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OCEANOGRAPHY
SPECIAL REPORT

Scientists hope to save more lives by learning better ways to predict the approach of killer waves.

By Laura Kong

Shortly after 7 a.m. on April 1, 1946, the first devastating tsunami waves hit Hilo, Hawaii. As one survivor, Kapua Wall Heuer, described it, "I looked out . . . and saw this great big black wall coming in. . . . The noise was terrific. . . . And then you heard the screaming . . . people were stomping, trying to reach earth, trying to get out. Dogs swimming around. Then came the crash. . . . [I]t hit buildings, the lighthouse, and the railroad track and everything. And the roar. And I said, 'Oh, that's good-bye to Hilo.'" Waves 8 meters (25 feet) high smashed every house facing Hilo Bay. Survivors struggled for days to retrieve the bodies of the victims and to clear the massive amounts of debris.

Tsunami (tsoo NAH mee) is a Japanese word that means *harbor wave,* though scientists now know that tsunamis do not originate in harbors. Furthermore, though tsunamis have often been called *tidal waves,* they

Big Waves:

Tracking Deadly Tsunamis

Residents flee downtown Hilo, Hawaii, in April 1946, as waves from a tsunami that originated in Alaska's Aleutian Islands inundate the city. Throughout the Hawaiian Islands, 159 people were killed by the deadly waves.

have nothing to do with tides. Rather, a tsunami is a series of waves that forms when a strong disturbance—most often an earthquake—occurs on the ocean floor. The waves travel outward from the point of the disturbance. On the surface of the water, the waves spread as a succession of expanding circles, like the waves produced when a pebble is thrown into a pond.

The cause of the tsunami that struck Hilo in 1946 was an earthquake that occurred about 145 kilometers (90 miles) off Unimak Island, one of the Aleutian Islands in Alaska. The waves reached Unimak 48 minutes after the earthquake, leveling a lighthouse and killing five members of the United States Coast Guard who were stationed there. Waves that reached as high as 42 meters (135 feet) above sea level inundated the coast.

TERMS AND CONCEPTS

Crest: The highest part of a wave.

Distant tsunami: A tsunami that travels great distances—usually from one coast of the Pacific Ocean to the other—before it strikes a particular area.

Epicenter: The point on the Earth's surface from which earthquake waves seem to radiate, located directly above the *focus,* the true center of the earthquake.

Focus: The point in the Earth where rocks first break during an earthquake.

Local tsunami: A tsunami that strikes a coastal area near the place it was generated.

Period: The time between crests of successive waves.

Ring of Fire: A horseshoe-shaped zone along the rim of the Pacific Ocean that is the site of many volcanoes and earthquakes.

Tsunami: A series of waves that forms when a strong disturbance—usually an earthquake—occurs on the ocean floor. The waves travel outward from the point of the disturbance in a succession of expanding circles.

Wavelength: The distance from crest to crest of a wave.

The author:
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Meanwhile, on the opposite side of the circle of waves, the tsunami sped across the ocean at 800 kilometers (500 miles) per hour. It reached Hawaii less than five hours after the earthquake occurred, killing 159 people and causing $26 million in property damage.

After the catastrophe of 1946, the United States and other countries took steps to better prepare themselves for tsunamis. National and international agencies set up monitoring systems to help them spot earthquakes and other underwater disturbances as they occur and to determine which disturbances might generate tsunamis. Local governments developed warning systems that can alert people to an impending tsunami in time for them to leave a dangerous area.

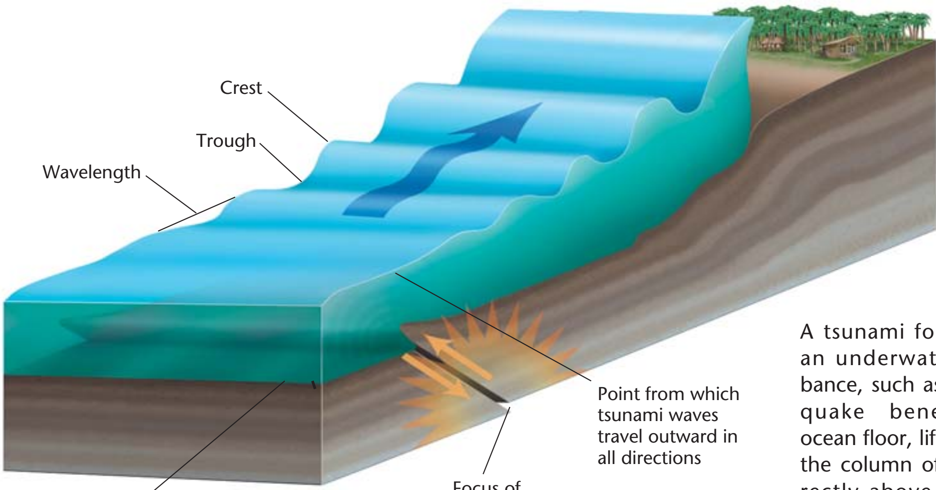
But even with all this preparation, tsunamis remain deadly. During the 1990's alone, 10 tsunamis killed more than 4,000 people. So scientists throughout the world continue to study the causes of tsunamis. By looking at past tsunamis, researchers are learning where and how often tsunamis are most likely to occur. By measuring the heights of previous tsunami waves, they are able to estimate flooding limits at specific coastal locations. The main objectives of all this research are to develop ways to detect the deadly waves more quickly and more accurately and to forecast where the waves will hit and how big they will be.

How tsunamis form

A tsunami begins when an underwater disturbance suddenly *displaces* a column of ocean water—that is, moves the water from its normal position. Sometimes, landslides trigger tsunamis. A chunk of land may break off the coast of a continent or an island and slide into the ocean. Or a volcano may erupt, spewing ash and molten rock onto the ocean floor. Even a meteorite or asteroid can set off a tsunami by plummeting into the sea.

However, most tsunamis occur because of earthquakes on or beneath the ocean floor. Most earthquakes, in turn, are a result of movements of the enormous tectonic plates that make up Earth's outer shell. Each plate consists of *crust* and the uppermost layer of *mantle.* The crust is the outermost layer of Earth. It makes up the continents and the ocean floor. The mantle is a thick layer of hot rock under the crust. The plates slide about on an even hotter layer of mantle. In some cases, plates press against each other. When a plate beneath the ocean presses against a plate that supports a continent, the oceanic plate can lift the continental plate or force it downward. Tectonic movements place a tremendous stress on the plates. So sometimes huge masses of rock suddenly break and shift, and an earthquake occurs.

If rock on or beneath the ocean floor shifts upward, the huge



A tsunami forms when an underwater disturbance, such as an earthquake beneath the ocean floor, lifts or drops the column of water directly above it (above left). As the water in the surrounding area tries to regain its *equilibrium* (state of balance), the motion sets off waves that travel out in all directions from the point on the surface of the ocean directly above the spot where the earthquake began. Out in the ocean, tsunami waves are only a few meters high and have much longer *wavelengths* (the distance from crest to crest) than wind-generated waves. However, as the tsunami approaches land (above right), where the ocean floor slopes upward, the height of the waves increases and their wavelengths decrease. An enormous wall of water builds up and then inundates the land in a tide-like flood.

column of water above the earthquake site also shifts upward. But then the water column falls to the surface under the force of gravity, as the ocean seeks to flatten itself out again, or regain its *equilibrium* (state of balance). If the rock shifts downward instead of upward during the earthquake, the water column also drops down. The sea around the water column then rushes in, trying to reestablish equilibrium. In either case, the ocean's attempt to regain its normal shape produces tsunami waves that begin in the ocean above the *epicenter* of the earthquake and travel outward in all directions. (The epicenter of an earthquake is the point on the Earth's surface dirctly above the *focus,* the point within Earth where the rocks first break.)

As tsunami waves move across the ocean, they look and act different from ordinary, wind-driven waves. A wind-driven wave has a pronounced *crest* (highest point), but the crest of a tsunami wave is usually indistinguishable from the rest of the wave. Wind-driven waves also have a much shorter *wavelength* (distance between crests). The average wavelength of wind-driven waves is 100 to 200 meters (300 to 600 feet), but tsunami waves in the deep ocean are often 200 kilometers (125 miles) long. The tremendous wavelengths of such tsunamis make the waves virtually unnoticeable. A tsunami wave can be 1 to 2 meters (3 to 6 feet) high as it begins to move from the point above an earthquake. But its height is spread out over such a large wavelength that the wave cannot be seen or felt by people aboard ships, nor can it be noticed by anyone in an airplane above.

Tsunami waves also differ from wind-driven waves in their *period* (time between crests). Wind-driven waves usually have periods of 5 to 20 seconds, but the period of a tsunami wave can range from 10 minutes to an hour.

Tsunamis that have caused 2,000 or more deaths

Year	Deaths	Location*
1293	23,024†	Sagami Bay, Japan
1341	2,600	Jusanko, Aomori, Japan
1498	31,000	Nankaido Region (Shikoku Island, Kii Peninsula), Japan
1570	2,000	Southern coast, Chile
1605	3,862	Enshunada (Shizuoka Prefecture), Japan
1605	5,000	Nankaido Region (southeastern Honshu Island), Japan
1611	5,000	Sanriku Region (northeast coast of Honshu Island), Japan
1674	4,487	Banda Sea, Indonesia
1687	5,000†	Lima, Peru
1692	2,000	Jamaica
1703	5,233	Southwestern Boso Peninsula, Japan
1707	4,900	Enshunada, Japan
1707	30,000	Nankaido (Kyushu Island to southern Honshu Island), Japan
1741	14,810	West Hokkaido Island, Japan
1746	3,800	Lima, Peru
1771	13,486	Ryukyu Islands, Japan
1782	40,000†	South China Sea, Taiwan
1792	15,030	Southwest Kyushu Island, Japan
1854	3,000	Nankaido Region, Japan
1854	5,000	Enshunada, Japan
1868	25,674	Northern Chile
1883	36,000	Krakatau, South Java Sea, Indonesia
1896	26,360	Sanriku Region, Japan
1899	3,620	Banda Sea, Indonesia
1923	2,144	Sagami Bay, Japan
1933	3,000	Sanriku Region, Japan
1945	2,306†	Mikawa Bay (Aichi Prefecture), Japan
1952	2,336	Southeast Kamchatka Peninsula, Russia
1976	8,000	Moro Gulf, Mindanao, Philippines
1992	2,200	Flores Island, Indonesia
1998	2,182	Aitape, north coast of Papua New Guinea

* Sources use the term *location* as a way to name a particular tsunami. *Location* can refer to either the place in which the tsunami originated or an area that the tsunami struck.

† Includes deaths from the tsunami and the earthquake that generated it.

Sources: United Nations Educational, Scientific, and Cultural Organization; International Tsunami Information Center; Russian Academy of Sciences Tsunami Laboratory; U.S. National Geophysical Data Center.

Despite their tremendous size, tsunami waves travel at incredibly high speeds. The speed of a tsunami depends on the depth of the ocean through which it is passing: the deeper the water, the greater its speed. Where the ocean is 6 kilometers (3.7 miles) deep, tsunamis travel faster than a commercial jet plane, about 800 kilometers (500 miles) per hour.

As a tsunami reaches shallower coastal waters, friction with the ocean floor slows it down. In addition, the height of each successive wave increases rapidly, as the wave encounters less and less room between the ocean surface and the ocean floor. As a result, the water piles up in a wall of destruction 30 meters (98 feet) or more in height—but even a tsunami 3 meters (10 feet) high can be extremely destructive.

Although tsunamis are popularly depicted as a giant breaking wave with a crest that towers over the land, most tsunamis actually strike the

coast as a plateaulike wall of water or a tidelike flood. But sometimes the first sign of a tsunami is actually a withdrawal of water from the shore. If the tsunami originated when rock sank during an earthquake—causing the water column to drop down at the earthquake site—coastal waters may recede just before the tsunami strikes. The outward flow will expose more shoreline than shows at even the lowest tide. Many coastal dwellers have perished as they rushed to gather fish left high and dry by the departing waters, only to be hit by the incoming wall of water.

The energy driving the wave

How destructive a particular tsunami will be depends on a number of factors, including the amount of energy the wave contains and the area over which the energy is spread. The tsunami gets its energy from the underwater disturbance that created it, and the amount of energy varies widely. A major earthquake (one with a magnitude of 9 on the *Richter scale,* a numerical scale for measuring the strength of earthquakes) that raises rock several meters or feet above the ocean floor generates much more energy than a small earthquake that lifts a plate a few centimeters or inches. An earthquake that moves a section of tectonic plate 100,000 square kilometers (38,600 square miles) in area produces

About 80 percent of all tsunamis occur in an area known as the Ring of Fire. The Ring of Fire is a horseshoe-shaped zone along the rim of the Pacific Ocean. In this zone, Earth's *tectonic plates* often rub against each other. Tectonic plates are formed of layers of rock that make up Earth's outer shell. The movement of the plates causes earthquakes and volcanoes, both of which can generate a tsunami.

much more energy than one that displaces a piece with an area of a few hundred square kilometers or square miles. And a landslide or volcano that drops tons of rock or ash to the ocean floor generates more energy than one that drops a few hundred kilograms or pounds. Energy produced by the disturbance is transferred to the column of water above it. The water column then transfers the energy horizontally to the surrounding water, generating tsunami waves that emanate outwards.

The energy of a wave becomes less concentrated as the wave spreads. Thus, a tsunami has more energy when it strikes a shoreline that is relatively close to its point of origin than it does when it reaches a distant coast.

Scientists use special terms to describe tsunamis according to the distances from their point of origin to the shore. A *local tsunami* is one that strikes the shore near the place where the earthquake occurred, while a *distant tsunami* travels a great distance before reaching shore. But a tsunami may be local relative to one place and distant with respect to another. For example, the tsunami of 1946 was local with respect to Unimak—it took only 48 minutes to get there—but distant with respect to Hawaii (travel time, almost 5 hours). Local tsunamis can be more destructive than distant ones, because their energy is concentrated over a much smaller area. But distant tsunamis can cause damage over large areas all around the Pacific Basin.

The depth of a tsunami's point of origin also determines the energy of its waves. The energy of a tsunami wave is distributed vertically throughout an area that extends from the surface of the ocean to the sea floor. Therefore, as the water becomes shallower, the energy becomes more concentrated. The most destructive tsunamis of all are a result of earthquakes that occur at depths of less than 50 kilometers (31 miles). Their points of origin are both shallower and closer to shore.

Reaching the shore

Offshore and coastal features can alter the size and impact of tsunami waves. Reefs, bays, entrances to rivers, undersea features, and the slope of the beach modify the tsunami as it reaches the coastline. Deep water close to shore, for example, hampers the build-up of a very high wave. A coral reef can act as a breakwater, diminishing some of a tsunami's energy. However, a V-shaped bay—such as the one at Hilo—can act as a funnel, concentrating the energy of the tsunami into a smaller area. And when tsunami waves hit the mouth of a river, they often form a *bore,* a steep, rapidly advancing wave with an almost vertical face.

When a tsunami reaches a coast and moves inland, the water level often rises many meters. Scientists have recorded increases of 15 meters (50 feet) or more because of distant tsunamis and 30 meters (100 feet) or more because of local ones.

The first wave to hit the coast is not necessarily the largest. Energy from the wave that formed at the time of the underwater disturbance is distribut-

A tsunami wave that originated in the Aleutian Islands reaches the coast of Oahu in the Hawaiian Islands as a rushing flood five hours later (top) in March 1957. Within seconds, the wave moves inland (bottom), causing extensive property damage.

ed over several waves, some of which are taller than others. Those waves can strike the shore at intervals of 15 minutes or longer. Thus, they can trap unsuspecting residents who have returned to the coast believing the worst is over. The waves can travel inland for more than 300 meters (1,000 feet), covering large expanses of land with water and debris.

Clues from the past

Scientists cannot predict when and where underwater disturbances such as earthquakes will occur. But they have learned, by studying past tsunamis, where tsunamis are most likely to be generated and approximately how often they will strike. In the late 1980's, two teams of scien-

tists began to compile databases on tsunamis. One team was led by geophysicist James F. Lander of the U.S. National Geophysical Data Center in Boulder, Colorado, and the other by geophysicist Viacheslav K. Gusiakov of the Tsunami Laboratory in Novosibirsk, Russia. The databases enabled researchers to more clearly see that tsunamis threaten coastlines around all the oceans of the world, as well as the shores of the Mediterranean and Caribbean seas. However, 80 percent of all tsunamis occur in the Pacific Ocean, in an area known as the Ring of Fire.

The Ring of Fire is a horseshoe-shaped zone along the edge of the Pacific Ocean. It stretches from Alaska and Japan in the north to New Zealand and the tip of South America in the south. In this zone, Earth's tectonic plates continually press against each other. Where one plate slides under another, hot gases and melted rock called *magma* rise from deep within the planet. Over time, the magma forms volcanoes. The tectonic action along the Ring of Fire is so intense that more than half of the world's active volcanoes occur there. The Ring of Fire is also the site of thousands of earthquakes each year, because of the colliding of the plates. Thus, the Ring of Fire contains two of the primary forces that generate tsunamis.

Lander's and Gusiakov's databases indicate that tsunamis have been devastating communities around the Ring of Fire for thousands of years. Chinese accounts of tsunamis begin 4,000 years ago, and Japanese accounts date back about 1,300 years. However, detailed information is available only for tsunamis that occurred in the past 500 years or so.

One such account indicates that an earthquake in 1692 destroyed the town of Port Royal, near Kingston, Jamaica, when it caused the ground to subside, thus sinking the town. A tsunami generated by the earthquake is said to have lifted a large English sailing vessel from its harbor on one side of the peninsula on which the town lay, carried it over the two-story buildings of the town, and deposited it in the sea on the other side of the peninsula. Some desperate residents, according to the account, managed to grab the ship's cables and rigging and climb aboard to safety as the ship swept by. However, about 2,000 other people were killed by the earthquake and tsunami.

In 1883, a volcano on the Indonesian island of Krakatau erupted, generating a powerful tsunami with waves that reached 40 meters (131 feet) in height and flooded land as far as 10 kilometers (6 miles) inland. About 36,000 people were killed on nearby islands. Much of Krakatau was destroyed, as were 295 towns and villages on the islands of Java and Sumatra. The tsunami waves reached as far as Panama, 18,200 kilometers (11,400 miles) away, and the sound waves from the eruption could be heard 4,000 kilometers (2,485 miles) away in southern Australia.

One of the most powerful tsunamis of modern times was a result of the Great Alaskan Earthquake of 1964. That earthquake occurred when

An area that was once a wharf on Okushiri Island, southwest of Hokkaido, Japan, lies flattened after a *local tsunami* struck the island in July 1993. Local tsunamis strike the coasts only minutes after the occurrence of the earthquake that generated them. Such timing usually does not allow tsunami warning centers and emergency officials enough time to issue evacuation messages to the public before the first wave arrives at the coast. The 1993 tsunami, for example, reached Okushiri in fewer than 5 minutes.

a section of the plate containing most of North America was lifted. The area of the section was about 520,000 square kilometers (200,770 square miles), making the section the largest ever raised in a single earthquake. Parts of the ocean floor rose as much as 9 meters (30 feet). The resulting tsunami damaged the coasts of Alaska, Vancouver Island in Canada, northern California, and Hawaii, and it killed 119 people.

In 1998, tsunami waves up to 20 meters (65 feet) high—taller than palm trees—hit Papua New Guinea, resulting in the deaths of 2,182 people. Most of the victims had lived in fishing villages on a long, narrow strip of land separating the Pacific Ocean from a large saltwater lagoon. The tsunami, made up of three large waves, destroyed every structure and uprooted most of the trees on the strip. The residents had nowhere to run when the killer waves struck.

Lander's and Gusiakov's databases have also helped researchers determine how often tsunamis strike particular areas. Scientists have found that, on average, one to two destructive tsunamis occur in the Pacific Ocean each year. Research has shown that Pacific-wide tsunamis—those that travel from one ocean coast to another—are relatively rare. Only three to four such tsunamis have occurred during each of the last five centuries.

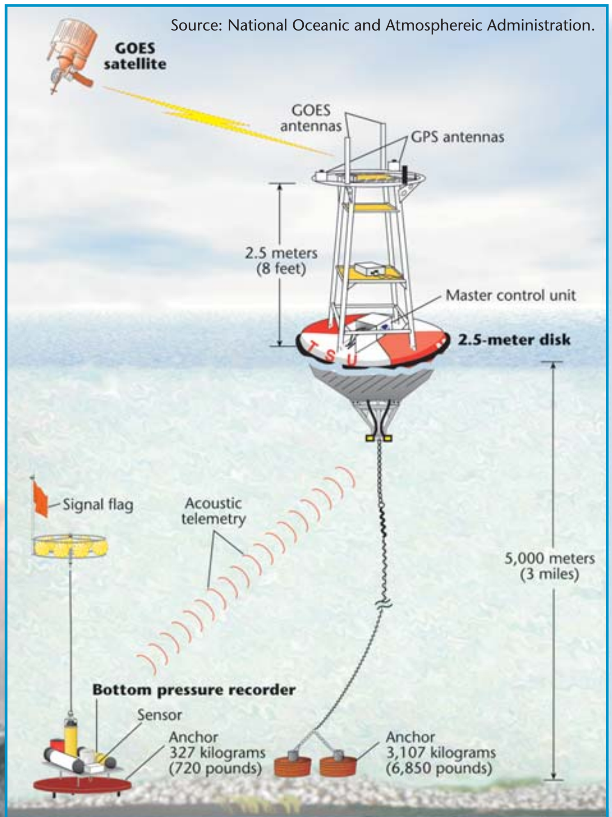
Learning from the tsunamis of today

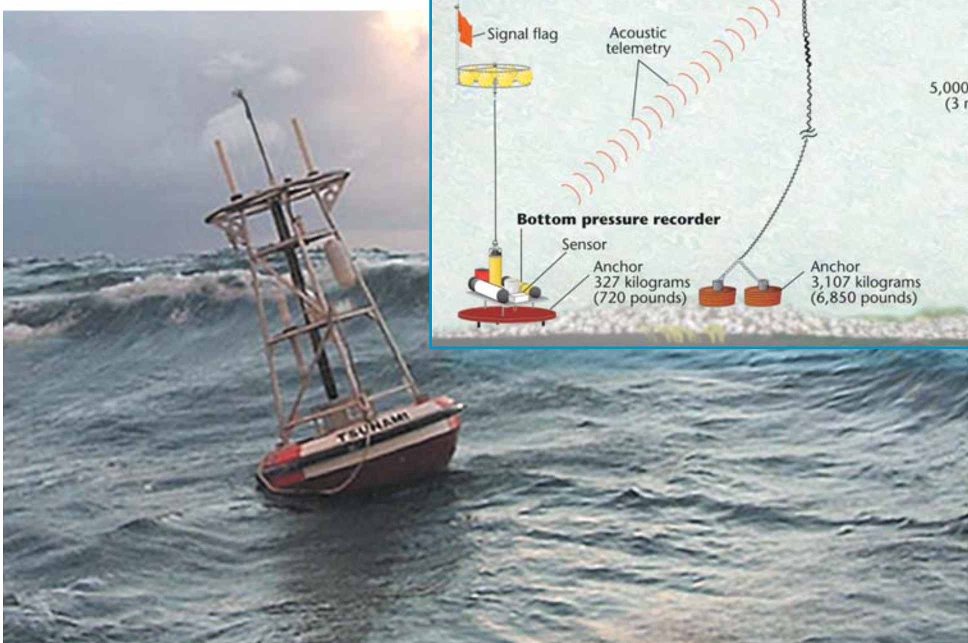
During the 1990's, other scientists studied the conditions that contributed to the formation of tsunamis in the past and compared them with current conditions in various parts of the world. For example, Costas Synolakis at the University of Southern California in Los Angeles extensively explored the site of the 1998 Papua New Guinea tsunami. Synolakis is a *hydrodynamic engineer*—that is, he studies the force of wa-

ter in motion. He became convinced that the relatively moderate earthquake that generated the tsunami could not have been the sole cause of the tremendous destructive force that resulted. Synolakis noted that the sea floor along the Papua New Guinea coast falls steeply to a deep underwater trench. He then suggested that a landslide triggered by the earthquake may have contributed to the tsunami's destructiveness.

Over the next three years, teams of researchers photographed the ocean floor off Papua New Guinea. Their expeditions were sponsored by the Japan Marine Science and Technology Center in Yokosuka and the South Pacific Applied Geoscience Commission—a regional organization of South Pacific island nations with headquarters in Suva, Fiji. Other groups, including one led by *seismologist* (earthquake expert) Emile Okal of Northwestern University in Evanston, Illinois, studied seismologic and *hydroacoustic* (underwater sound) data recorded the day of the 1998 tsunami. The researchers pooled their data to create a computer program that mathematically describes the events of that day. The

A buoy launched by the U.S. National Oceanic and Atmospheric Administration (below) transmits water presssure readings as part of a system that monitors and tracks tsunamis. A bottom pressure recorder located on the ocean floor near a buoy floating on the ocean surface (right) measures the change in water pressure as a tsunami passes overhead and sends the data to the buoy. The buoy transmits the data to a satellite that in turn relays the information to scientists at several tsunami warning centers. The buoy is one of several anchored in the Pacific Basin as part of a system called DART (Deep-ocean Assessment and Reporting of Tsunamis).





program showed that, indeed, an underwater landslide could have generated tsunami waves of the height recorded on Papua New Guinea.

Other scientists working at about the same time found evidence that a similar tsunami might someday flood southern California's coastal communities. Those researchers studied the sea floor off the southern California coast. There, they found small *faults* similar to those in the Papua New Guinea area. Faults are breaks in the crust that are often sites of earthquakes. The scientists also discovered steep canyons that are vulnerable to landslides. Both the faults and the canyons, Synolakis believes, are potential points of origin for local tsunamis similar to the 1998 Papua New Guinea event. Some researchers estimate the probability of a tsunami striking southern California at 35 percent by 2045.

Reading the sands of time

In the 2000's, scientists also studied a group of past tsunamis called *paleotsunamis* (prehistoric tsunamis). Paleotsunami research is a relatively new science in which geologists examine *sediments* (earth, stones, or other matter deposited by water) found in a particular area. The goal of the research is to determine how types of sediment that are not normally characteristic of a given area arrived there. For example, a scientist who is working inland might discover a kind of sand or gravel that is normally found only on an ocean coast. By studying the material and the surrounding area, the scientist might determine that a tsunami carried the material inland. Perhaps he or she could even learn when and where the tsunami struck and how much land the waves covered.

Beginning in the 1980's, Brian F. Atwater of the U.S. Geological Survey and other geologists began to map deposits in the Pacific Northwest of the United States. They wanted to determine whether that area could have experienced earthquakes and tsunamis before written records were kept. Researchers had long thought that the coast of the Pacific Northwest shares many similarities with places around the Pacific Basin where earthquakes and tsunamis are known to have occurred.

In 2001, the researchers reported that sand and gravel found at more than 50 inland sites in northern California, Oregon, Washington, and Vancouver Island in Canada had been deposited by a tsunami in about 1700. In some places, the deposits extended as far as 10 kilometers (6 miles) inland. In others, the waters bearing the sediment had poured over coastal barriers 8 meters (26 feet) high.

Some of the sediments uncovered by the researchers were about 3,500 years old, and the scientists planned to study them for possible evidence of even earlier tsunamis. However, the most important goal of the research had already been achieved. Researchers had proved that tsunamis had struck the area in the past and had found evidence of how far inland the waters had flowed. As a result, they had shown that dam-

The Tsunami Warning System in the Pacific consists of a number of *tide stations,* which measure changes in sea level, and *seismographic stations,* which monitor earthquakes. The time it would take a tsunami detected at any of the stations to reach the Pacific Tsunami Warning Center in Honolulu, Hawaii, which runs the system, is indicated by the hour markings in red.

aging tsunamis may occur in the area again and that such waves would affect many currently populated areas.

Developing a warning system

While scientists are amassing information about tsunamis, a number of national and international organizations are striving to put that information to vital use in three ways: (1) by assessing conditions that could lead to the development of a tsunami, (2) by designing and implementing warning techniques that would alert coastal dwellers when a tsunami has formed, and (3) by educating people who live in or visit potentially dangerous areas so that they can take appropriate actions when a tsunami has been forecast.

One of the first such programs to be established was the U.S. Seismic Sea Wave Warning System, set up at the Honolulu Observatory following the tsunami of 1946. The purpose of the program was to monitor earthquake activity—because most tsunamis are generated by earthquakes—and to send warning information about developing earthquakes to civil and military authorities in and around the Hawaiian Islands.

After an extremely destructive tsunami hit Chile in 1960 and another struck the coasts of Alaska and Hawaii in 1964, many other nations of the Pacific Basin became interested in joining the warning system. In 1965, the United Nations Educational, Scientific, and Cultural Organization's Intergovernmental Oceanographic Commission (UN-

ESCO/IOC) accepted an offer from the United States to expand the warning center at the Honolulu Observatory. As a result, that facility, now known as the Richard H. Hagemeyer Pacific Tsunami Warning Center (PTWC), has become the headquarters of the multinational Tsunami Warning System of the Pacific. Twenty-five nations participate in the system, which is operated by the U.S. National Weather Service, part of the U.S. National Oceanic and Atmospheric Administration (NOAA). UNESCO also established the International Tsunami Information Center in Honolulu in 1965, to coordinate the activities of the PTWC with those of other tsunami warning centers around the world.

A standardized sign on the Pacific Coast of the United States warns residents and visitors that they are in an area that may experience a tsunami and instructs them how to protect themselves. Such signs have been erected by local governments as part of an emergency evacuation plan.

The warning systems of today

The first tsunami warning system monitored only earthquakes. However, scientists soon learned that they also needed another kind of information. At least 75 percent of the warnings that had been issued in the early years of the program were false alarms, because not every underwater earthquake produces a tsunami. To make the warnings more accurate, researchers added *tide stations* to the system. A tide station consists of a gauge that measures changes in sea level and equipment that transmits the measurements to satellites. The satellites then relay the information to the warning centers.

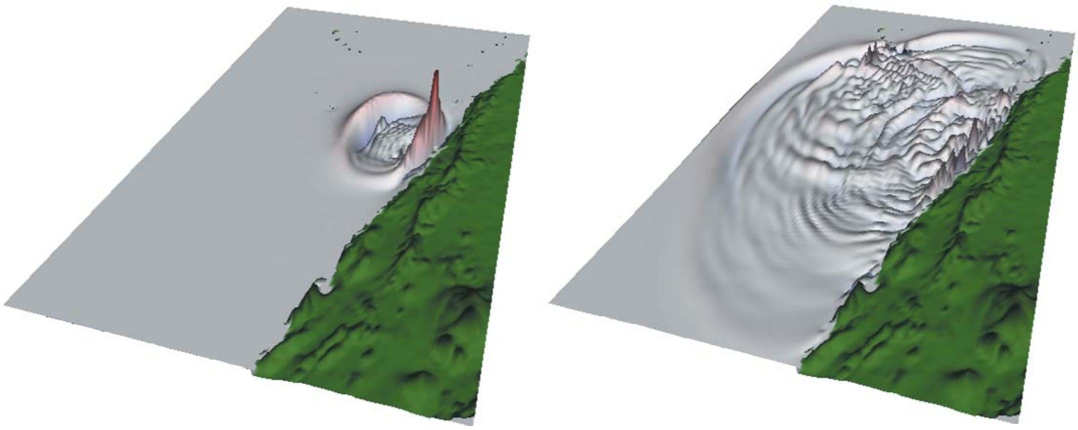
But tide stations also have their limitations. The gauges are all located at the shore. Although they can warn of approaching local tsunamis, they cannot predict the development and impact of distant tsunamis.

In 1997, the United States addressed this limitation through a new project called the National Tsunami Hazard Mitigation Program. NOAA began to put deepwater instruments in the Pacific Ocean as part of a system called DART (Deep-ocean Assessment and Reporting of Tsunamis). Scientists placed several DART instruments along the Aleutian Islands of Alaska and off the Oregon coast. Later, they added one more instrument near the equator. By the end of 2003, seven instruments were monitoring the deep ocean of the Pacific Basin.

Each DART instrument consists of a *bottom pressure sensor* and a *surface buoy.* The sensor lies on the ocean floor, anchored by a weight. As a tsunami passes overhead, the sensor detects an increase in pressure caused by the weight of the added volume of water. The instrument can detect a tsunami that has increased the height of the ocean by as little as 1 centimeter (2.54 inches) at depths up to 6,000 meters (19,700 feet).

The bottom pressure sensor transmits its readings by sending sound waves through the water to an automobile-sized buoy anchored nearby on the ocean surface. The buoy, in turn, transmits the data to a U.S. weather satellite called GOES. The satellite then relays the data to its land receiving station on Wallops Island, Virginia, and then to several tsunami warning centers.

PTWC scientists who monitor the Pacific Basin usually receive *seismic* (earthquake) data first. An earthquake with a magnitude of at least 6.5 on the Richter scale triggers an alarm that alerts PTWC stand-by personnel that an earthquake has just occurred. PTWC scientists then analyze the data, estimate the magnitude of the earthquake, and watch for reports from tidal stations in the area of the earthquake. Such reports will tell them whether tsunami waves have raised the water level of the



A computer model (above) recreates the tsunami that destroyed three villages in Papua New Guinea in 1998, leaving a barren sand-spit where the villages once stood (right). Scientists used mathematical equations and measurements from the actual event to create the model. The researchers believe that an underwater earthquake near the shore started a landslide that displaced several columns of water (above, left), generating the tsunami waves. Within 15 minutes, the waves had spread out along the 550-kilometer (340-mile) length of the sand-spit (above, right).

coast and whether they need to be concerned about a tsunami hazard to other areas. And if a tsunami is crossing the Pacific, one or more DART stations will report a telltale increase in water pressure.

Tsunami emergency procedures

When PTWC scientists have determined that a tsunami hazard exists, they inform emergency authorities in the threatened areas. PTWC issues tsunami watches or warnings for distant tsunamis to nations in the Pacific, and local tsunami warnings to the state of Hawaii. Many coastal communities have developed—or are developing—emergency evacuation procedures, so that when a warning comes through, emergency personnel and the general public will know what to do. Usually, sirens and radio and television announcements warn residents of an impending tsunami. In some places, there is a tsunami evacuation map in the front of the local telephone directory. The map shows what areas are not safe from tsunami flooding and what evacuation routes to use to move inland or to higher ground. In many coastal areas, safety authorities have erected signs pointing to higher ground.

Although public warnings and evacuations may be possible when authorities know that a distant tsunami is crossing the ocean, people who live in or visit areas that are prone to tsunamis also need to be alert for signs of local tsunamis. A tsunami can take hours to cross the Pacific, but a tsunami generated by a local earthquake can hit within minutes. Coastal residents should head inland at the first sign of strong, prolonged tremors.

Researchers hope that programs such as those using the DART system will help them develop even better, faster warning systems. However, until advanced methods become available, tsunami survivors say that there is only one thing to do if you feel a strong earthquake, can see the ocean, and hear a roar. Don't wait to see what happens next—get moving inland and to higher ground!

FOR ADDITIONAL INFORMATION

Books and periodicals

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Koenig, Robert. "Researchers Target Deadly Tsunamis." *Science,* Aug. 17, 2001, pp. 1251-1253.

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Web sites

International Tsunami Information Center—www.prh.noaa.gov/itic

Pacific Tsunami Museum—www.tsunami.org

University of Washington Geophysics Department Tsunami! page—www.ess.washington.edu/tsunami

West Coast & Alaska Tsunami Warning Center About Tsunamis page—wcatwc.gov/subpage1.htm