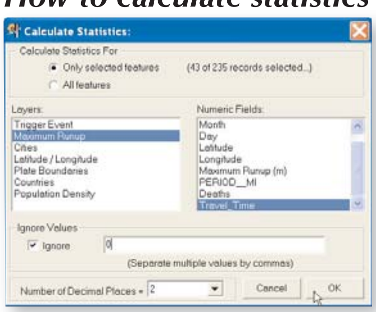
- If you have difficulty entering the query statement correctly, refer to the **QuickLoad Query** described at left.

The run-up sites in the Hawaiian Islands should now be highlighted on your map.

- Click the Statistics button in the Select By Attributes window.
- In the Statistics window, calculate statistics for **only selected features** of the **Maximum Run-up** layer, using the **Travel_Time** field.
- Choose the **Ignore** option and enter a value of **0**.
- Click **OK**. Be patient while the statistics are calculated.

The shortest travel time is reported as the **Minimum**.

How to calculate statistics



Travel-time data format

The travel-time data are given in decimal hours, not hours and minutes.

5. Record the shortest travel time (hours) in the table on page 130.

- Close the Statistics window.
- Click the Statistics button in the Select By Attributes window.
- In the Statistics window, calculate statistics for **only selected features** of the **Maximum Run-up** layer, using the **Maximum Run-up (m)** field.
- Click **OK**. Be patient while the statistics are calculated.

The highest run-up is reported as the **Maximum**.

6. Record the highest run-up (m) in the table on page 130.

- Close the Statistics window.

To find the shortest time required for the leading wave to reach Japan:

- Click the **Clear** button in the Select By Attributes window.
- To display run-up sites in Japan, query the **Maximum Run-up** layer using the query statement **(“Run-up Location” = ‘Japan’)**. Your query will actually read:

(“RUNUP_LOCA” = ‘JAPAN’)

QuickLoad Query

- Click the QuickLoad Query button and select the **Japan Run-up** query.
- Click **OK**.
- Click **New**.

- Click **New**.
- If you have difficulty entering the query statement correctly, refer to the **QuickLoad Query** described at left.
- Repeat the statistics procedure above to find and record the shortest travel time and maximum (highest) run-up for sites in Japan in the table on page 130. (Hint: Remember to choose the **Ignore** option and enter a value of **0** when calculating statistics on travel times.)

7. Calculate the average speed of the tsunami between its source and each location using the formula: speed = distance ÷ time, and record it in the table on page 130.

- Close the Statistics and Select By Attributes windows.
- Click the Clear Selected Features button.

The average depth of the Pacific Ocean between Hawaii and Japan is greater than it is between Chile and Hawaii.

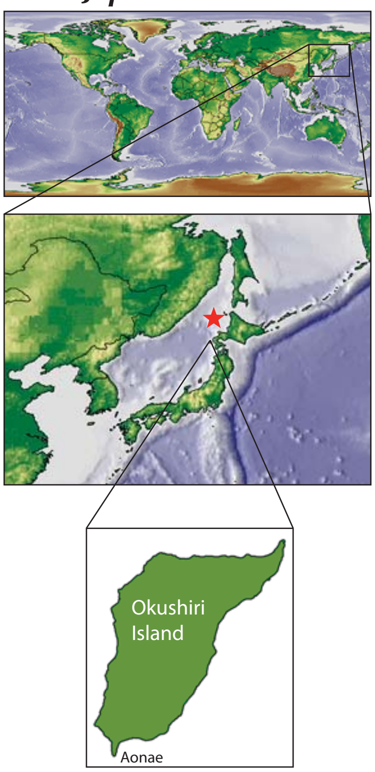
8. Based on the speeds you calculated, what happens to the speed of a tsunami when the water depth increases?

9. Based on the highest run-up recorded at each location, what happens to the energy of the tsunami as it travels away from its source?

Local effects

- Click the QuickLoad button.
- Select **Data Frames**, choose **1993 Japan Tsunami** from the list, and click **OK**.

Location of the 1993 Japan tsunami



Note: Your map does not show the island in this much detail.

At 10:17 p.m. local time on July 12, 1993 a magnitude 7.8 earthquake struck in the Sea of Japan off the coast of Hokkaido, generating one of the worst tsunamis in Japanese history. Run-up reached as high as 30 m on the nearby island of Okushiri. (See locator map in the sidebar at left.) In the map on your screen, the red star shows the location of the quake's epicenter.

Particularly hard-hit was the resort town of Aonae, on the southern tip of the island, where 185 people lost their lives.

Researchers have modeled the impact of the tsunami on Aonae to help understand what happened and to learn how to better protect coastal communities from damage.

To view an animation of the effects of the tsunami on Aonae:

- Select the **Trigger Event** layer.
- Using the Hyperlink tool, click on the red star symbol. Be patient while the movie loads.
- The animation shows, from several different angles, the tsunamis striking the coastline. Watch the movie several times, then answer this question.

10. In the animation, where do the waves appear to wash the highest and farthest inland? Where do you think are the most dangerous places to live in this area?

- Close the Media Viewer window.

To see before and after pictures of damage to the Aonae peninsula:

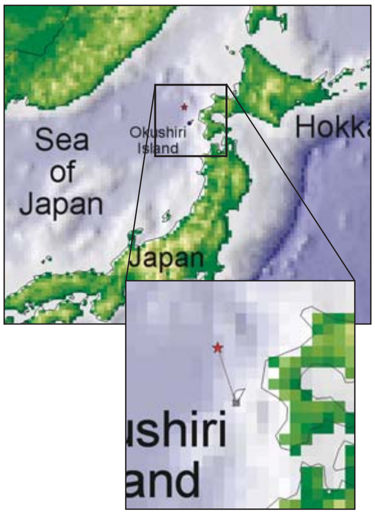
- Click the Media Viewer button and choose **Aonae Before & After** from the media list.

The tsunami struck at night, and the "After" picture shows what the area looked like the morning after the tsunami.

- Close the Media Viewer window.

How much warning?

Aonae locator map



In the 1960 tsunami, it took many hours for the wave to reach Hawaii and Japan. Had an effective warning system been in place, many lives could have been saved. Next, you will find out how much warning the community of Aonae had. Could a warning system have saved the people who died there?

- Turn on the **Maximum Run-up** layer, then zoom in on the Sea of Japan until you can see the run-up symbol on the southern tip of the island of Okushiri. (See locator map at left.)
- Using the Measure tool, measure the distance from the tsunami trigger event to the Aonae run-up symbol.
- Read the distance from the status bar in the lower left corner of the data frame.

11. Assuming that the tsunami traveled at about 15 km/min (900 km/hr), calculate the travel time to Aonae in minutes using the formula:

$$\text{time} = \text{distance} \div \text{speed}$$

12. Do you think a tsunami warning system could have saved many lives, based on the travel time you calculated in question 11? Explain.

- Quit ArcMap and do not save changes.

Reading 5.3

Analysis of a tsunami

Introduction

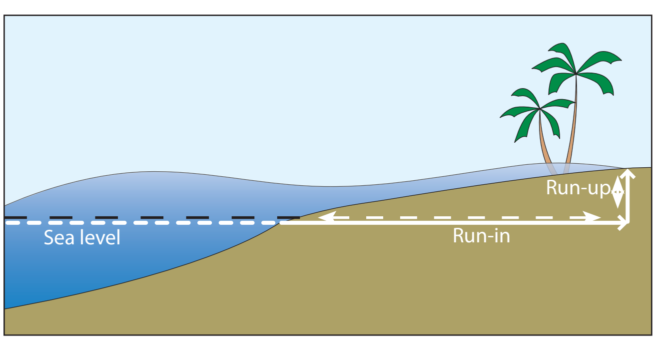
Life on Earth evolved in the protective environment of its oceans. To this day, humankind continues to take advantage of the benefits of living along the shore. Moderate temperatures, abundant food, and easy transportation are all provided courtesy of our planet's seas and oceans. Living near the ocean is not without its perils though. Perhaps the most unpredictable and terrifying of these hazards is the tsunami.

A tsunami is a series of large waves created when a disturbance displaces, or moves, an enormous volume of ocean water. The waves of a tsunami spread outward from their source at very high speed. This means that tsunamis can cross an entire ocean in a matter of hours, making them a truly global hazard for coastal communities.

Tsunamis are a special class of waves called **shallow-water waves**. The speed at which they travel is proportional to the depth of the water. In the open ocean, tsunamis move very fast but have wave heights of 1 m or less. As the water shallows near coastlines, the speed of the waves decreases while their height increases. When the waves reach the shore, they may be tens or, in extreme cases, hundreds of meters high.

Two measurements are used to describe the effect of tsunamis on the coastline.

- **Run-up** is the maximum height of the tsunami wave above normal tide level.
- **Run-in** is a measure of how far inland the wave reaches beyond the normal shoreline.



Tsunami intensity scale

Tsunami researchers have developed a scale, based on the run-up height, for describing the intensity of a tsunami.

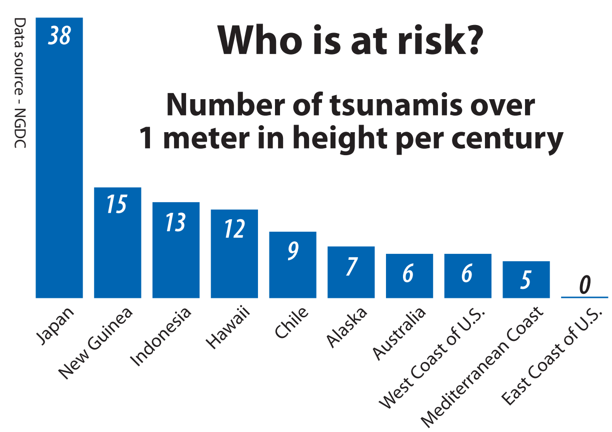
Intensity	Run-up height *m*	Description	Frequency in Pacific Ocean
4	16	Disastrous. Near complete destruction of man-made structures.	1 in 10 years
3	8	Very large. General flooding, heavy damage to shoreline structures.	1 in 3 years
2	4	Large. Flooding of shore, light damage to structures.	1 per year
1	2	Moderate. Flooding of gently sloping coasts, slight damage.	1 per 8 months

Tsunami intensity (similar to earthquake intensity) is a measure of the local size of a tsunami.

Where tsunamis occur

In the Pacific Ocean, where the majority of tsunamis occur, the historical record shows extensive loss of life and property. Japan, in particular, has repeatedly seen entire towns and cities wiped out by tsunamis, most recently in 1993.

Most coastal communities have some degree of tsunami risk, but the chart below shows that



tsunamis are far more common in Pacific coastal areas than on the U.S. East Coast. This is because earthquakes and volcanoes, the features that most commonly cause tsunamis, occur more often in the Pacific Basin than in the Atlantic Basin.

Tsunamis of all sizes

Tsunamis occur at various scales, depending on the magnitude of the event that triggers them, the location, and the surrounding topography.

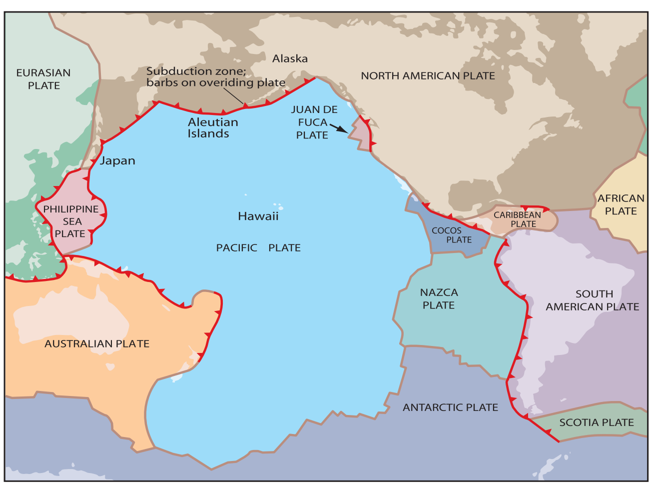
- **Local tsunamis** affect an area within 200 km of their source.
- **Regional tsunamis** affect an area within about 1000 km of their source.
- **Teletsunamis** travel great distances (over 1000 km), often across entire oceans.

What causes tsunamis?

There are four types of events capable of producing tsunamis: earthquakes, volcanoes, landslides, and asteroid impacts.

Earthquakes — Normally, only large earthquakes in or near ocean basins produce tsunamis. Of these, only the strongest — magnitude 8 and higher — create teletsunamis. However, smaller earthquakes sometimes indirectly cause tsunamis by triggering landslides.

USGS



This map explains the prevalence of tsunamis in the Pacific Ocean. The red lines are subduction zones, where one tectonic plate is plunging beneath another. Earthquakes and volcanoes, two common triggers for tsunami events, are typical features of subduction zones.

Landsat 7/USGS

Krakatoa (Krakatau) sits in the Sunda Strait, a major shipping lane between the Indian Ocean and the Java Sea.

Lyn Topinka, USGS/CVO

Volcanoes — Some of the most devastating tsunamis in recorded history occurred during the 1883 eruption of the volcano Krakatoa. Tsunamis with 40-m run-ups destroyed 165 coastal villages on the Indonesian islands of Java and Sumatra, killing over 36,000 people. The tsunami formed when the volcano either collapsed into its magma chamber or exploded, creating a 5- by 9-km crater. Seawater quickly filled the void, then sloshed outward as an enormous and deadly tsunami.

Landslides — The movement of rocks and soil can displace large volumes of water, creating a tsunami. These landslides can develop on land and fall into the water or take place completely underwater. One of the highest tsunamis in modern history occurred in Lituya Bay, Alaska when a magnitude 8.3 earthquake triggered a landslide that fell into the nearly enclosed bay. The slide created a tsunami splash wave that washed 524 m (1720 ft) over a ridge on the opposite side of the bay.

Scientists are also investigating submarine landslides for their tsunami-causing potential. Far more massive than terrestrial landslides,

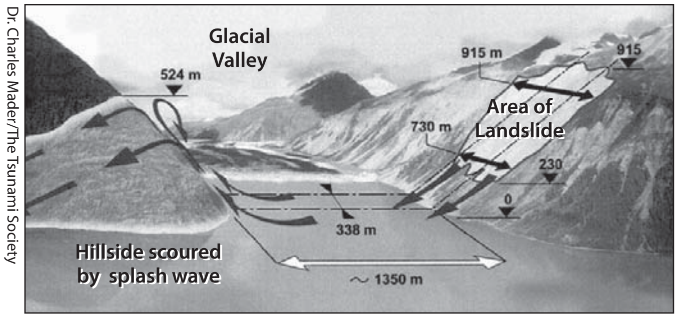
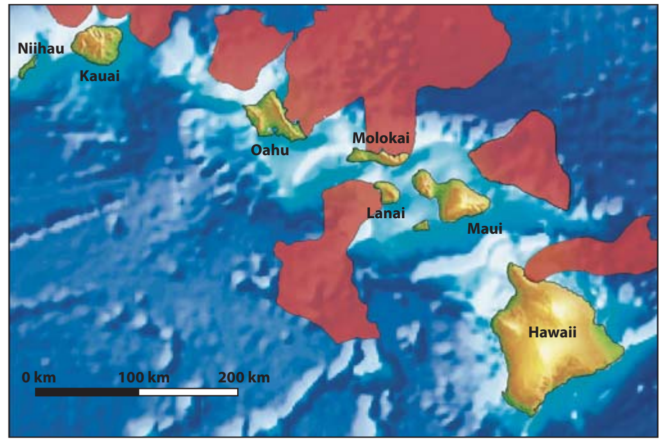


Diagram of the July 9, 1958 Lituya Bay landslide that produced a 524-m (1720-ft) local tsunami, the highest in historical times.

underwater landslides off the Hawaiian Islands have sent thousands of cubic kilometers of material sliding almost 200 km from their source.

The resulting tsunamis would have been enormous. There is speculation today about the origin of coral boulders 200 m above sea level on the Hawaiian Island of Molokai. Were they tossed there by a massive tsunami, or deposited by normal processes when the sea level was significantly higher?

Asteroid [and comet] impacts—The rarest yet most catastrophic cause of tsunamis is an asteroid [or comet] impact in one of Earth's oceans. Scientists estimate that a 1-km diameter asteroid striking the middle of an ocean would produce a tsunami with run-ups ranging from 6 to 50 m.

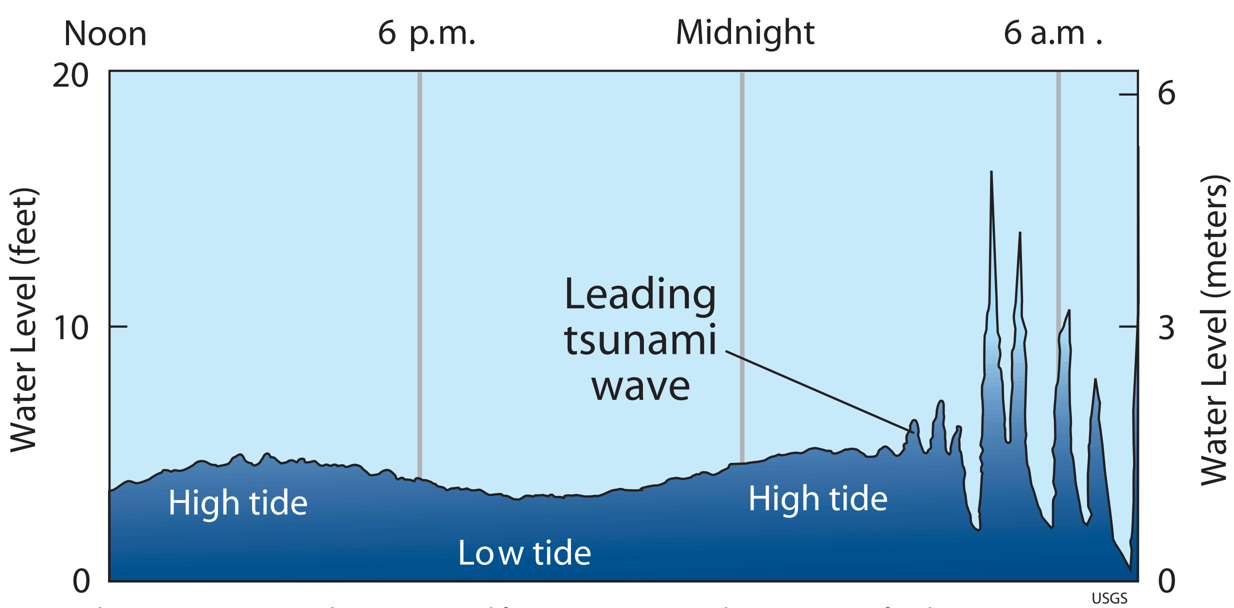


Locations of major Hawaiian submarine landslides. Similar landslides may threaten the northwestern and eastern U.S. coasts with tsunamis.

The asteroid that hit near Mexico's Yucatán Peninsula 65 million years ago, contributing to the extinction of the dinosaurs, was about 10 km in diameter. Evidence suggests that the impact generated a tsunami 100 to 250 m high that washed hundreds of kilometers inland.

Record of a tsunami event

A tsunami is not a single wave, but a series of wave build-ups and retreats. The waves may be spaced minutes or hours apart. People often believe that the tsunami danger is over after the first wave has passed and are then killed when they return to



The May 23-24, 1960 tide gauge record for Onagawa, Japan shows a series of eight tsunamis over a 5-hour period. The first waves are not the highest. Note the deep trough preceding the first large tsunami.

coastal areas to clean up after the event.

To complicate matters, tsunamis reflect off coastlines and may pass a given location several times and from different directions. The highest run-up can occur several hours after the arrival of the first wave. Tides are another key factor, as run-up is more severe when it occurs at high tide than at low tide. All of these features of a tsunami event can be seen in the tide gauge record from the 1960 Chilean tsunami shown on the previous page.

Tsunami effects

Direct Impact — Most of a tsunami's initial damage comes from the direct impact of waves on structures and harbor facilities, and from wave run-up on coastal buildings.

To get a better idea of the damage a large tsunami can do, consider that a cubic meter of pure (i.e., fresh) water has a mass of 1000 kg (2200 lb). Therefore, a 15-meter-high tsunami with a wavelength of 300 m would hit a 30-m length of seawall with a 135-million-kg (298-million-lb) wedge of water — enough to do incredible damage. Debris caught in the backwash of the leading wave makes the secondary waves even more destructive as they come ashore.

Flooding—In addition to the destructive force of the tsunamis, flooding can kill people, damage property, and spread pollution over a large area.

As shown in the photograph below, run-in from the 1960 Chilean tsunami extended about 3.2 km (2 mi) inland over flat coastal areas and penetrated almost 8 km (5 mi) up the river channels. Run-in is influenced by many factors including the run-up height, orientation relative to the coast, tidal conditions, local topography, and vegetation.

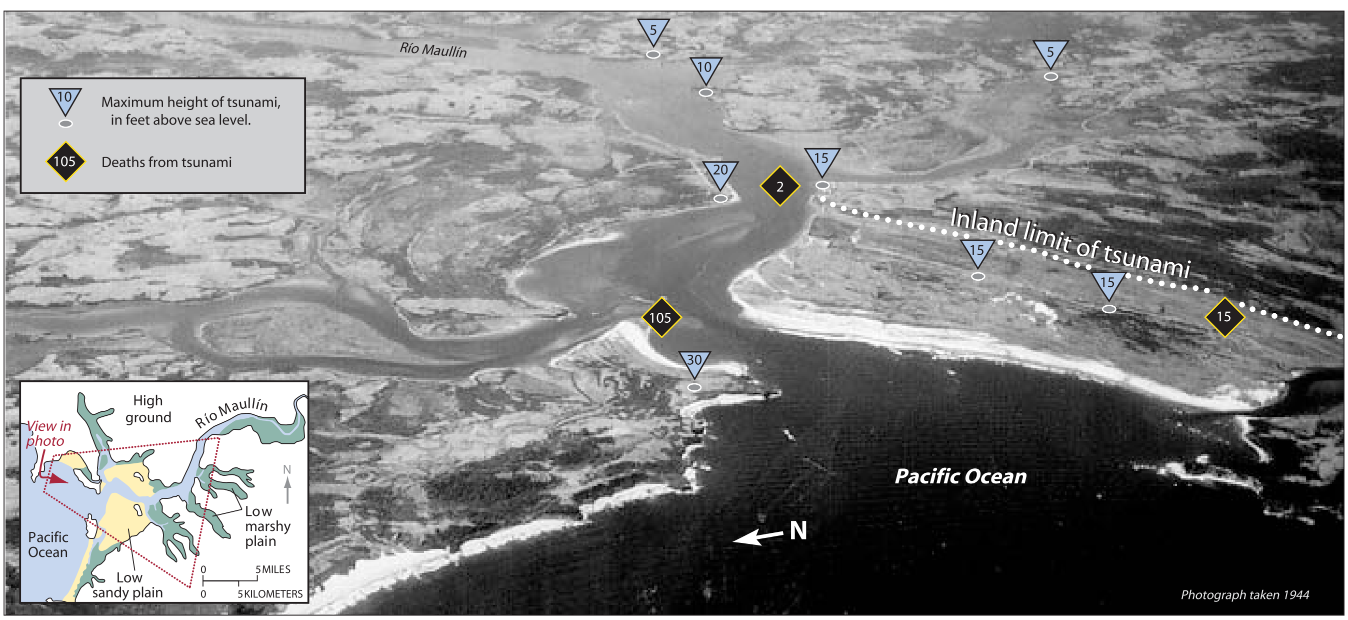
Preparing for tsunamis

Although we cannot prevent natural disasters from occurring, we can reduce their damaging effects through effective planning. Scientists and planners are working to improve our ability to detect tsunamis and issue accurate and timely warnings, to respond appropriately when they occur, and to avoid hazardous situations wherever possible.

Planning ahead

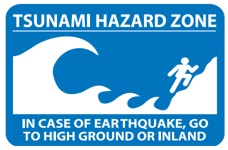
Using historical and geological records, planners can predict where and how often tsunami trigger events are likely to occur. Simulating these events using mathematical models allows them to "see" the effects of tsunamis before they occur

USGS



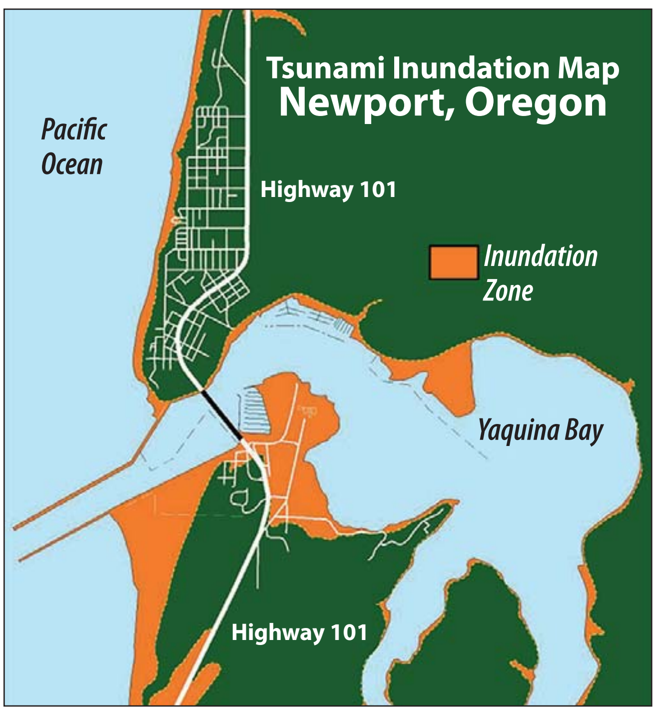
Markings on this 1944 photograph of the area surrounding the mouth of Río Maullín on the Chilean coast show the extent of run-in from the 1960 tsunami. The triangle symbols are labeled with the maximum run-up, in feet, and the diamond symbols indicate where fatalities occurred.

and to take corrective measures. Many coastal communities are developing tsunami preparedness plans using inundation models like the one shown below. Public education programs are a big part of these plans. For example, some communities now use special signs to alert the public to tsunami hazard zones and evacuation routes.



When high-risk areas are identified before they are developed, appropriate zoning laws ensure that residential developments and large construction projects such as power stations are restricted to higher ground. In areas that have already been developed, retaining walls can be built to provide a higher level of protection. Following the 1993 tsunami, Japan's Okushiri Island built a 15-m reinforced concrete wall to protect vulnerable areas.

Oregon Department of Geology/NOAA/PMEL

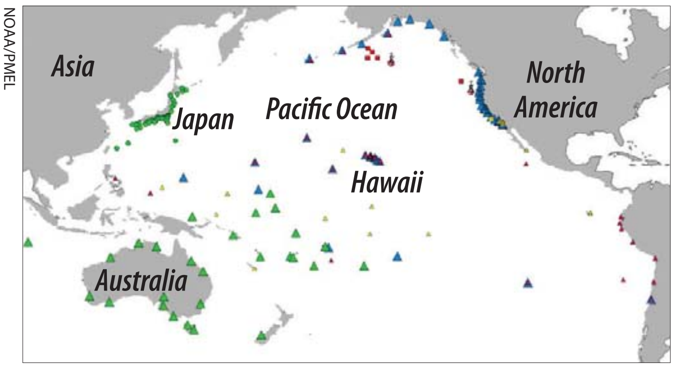


Emergency managers use mathematical modeling to create tsunami inundation maps such as this. Areas prone to flooding are shown in orange, and roads and highways usable as evacuation routes are in white.

Monitoring and warning

Today, Pacific Rim countries use a combination of technology and international cooperation to detect tsunamis. The center of operations for this system is the Pacific Tsunami Warning Center located in Ewa Beach, Hawaii. The Center's objectives are to detect and pinpoint major earthquakes in the Pacific region, determine whether they have generated a tsunami, and provide timely warnings to people living in the Pacific region.

NOAA/PMEL



The Pacific tsunami detection system uses 24 seismic stations, 53 tide stations, 52 dissemination points, and 6 DART systems scattered throughout the Pacific Basin.

Deep-ocean tsunamis are difficult to detect. They average less than half a meter high, have wavelengths of hundreds of kilometers, and move at hundreds of kilometers per hour. In 1995, the Pacific Marine Environment Lab (PMEL) developed a system called DART, short for Deep-ocean Assessment and Reporting of Tsunamis. This system uses sensitive detectors to measure water pressure changes from passing tsunamis. It is capable of detecting deep-ocean tsunamis with amplitudes as small as 1 cm.

Large tsunamis are rare, and developing an accurate warning system is a challenging goal. Historically, nearly 75 percent of tsunami warnings have been false alarms. For this reason, people are often hesitant to evacuate their homes and businesses, and their response to warnings in general is poor. Emergency managers in tsunami-prone areas must work constantly to increase public awareness and acceptance of the risks of tsunamis and the emergency plans that are in place.

NOAA/PMEL

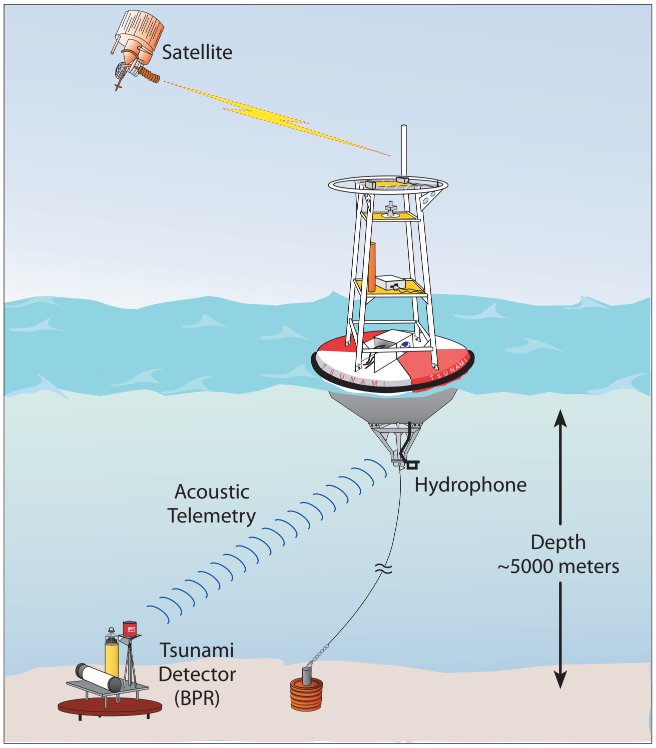


Diagram of a DART station. Placed on the seafloor, a Bottom Pressure Recorder (BPR) transmits pressure information to a surface buoy. The buoy then sends the data to the warning center through a satellite link.

Surviving a tsunami

By interviewing tsunami survivors, planners have put together these survival tips:

- **Heed natural warnings.** An earthquake is a warning that a tsunami may be coming, as is a rapid fall or rise of sea level.
- **Heed official warnings.** Play it safe, even if there have been false alarms in the past or you think the danger has passed.
- **Expect many waves.** The next wave may be bigger, and the tsunami may last for hours.
- **Head for high ground and stay there.** Move uphill or inland, away from the coast.
- **Abandon your belongings.** Save your life, not your possessions.
- **Don't count on the roads.** When fleeing a tsunami, roads may be jammed, blocked, or damaged.
- **Go to an upper floor or roof of a building.** If you are trapped and unable to reach high ground, go to an upper story of a sturdy building or get on its roof.
- **Climb a tree.** As a last resort, if you're trapped on low ground, climb a strong tree.
- **Climb onto something that floats.** If you are swept up by a tsunami, look for something to use as a raft.
- **Expect company.** Be prepared to shelter your neighbors.

Excerpted from U.S. Geological Survey Circular 1187.

Questions

1. What country is most at risk from tsunamis? Why is this?

2. Why doesn't the East Coast of the U.S. experience tsunamis more often? Are tsunamis possible there?

3. Over geological time, what has caused the most destructive tsunamis in the Hawaiian Islands?

4. How often do devastating tsunamis with run-ups of 15 m or more occur in the Pacific Basin?

5. Why is the first wave of a tsunami often not the most dangerous?

6. Why are tsunamis difficult to detect in the open ocean?

7. How can a community prepare for a tsunami?

8. When is it safe to return to coastal areas after a tsunami?

Investigation 5.4

Tsunami warning

The 1964 Alaska tsunami

- Launch ArcMap, and locate and open the **ddde_unit_5.mxd** file.

Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.

- In the Table of Contents, right-click the **1964 Alaska Tsunami** data frame and choose Activate.
- Expand the **1964 Alaska Tsunami** data frame.

The 1964 Alaska earthquake was the second strongest earthquake in recorded history and the strongest to strike U.S. territory. The earthquake, shown with the red star symbol, caused extensive damage to Anchorage both through shaking and *liquefaction* (i.e., making liquid) of the soil. The earthquake also triggered a major tsunami that seriously impacted many coastal communities, causing fatalities as far away as Eureka, California.

- Turn on the **Plate Boundaries** layer.

Although the epicenter of the earthquake (marked by the red star on your map) was inland, the greatest motion of the seafloor took place some distance offshore, along the Aleutian Trench. An 800-km-long slab of the North American plate was thrust suddenly upward by as much as 40 m as the Pacific plate plunged beneath it.

- Turn on the **Tsunami Source** layer. This shows the approximate extent of the displaced seafloor.
- Turn on the **Run-up Locations** layer. This layer shows sites that recorded one or more run-up measurements from the tsunami.

To view an animation of the effects of the 1964 Alaska tsunami:

- Select the **Trigger Event** layer.
- Click on the trigger-event symbol (red star) using the Hyperlink tool ⚡. Be patient while the movie loads.
- Use the Pause button to examine the movie at various times.

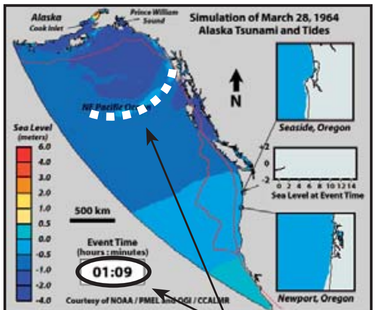
This movie is different from others you have seen. Rather than show a simulated wave, this movie uses colors to show changes from average sea level. Light blues, oranges, and reds are higher than normal sea level; darker blues are lower than normal.

The digital clock at the bottom of the movie screen shows the number of hours and minutes that have passed since the trigger event. The movie begins 27 minutes before the earthquake and ends almost 15 hours later.

Tracking the leading wave

At 1:09 after the earthquake event, the leading wave of a tsunami appears as a light blue arc traveling southward from the source. (The dashed white line does not appear in the movie.)

NOAA/PMEL



Leading wave at 1:09

Use Pause and Play buttons to return to the frame where the clock reads 00:03. Notice the long red-orange "hill" of water that forms off the Alaska coast. As the movie advances forward in time, the hill spreads out. Follow the light blue leading edge of the tsunami southward (shown as a white dashed line in the figure at left).

Tides and tsunamis

Tide gauges are devices used to record changes in sea level at coastal locations. Run the movie through several more times, each time focusing your attention on the tide gauge record at Seaside, Oregon. Normal tides would create a regular, gently changing record of the water level like the one shown at left. Watch the leading wave and the tide gauge; you should be able to see the "arrival signature" of the leading wave on the tide gauge readout.

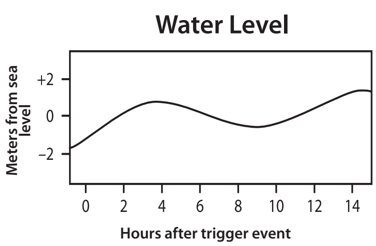
The arrival signature is found where the gauge readout in the movie first differs from the plot in the sidebar (bottom left).

1. How long did it take the leading wave to reach Seaside, Oregon?

Tide gauge plots

Tide gauge plots show the local water level at a gauge as it changes over time. A typical plot, in the absence of factors such as tsunamis, shows a gentle pattern of high and low tides that repeats with a period of around 13 hours.

This plot shows what the Seaside, Oregon tide gauge might have registered if the 1964 Alaska tsunami had never happened. The starting point and time scale of the plot are the same as the graph in the movie.



Continue the movie and watch the tide gauge. Earlier you read that tsunamis slosh around an ocean basin (like water in a bathtub). If the waves have enough energy, they can reflect off coastlines and return at a later time. When you reach the end of the movie, answer the following questions.

2. According to the tide gauge, how many secondary waves struck Seaside after the leading wave? (One wave may be very difficult to see in the plot.)

3. Was the leading wave the highest? If not, how many hours after the trigger event did the highest sea-level run-up occur? There were actually two peak waves at Seaside; record them both.

4. Based on what you've seen, is it safe to return to low-lying coastal areas immediately after the leading wave? Explain your answer.

- Close the Media Viewer window when you are finished.

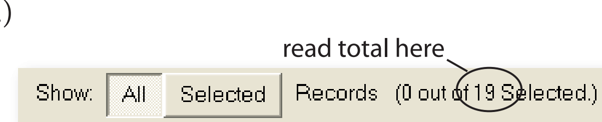
Tsunami trigger events

- Click the QuickLoad button.
- Select **Data Frames**, choose **Tsunami Hazards** from the list, and click **OK**.

Now that you have an idea what tsunamis are and how they travel, you will look at the geologic trigger events that cause them. Any event that displaces a large volume of seawater can generate a tsunami. These trigger events include volcanic eruptions, underwater and coastal landslides, earthquakes, and even (rarely, thank goodness) asteroid impacts. Each of the red star symbols in the **Tsunami Sources** layer represents an event that triggered a tsunami in the 20th century. Next, you will examine these data to find out how common each type of trigger event is.

How often do tsunamis occur?

- Select the **Tsunami Sources** layer.
- Click the Open Attribute Table button.
- Read the total number of events recorded since 1900 at the bottom of the table. (Your answer will be different than the example shown below.)



5. What is the average number of tsunami events recorded each year? (Divide the total number of events by 100 years.)

What causes most tsunamis?

- Scroll across the table to the **Event Type** field. Scroll down the table to see the different types of trigger events.

6. What is the most common type of tsunami trigger event?

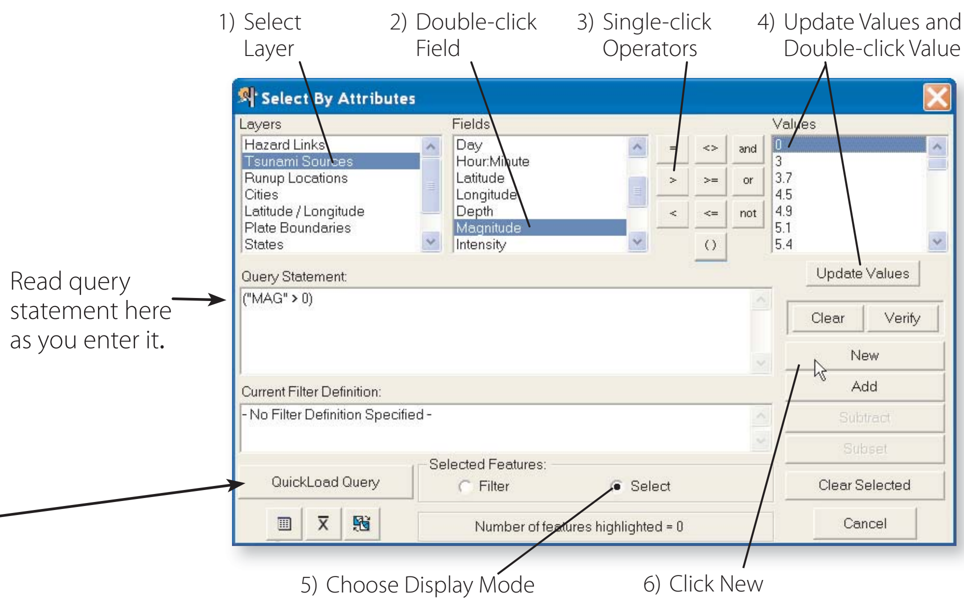
Close the attribute table.

Tsunami warnings

Not all earthquakes produce tsunamis. It's a good idea to warn people of an approaching tsunami, but evacuations are expensive and carry their own risks (panic, looting, etc.). Is there some minimum earthquake magnitude associated with tsunamis? To find out, you will examine the **Tsunami Sources** layer for all events that have an earthquake magnitude greater than zero.

- Click the Select By Attributes button.
- To display the locations of events with magnitudes greater than zero, query the **Tsunami Sources** layer for **("Magnitude" > 0)** as shown in steps 1-6. Your query will actually read:

("MAG" > 0)



QuickLoad Query

- Click the QuickLoad Query button and select the **Tsunami EQ Trigger Magnitude** query.
- Click **OK**.
- Click **New**.

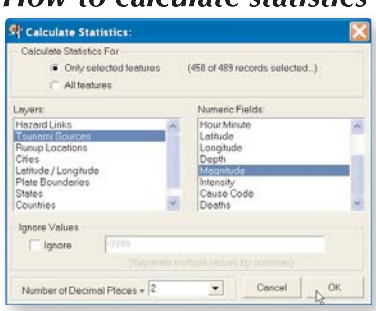
- If you have difficulty entering the query statement correctly, refer to the **QuickLoad Query** described at left.

The tsunamis generated by earthquakes with known magnitudes are now highlighted on your map.

To find magnitude statistics for these tsunamis:

- Click the Statistics button in the Select By Attributes window.
- In the Statistics window, calculate statistics for **only selected features** of the **Tsunami Sources** layer, using the **Magnitude** field.
- Click **OK**. Be patient while the statistics are calculated.

How to calculate statistics



7. Record the following statistics about the earthquakes that cause tsunamis.

   a. Average magnitude (**Mean**) =

   b. Highest magnitude (**Maximum**) =

   c. Lowest magnitude (**Minimum**) =

- Close the Statistics and Select By Attributes windows.
- Click the Clear Selected Features button.

Use these statistics to help answer the following questions.

8. Create a list of criteria that you would use to decide whether and when to issue a tsunami warning. Explain each of your criteria.

   a. What size trigger event requires a warning? How close or how far away would it have to occur?

   b. How would your local geography figure into your decision?

   c. When would you issue the warning?

   d. Which officials would you notify? How would you notify them?

   e. What would you tell them?

f. When would you issue an "all clear" signal?

9. Since 1948, more than 75 percent of tsunami warnings have been false alarms, because it is difficult to predict the impact of a tsunami. Currently a warning is issued each time there is an earthquake of magnitude 6.7 or greater near a coastline or in the open ocean. Do you think it is better to "assume the worst" and send out too many warnings or "assume the best" and send out too few? Explain.

Quit ArcMap and do not save changes.

Investigation 5.5

2004 Indonesian tsunami

On December 26, 2004, at 7:58 a.m. local time, the fourth strongest quake in recorded history (magnitude 9.0) struck off the west coast of Sumatra, part of the island country of Indonesia. The earthquake occurred at the boundary where the India plate subducts beneath the Burma plate. The earthquake caused approximately 1200 km of the plate boundary to uplift several meters. This sudden upward movement of the seafloor displaced trillions of tons of ocean water, generating a tsunami that devastated countries bordering the Indian Ocean and eventually affected all of the world's oceans.

- Launch ArcMap, and locate and open the **ddde_unit_5.mxd** file.

Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.

- In the Table of Contents, right-click the **2004 Indonesian Tsunami** data frame and choose Activate.
- Expand the **2004 Indonesian Tsunami** data frame.

This data frame shows the location of the main earthquake (the red star), and the locations in which tsunami run-ups were reported.

- Click the Identify tool.
- In the Identify Results window, select the **Affected Countries** layer from the list of layers.
- Use the Identify tool to click on each of the countries listed in the table on the following page in order to find the number of deaths and per capita income for each country.

Per capita [Latin] — by or for each person.

1. Complete the table below using the information obtained from the Identify Results window for each country.

Country	Deaths	Per capita income
Indonesia		
Sri Lanka		
India		
Thailand		
Bangladesh		
Malaysia		
Myanmar		
Somalia		
Tanzania		
Kenya		

- Close the Identify Results window when you are finished.

2. How would per capita income affect a country's ability to respond to a natural disaster of this magnitude?

- Select the **Trigger Event** layer.
- Using the Hyperlink tool, click on the tsunami source off the coast of Indonesia (the red star). Be patient while the movie loads.

The movie shows the initial earthquake and the tsunami as it spread across the Indian Ocean.

3. Did the waves appear to spread evenly in all directions, like circular ripples in a pond when a rock is thrown? Or did they appear to spread more forcefully or vigorously in some directions than in others?

4. If the tsunami does not appear to have spread evenly, how might that have affected the coastlines where the tsunami came ashore? Cite examples from the table.

- Close the Media Viewer window.
- Select the **Run-up Locations** layer.
- Click the Full Extent button to see the entire map.

5. *Teletsunamis* are tsunamis whose waves propagate around the world. Was the 2004 Indonesian tsunami a teletsunami? Why or why not? Use the **Affected Countries** layer as a guide to examine where the tsunami traveled and which coastlines it impacted.

- Quit ArcMap and do not save changes.