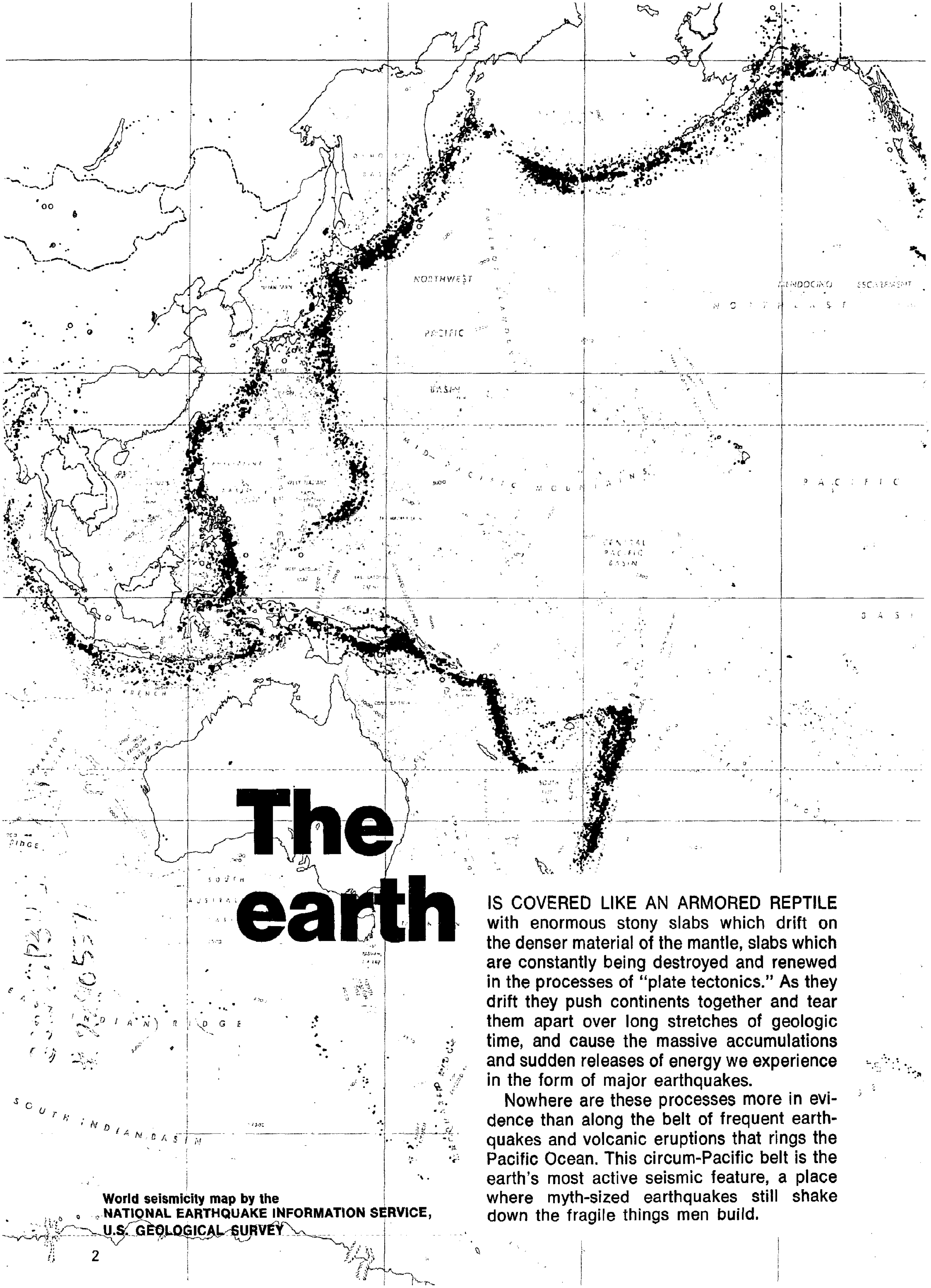
TSUNAMI
THE GREAT WAVES

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

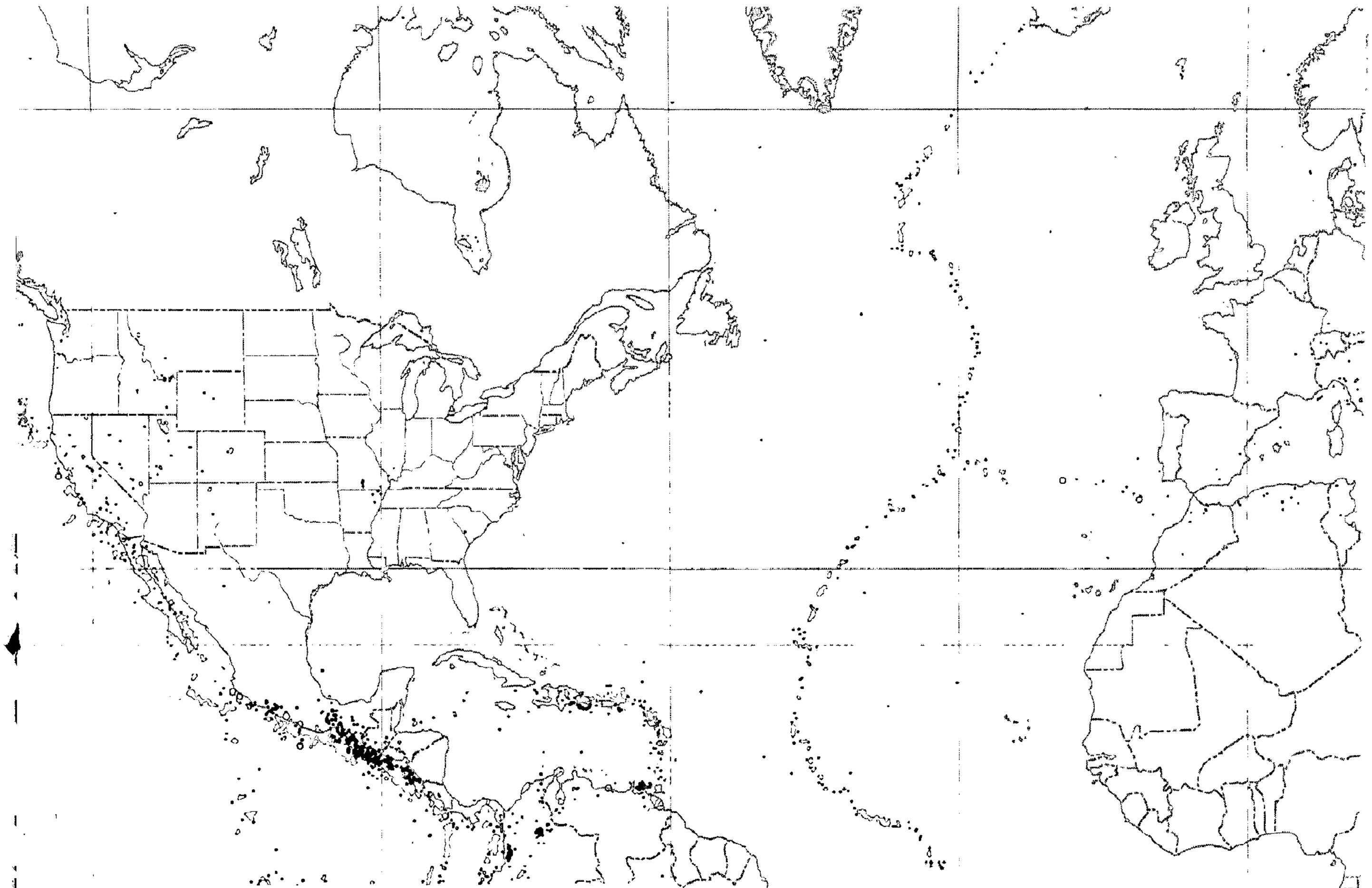


The earth

IS COVERED LIKE AN ARMORED REPTILE with enormous stony slabs which drift on the denser material of the mantle, slabs which are constantly being destroyed and renewed in the processes of "plate tectonics." As they drift they push continents together and tear them apart over long stretches of geologic time, and cause the massive accumulations and sudden releases of energy we experience in the form of major earthquakes.

Nowhere are these processes more in evidence than along the belt of frequent earthquakes and volcanic eruptions that rings the Pacific Ocean. This circum-Pacific belt is the earth's most active seismic feature, a place where myth-sized earthquakes still shake down the fragile things men build.

World seismicity map by the NATIONAL EARTHQUAKE INFORMATION SERVICE, U.S. GEOLOGICAL SURVEY



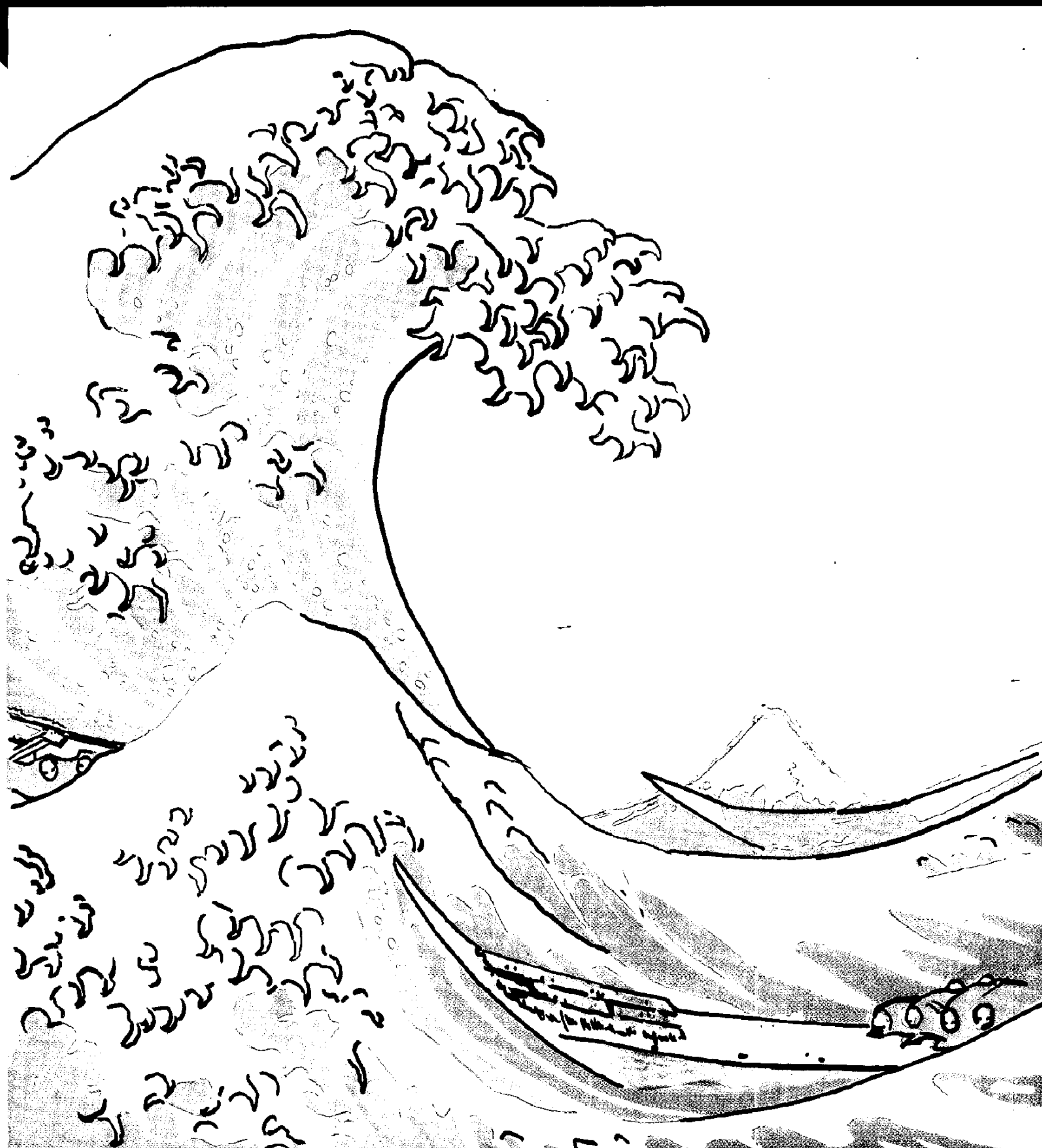
And these earthquakes, the destructive offspring of larger forces shaping and reshaping planet earth, have destructive oceanic offspring of their own—the great waves of the Pacific.

Every island and coastal settlement in the Pacific Ocean area is vulnerable to the onslaught of the great waves. Those of 1868 and 1877 devastated towns in northern Chile, and caused death and damage across the Pacific. A series of waves generated by the eruption and collapse of Krakatoa in 1883 killed more than 36,000 persons in the East Indies. Japan lost 27,000 lives to the wave of 1896, and 1,000 more to that of 1933. There have been hundreds more whose effects were less spectacular but which took many lives and did much damage.

The 1946 waves which struck Hawaii are a case in point. And the waves sent out by the 1960 Chilean earthquakes. And the Great Alaskan earthquake's sea waves, which in 1964 caused damage as far away as California, Hawaii, Chile, and Japan.

Some call them "tidal waves," a name as misleading as it has been persistent. The great waves are not related to the tides. The Japanese, whose islands have felt their destructive power for generations, give us the name used internationally: *tsunami.**

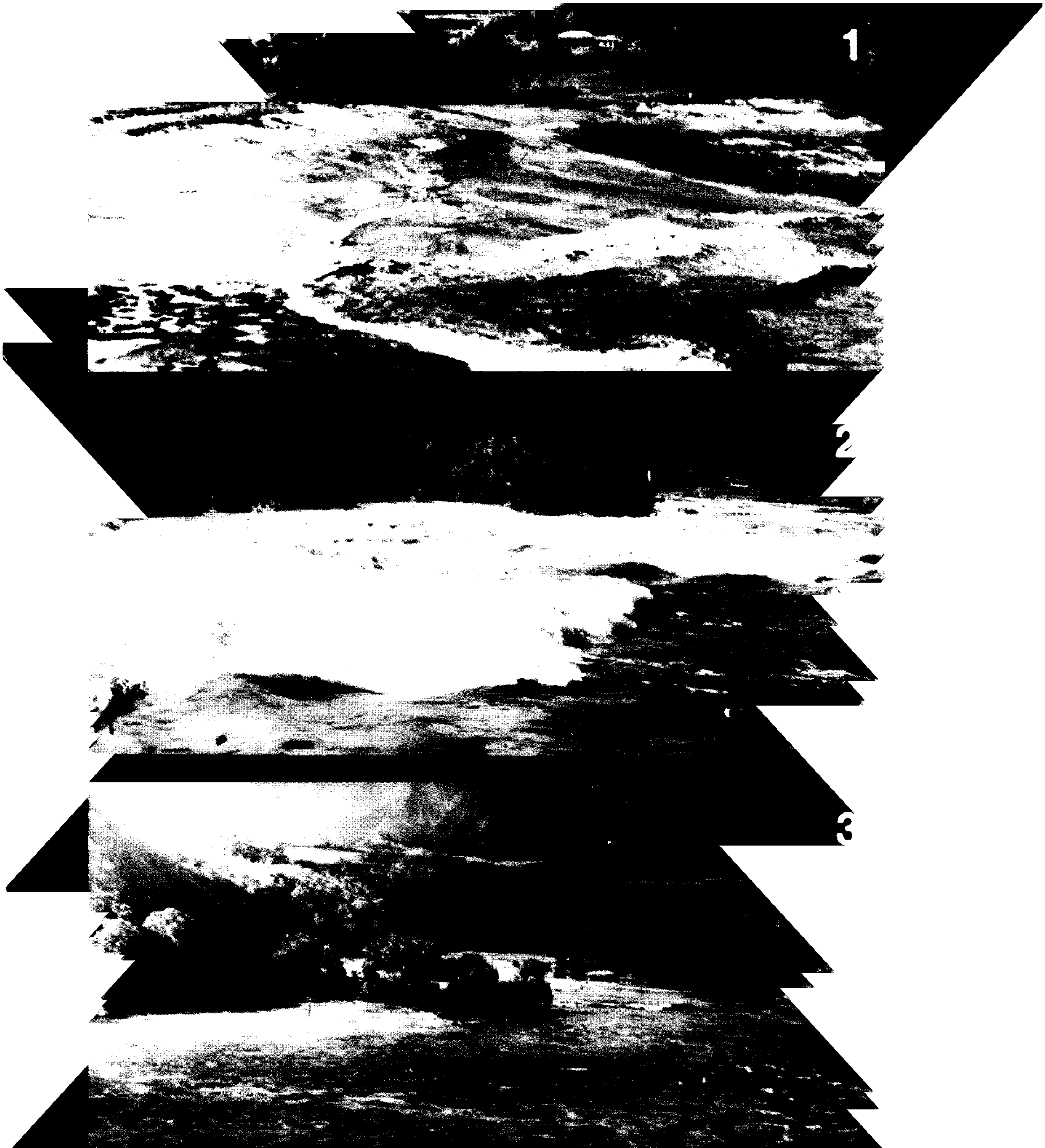
* *pronounced "soo-nah'-me"*



The phenomenon we call "tsunami" is a series of traveling ocean waves of extremely long length and period. In the deep ocean, their length from crest to crest may be a hundred miles or more, their height from trough to crest only a few feet. They cannot be felt aboard ships in deep water, and they cannot be seen from the air.

But the kinetic energy—the energy of motion—represented by a tsunami is impressive: a tsunami "feels the bottom" even in the deepest ocean, and it appears that the progress of this imperceptible series of waves represents the movement of the entire vertical section of ocean through which the tsunami passes. In the deep ocean, the waves may reach speeds of 600 miles per hour.

As the tsunami enters the shoaling water



A rare tsunami wave sequence shows (1) water draining away from the beach as the tsunami trough approaches shore, followed by (2) the churning onslaught of the wave crest, and (3) the great wave all the way in. These photographs were taken by Rev. S. N. McCain, Jr., Kauai, Hawaii.

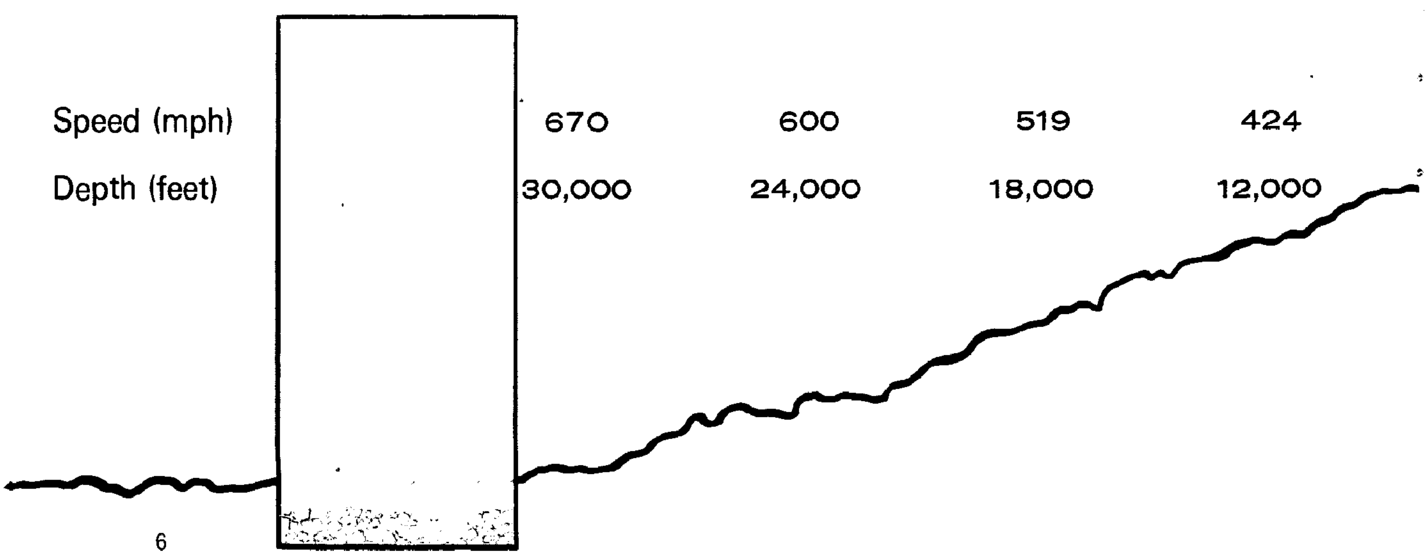
of coastlines in its path, the velocity of its waves diminishes and wave height increases. The arrival of a tsunami is often (but not always) heralded by a gradual recession of coastal water, when the trough precedes the first crest; or by a rise in water level of about one-half the amplitude of the subsequent recession. This is nature's warning that more severe tsunami waves are approaching. It is a warning to be heeded, for tsunami waves can crest to heights of more than 100 feet, and strike with devastating force.

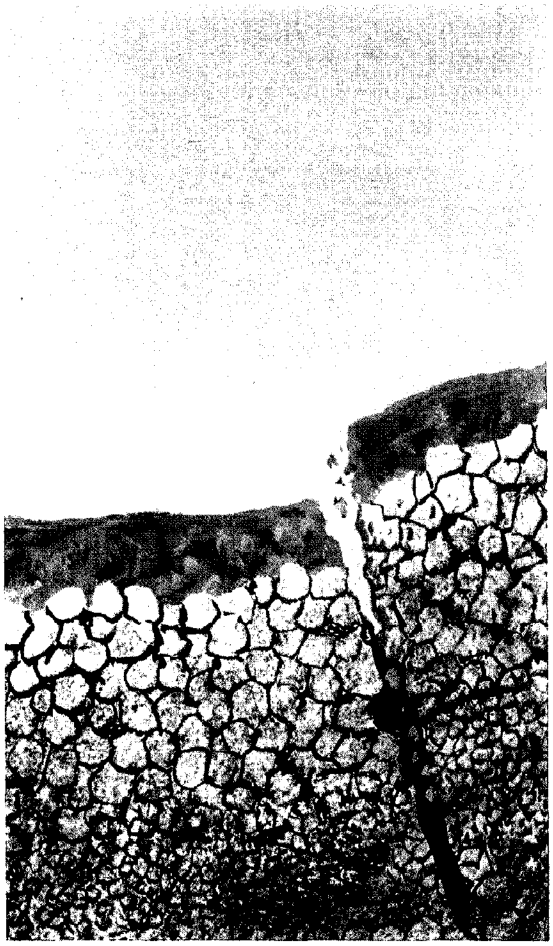
Tsunamis are caused by large earthquakes centered under or near the ocean—specifically, by the net vertical displacement of the ocean floor caused by such disturbances. These displacements can also be produced by volcanic eruptions and the submarine avalanches along the slopes of Pacific trenches, events which have been linked to tsunami generation.

But the tsunami-generating process is more complicated than a sudden push against the column of ocean water. The earthquake's magnitude and depth, water depth in the region of tsunami generation, the amount of vertical motion of the sea floor, the velocity of such motion, and the efficiency with which energy is transferred from the earth's crust to ocean water are all part of the tsunami birth equation.

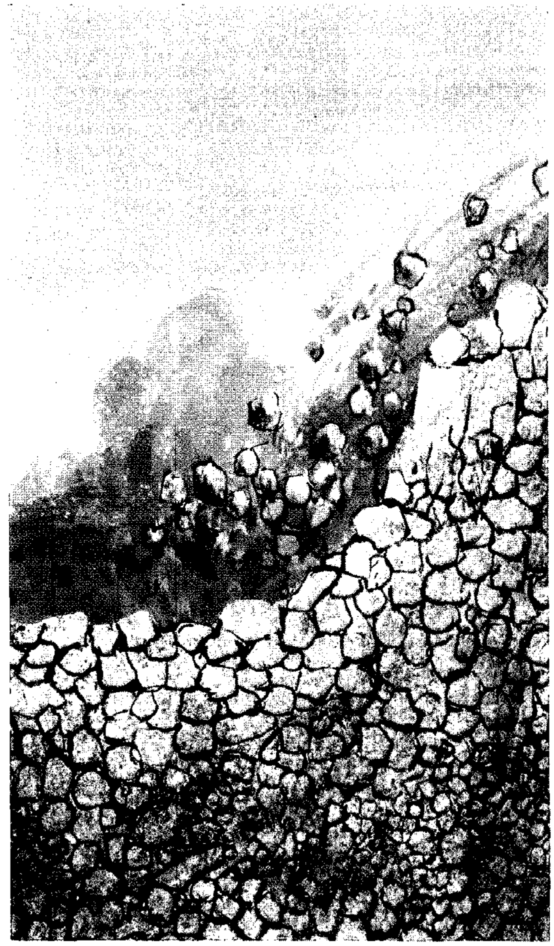
And there are other difficult questions. Except for focusing effects on tsunami wave energy, particularly the well-studied tsunamis of 1960 and 1964, not much is known about the relationship between ocean floor configuration and the shape taken by tsunamis there. It is not completely clear, for example, why a tsunami's waves may be of negligible size at one point along a coast, and much larger at other coastal points nearby. Tsunami run-up—the vertical distance between the maximum height reached by the water on shore and the mean-sea-level surface—is also impossible to predict at the present time. Nor is it possible to predict whether the destructive component of a tsunami will lie in its powerful surge across a beach, or in a gradual rising of sea level followed by a rapid draining back to sea.

The key known characteristic of tsunamis is that their speed varies with the square root of water depth. It is this relationship which permits prediction of tsunami arrival times at all points in the Pacific Ocean area.

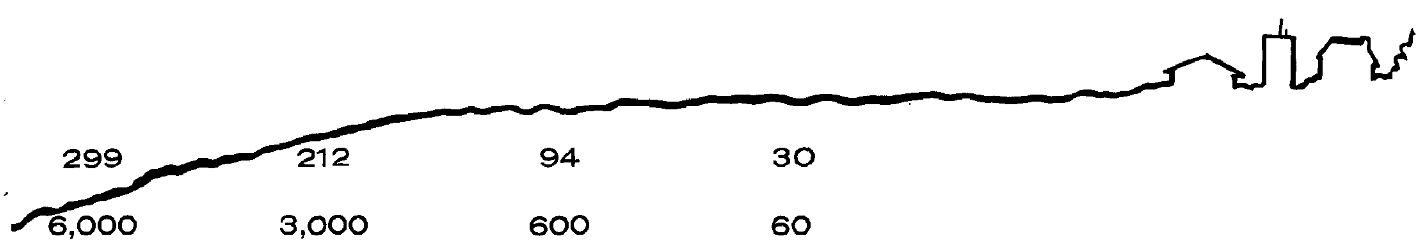




Vertical displacement.



Submarine Avalanches.



Tsunami speed is determined solely by water depth, and this fixed relationship makes it possible to forecast tsunami arrival times for distant locations. The tsunami illustrated here, although somewhat exaggerated in the vertical dimension, is characteristic.

The Tsunami Warn

In the early morning of April 1, 1946, a violent earthquake disturbed the northern slope of the Aleutian Trench, and triggered one of the most destructive tsunamis in recent years. Minutes after the earthquake occurred, waves more than 100 feet high smashed the lighthouse at Scotch Cap, Unimak Island, killing five. The first wave struck Hawaii less than five hours later. When the tsunami had gone, 159 persons were dead and 163 injured, and the islands had suffered some $25 million in property damage—the worst natural disaster in Hawaiian history.

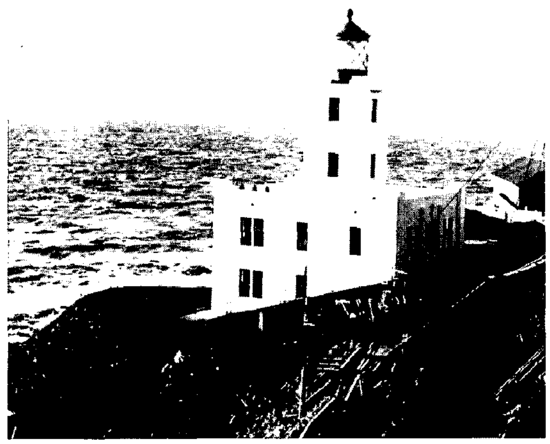
This was the thirty-sixth tsunami recorded in Hawaii in 127 years, and the first to do severe damage since 1877; other major tsunamis struck the islands in 1837, and twice in 1868. They came without warning, as the great waves had always come in the Pacific.

But the tsunami of April 1946 would be the last destructive tsunami to surprise Hawaii.

To a group of scientists in what is now the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce, there was nothing inevitable about the 1946 disaster in Hawaii. The victims of the tsunami, they believed, could have been warned and saved. And tsunamis could be detected and their arrival predicted with sufficient accuracy to provide early warning to the people of Hawaii.

The tsunami warning system they envisioned would use seismographs to detect and

Scotch Cap lighthouse before . . .



. . . and after the April 1946 Alaska tsunami.

ng System

The 1946 tsunami roars into Hilo harbor . . .

. . . causing widespread destruction in the Hawaiian city.

locate earthquakes, and tide gages to detect passing tsunami waves. These would be linked by an extensive communications network. It took two years and considerable tailoring of existing instruments and techniques to transform the belief into a functioning reality.

In 1948, what was then called the Seismic Sea-Wave Warning System was put into operation with its headquarters at the former Coast and Geodetic Survey's magnetic and seismological observatory near Honolulu. During the next four years, the system detected many submarine earthquakes, but no major tsunamis developed, and no full-scale alerts were necessary. Then, on November 4, 1952, a submarine earthquake near the Kamchatka Peninsula generated a tsunami felt across the Pacific. The waves caused some $800,000 damage in Hawaii, but they took no lives. The warning system had begun to pay its way.

Until 1964, three major tsunamis had crossed the Pacific since the Kamchatka tsunami of 1952. The Aleutian tsunami of March 9, 1957, caused damage in the Aleutians, Hawaii, Japan, and along the west coast of North America, but no lives were lost.

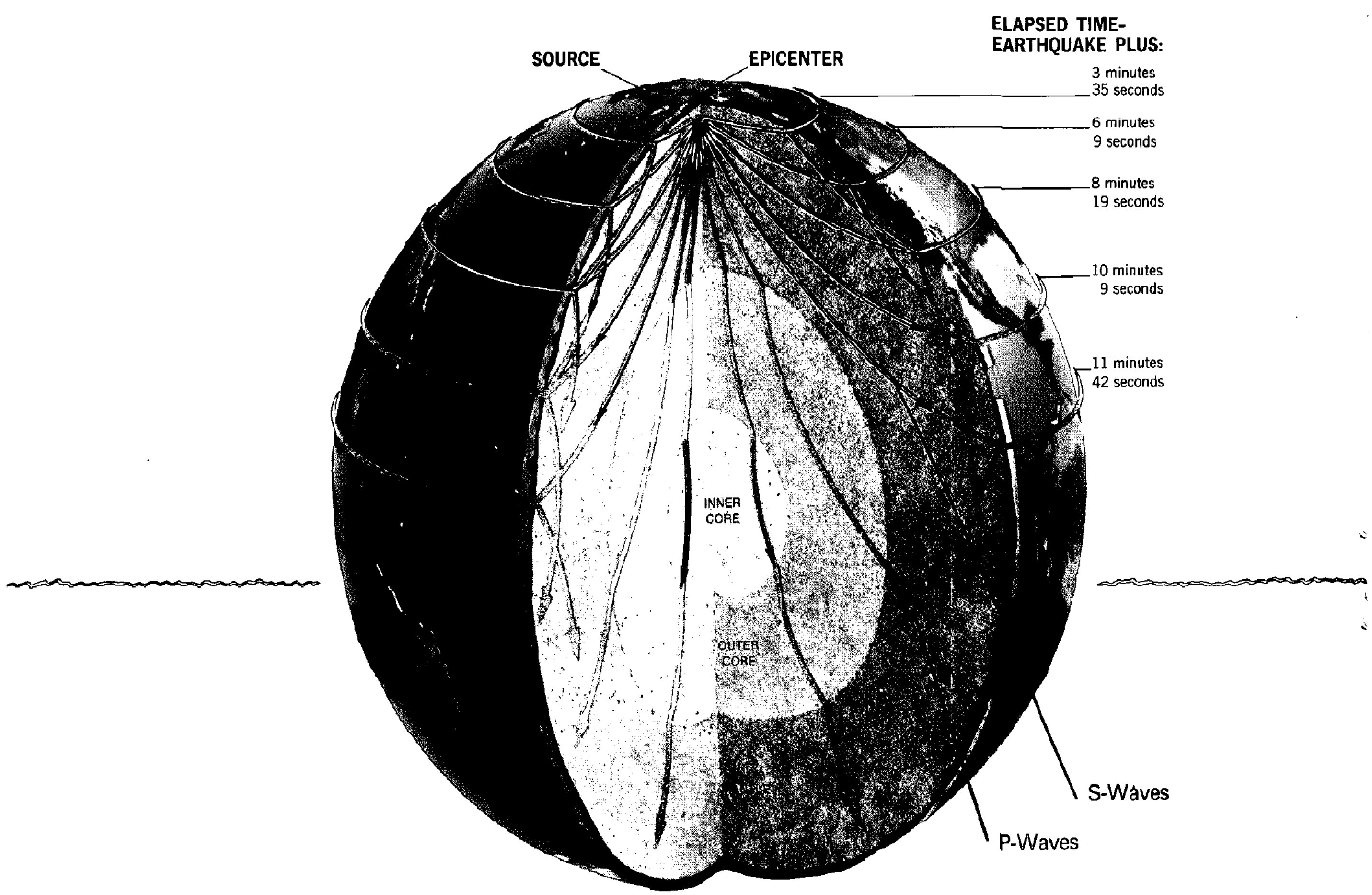
The Chilean tsunami of May 1960 was the most destructive in recent history, causing deaths and extensive damage in Chile, Hawaii, the Philippines, Okinawa, and Japan. Waves 15 to 35 feet high pounded the Hawaii city of Hilo, leaving 61 dead and causing $22 million property damage. But a warning had preceded the waves in Hawaii by six hours; the toll might have been much worse.

In Japan, no general tsunami alert was issued for it was not known then that a tsunami of such distant origin could be so destructive. The waves left at least 180 persons dead or missing in northern Japan and Okinawa, 20 dead in the Philippines, caused $500,000 damage along the western coast of the United States, and did considerable damage in New Zealand. All Chilean coastal towns between the 36th and 44th parallels were destroyed or severely damaged.

The third large tsunami, which originated off the coast of Peru on November 20, 1960, caused 11 deaths on nearby coasts but did little damage in other Pacific areas.

On March 28, 1964, a magnitude 8.5 earthquake struck the Prince William Sound area of Alaska. Called the Good Friday earthquake, this largest North American tremor ever recorded generated a tsunami that was felt across the ocean. Considerable damage was done along the coasts of Alaska and Canada, and at Crescent City, California. And there were casualties. But the number was in tens, not hundreds and not thousands. Warnings make an important difference!

Today's Tsunami Warning System, operated by NOAA's National Weather Service, is a truly international service, providing timely warning to 14 Pacific coastal and island nations and territories, including the United States. Honolulu Observatory is headquarters for the Tsunami Warning System, and the nerve center of an ocean-wide network of detectors. Here, the 24-hour watch is kept for the first reactions of instruments thousands of miles away.



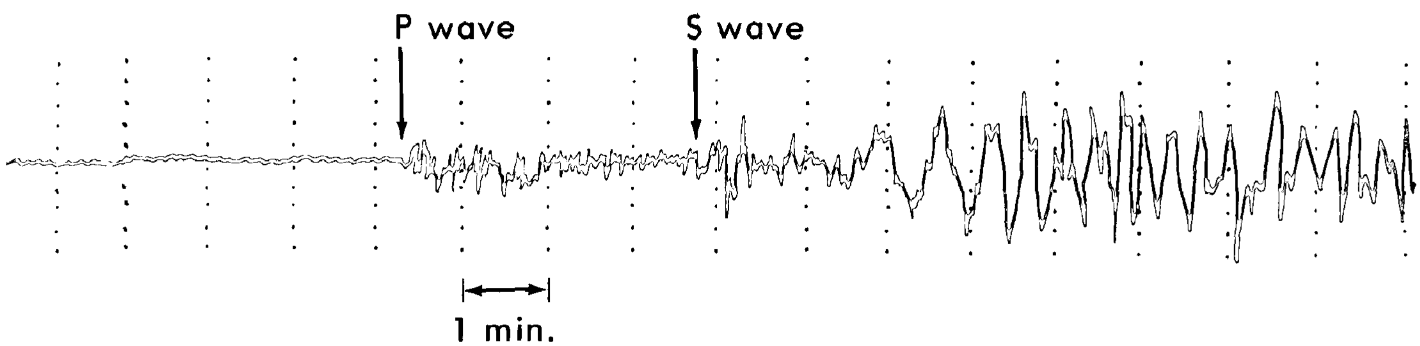
Most earthquakes are caused by slippage along strained faults in the earth's crust. The sudden release of energy as these faults move toward equilibrium produces a variety of earthquake waves, which travel through the earth and across its surface. At seismograph stations, these waves are picked up and translated into electrical signals, which are further translated into a written record that becomes the earthquake's "signature." From this signature, or seismogram, seismologists can determine the approximate magnitude of the earthquake, and the surface distance between their seismograph station and the source of the disturbance.

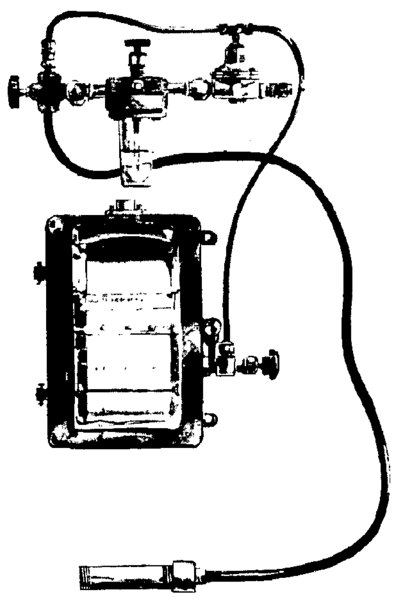
A diamond-shaped "quadripartite" array of seismic detectors on the island of Oahu, linked to Honolulu Observatory, forms the first line of detection for the Tsunami Warning System. The array permits automatic calculations of the surface point of origin (the epicenter) of incoming earthquake waves, earthquake magnitude, and something about the tsunami-generating potential of the earthquake. (Earthquakes below magnitude 6.5, for example, are not considered tsunamigenic, nor are earthquakes occurring in areas characterized by horizontal fault motion.)

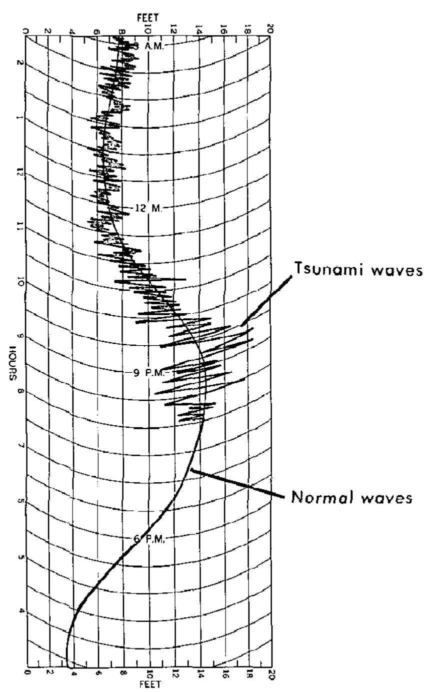
In addition, a network of seismograph stations around the Pacific contributes data as it comes in and is analyzed. Some of these are operated domestically by other government agencies and private institutions, and some are the private and governmental seismological observatories of cooperating Pacific nations. When an earthquake of sufficient magnitude to generate a tsunami occurs, each seismograph station equipped with an automatic alarm comes to alert, and the watch and warning process begins.

As the computers and scientists at Honolulu Observatory go to work on the developing tsunami emergency, participating seismograph stations begin reporting the local arrival times of earthquake waves. Because the propagative characteristics of earthquake waves are well established, the time interval between P (compressional, push-pull) and S (up-and-down and side-to-side shaking) waves can be used to compute the surface distance between each seismograph station and the source of the disturbance. The inter-

The difference between P and S wave arrival time at each seismograph station can be used to calculate the distance between the source and the seismograph locations. If the source falls near or under the ocean, and the earthquake is large enough, a tsunami watch goes out across the Pacific.







Tsunamis appear on the tide gage records, or marigrams, as distinct abnormalities. Marigrams are usually the first positive evidence that an earthquake has generated a tsunami. With the existence of a wave confirmed, the tsunami watch becomes a tsunami warning.

section of these arcs of surface distance—in a computer program or on a world globe—is the earthquake epicenter. If this point falls on or near the ocean, tsunami generation is possible.

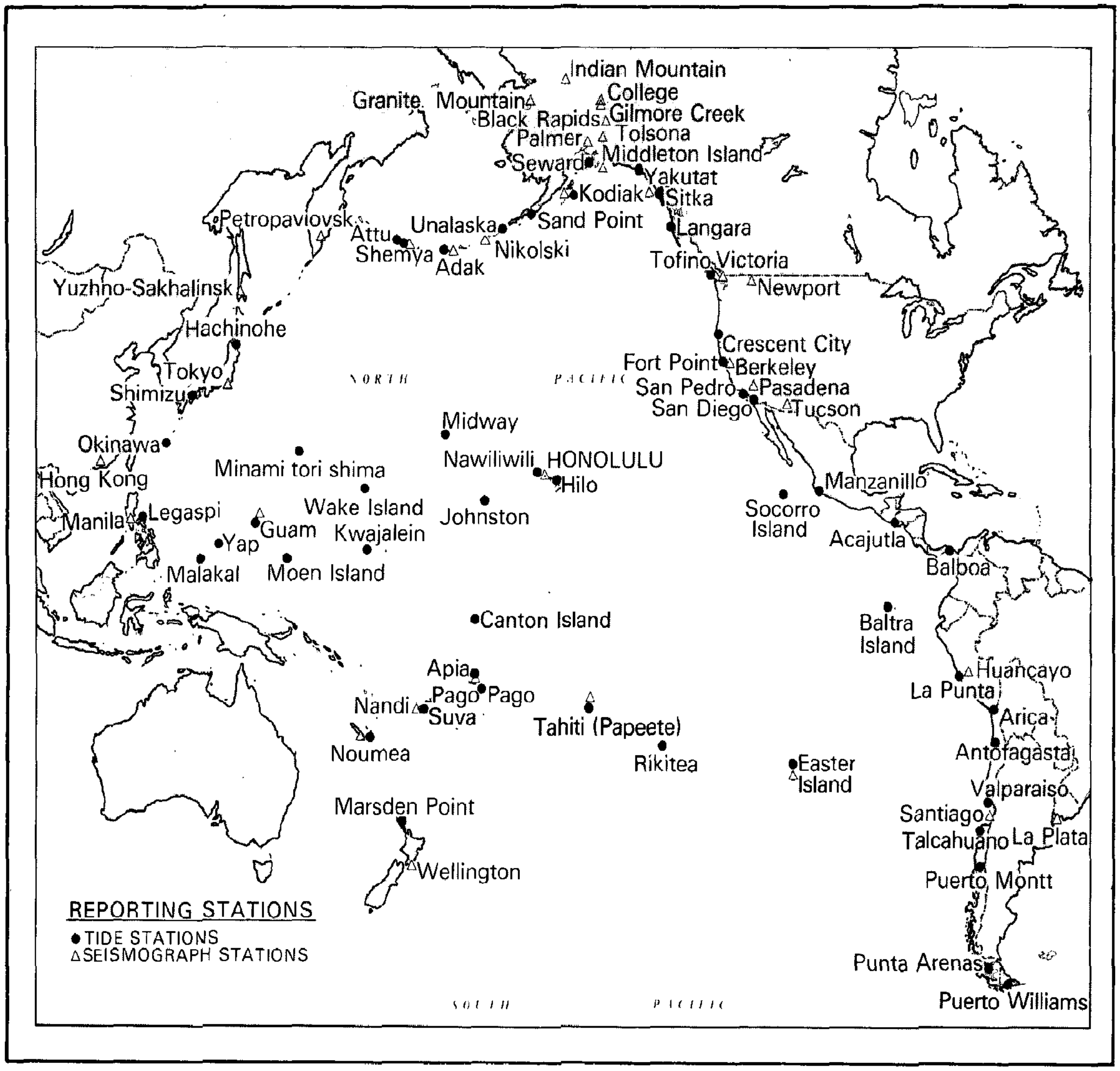
On the basis of such seismographic evidence, Honolulu Observatory issues a tsunami watch, which tells Tsunami Warning System participants that an earthquake has occurred, and where, and that the possibility of tsunami generation exists. Estimated times of arrival are also computed and transmitted for each participant's location.

Now the warning system turns to its second line of detection: a Pacific-wide network of tide stations. There, gages continuously record the cycles of the tides. Passing tsunamis appear on the tidal record, or marigram, as distinctive abnormalities. With the occurrence of a major earthquake, Tsunami Warning System headquarters requests tide observers closest to the epicenter to check their record for "unusual activity."

The first positive indication that a tsunami exists usually comes from tide stations nearest the disturbance. When confirmation is received, Honolulu Observatory issues its warning, alerting warning system participants to the approach of a potentially destructive series of waves and repeating tsunami estimated arrival-times for each location.

Local warning, evacuation, and other emergency procedures are then undertaken by designated emergency and relief forces in the regions covered by the warning. Because the main benefit of the Tsunami Warning System is to give participants time to prepare for the waves, transmission of watches and warnings is limited to a single point in each country, territory, or state.

These warning points differ from region to region. In the United States, Canada, and New Zealand, the messages are usually directed via military and aviation communications links to regional civil defense and other natural disaster offices. In Chile, the Department of Navigation and Hydrography is the tsunami warning agency. In Japan, the Philippines, and Taiwan, the national meteorological agency disseminates tsunami warnings to local and regional civil defense organizations. In the Fiji Islands it is the Harbour Master. In Papua and New Guinea, tsunami warnings come in over aviation lines and are disseminated to the general public by the Civil Defense and Emergency Services organization. In Nauru such dissemination is the respon-



sibility of the Chief Secretary of the Republic; in French Polynesia and New Caledonia, the warning office is designated by the Governor. In Hong Kong, warnings are relayed by the Royal Observatory to the Government Information Services Department, which disseminates them to the general public. In Tahiti, warnings are received and disseminated by the geophysical laboratory there.

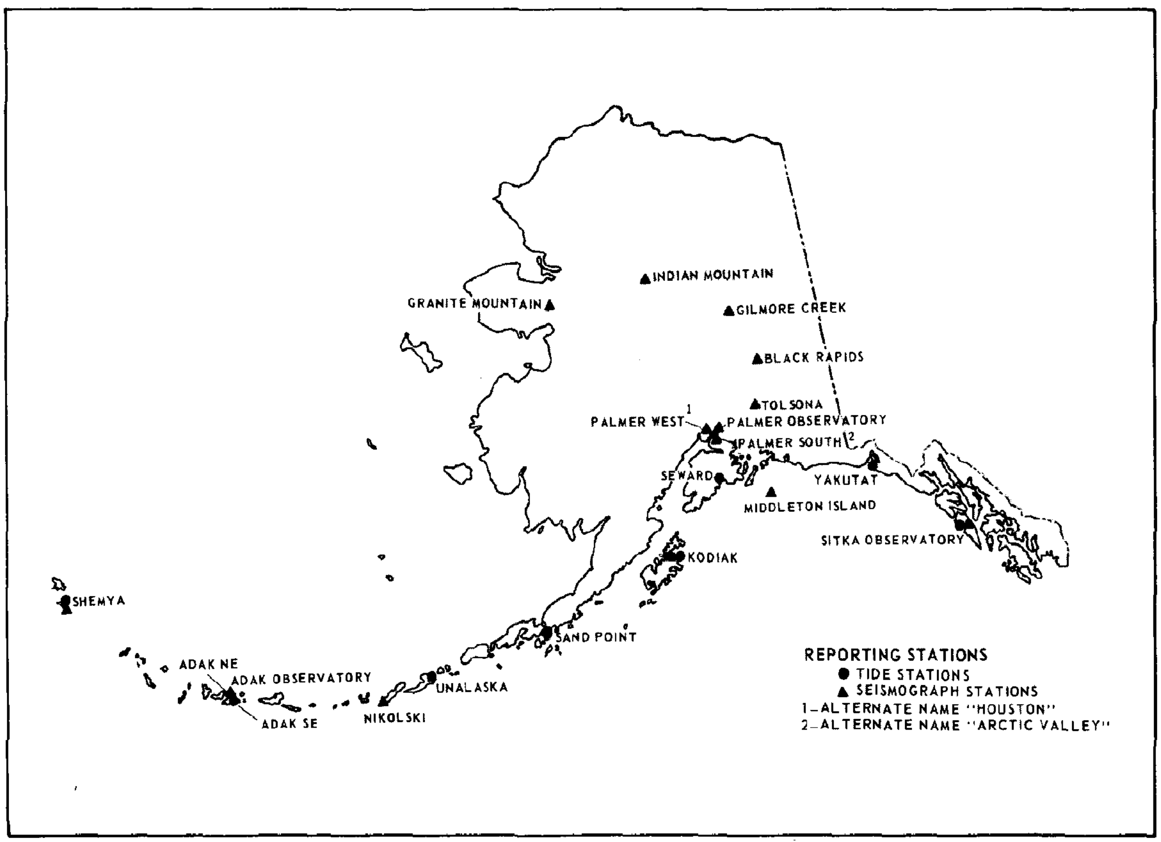
Because tsunamis respect no national boundaries, and because close liaison is essential between participating nations in the Tsunami Warning System, an International Coordination Group has been established, composed of interested member nations in the Intergovernmental Oceanographic Commission. The group helps tie together the three distinct tsunami warnings operations in the Pacific—those of the United States, the Soviet Union, and Japan—and generally promotes liaison and information exchange in the areas of tsunami detection and forecasting. It also deals with the establishment and operation of the International Tsunami Information Center at the Pacific Regional Headquarters of NOAA's National Weather Service and with World Data Center A for Tsunamis, located at the National Geophysical and Solar-Terrestrial Data Center (of NOAA's Environmental Data Service) in Boulder, Colorado. Nations participating in the International Coordination Group include Canada, Chile, Ecuador, France, Guatemala, Japan, Korea, New Zealand, Peru, the Philippines, Taiwan, Thailand, the United States, and the Soviet Union.

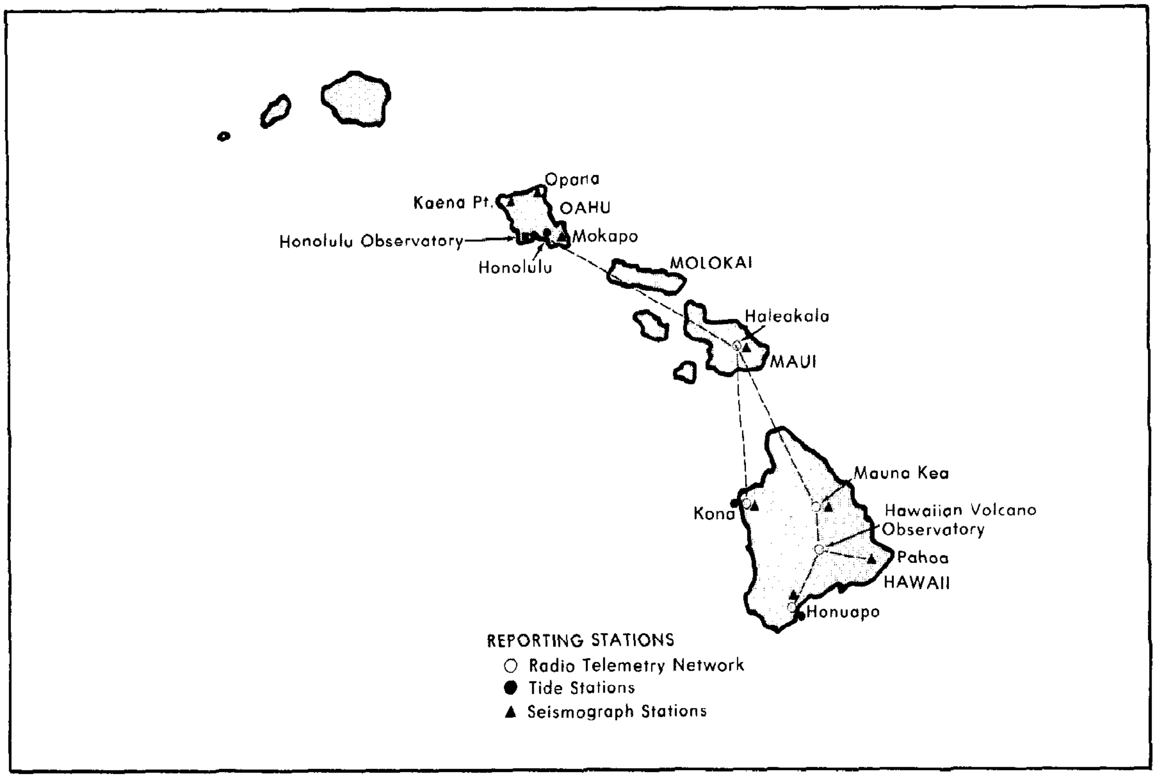
Regional Warning Systems

One of the important lessons of the 1964 Alaska earthquake was that a tsunami can swamp a coastal area near its epicenter long before Honolulu Observatory can confirm that a tsunami has been generated. The result of that lesson has been the establishment of two fast-response regional tsunami warning systems, one for Alaska and one for the Hawaiian islands.

The regional system in Alaska, operational since 1967, represents a unique collection of the most sophisticated equipment and techniques available to seismologists today. The system's nerve center is Palmer Observatory, north of Anchorage, a highly automated headquarters linked to telemetering robot tide and seismograph stations from Sitka to Shemya. The sophisticated data-collection and analysis operations at Palmer are only part of the regional system. The rest is communications—direct lines to crucial coastal communities, seismograph observatories, civil defense units, and other emergency forces—which help speed the urgent tsunami word to those who must put the warning to work.

When a major earthquake of magnitude 7 or greater occurs along the Pacific coast of Alaska, an immediate tsunami warning is issued for an area for at least a 200-mile radius around the epicenter, and including a Palmer system tide gage on two sides of the epicenter. An immediate tsunami watch is issued for the rest of the Alaskan coastline. If significant tsunami wave activity is detected on the marigrams (tide-gage records) telemetered into Palmer, the warning is extended



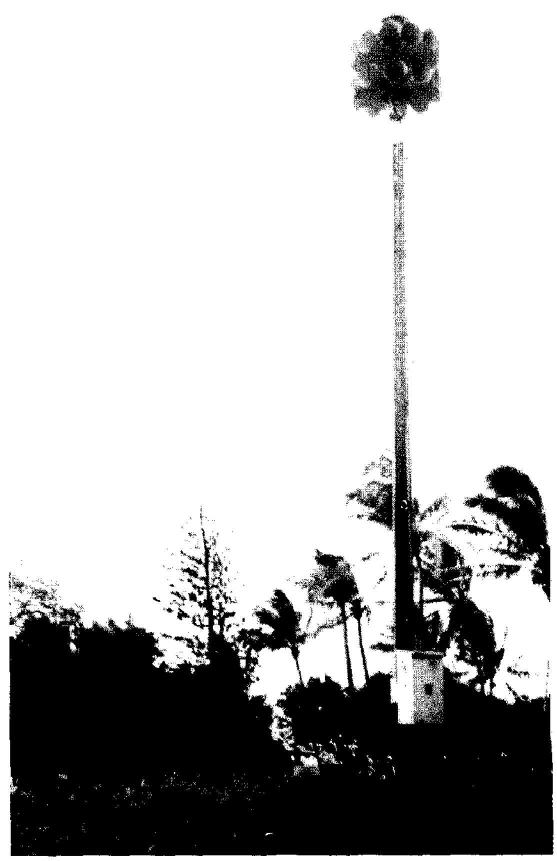


to include Alaska's entire coastline. Severe coastal earthquakes cause Palmer to issue an immediate tsunami warning for at least a 500 mile radius around the epicenter.

The Hawaii regional system entered service in 1975 to provide similar protection against locally generated tsunamis for the people of Hawaii. Directed from Honolulu Observatory, the Hawaiian system receives telemetered data from a quadripartite seismograph system on Oahu and stations on the big island of Hawaii and Maui. These, and telemetering tide stations and offshore pressure-sensing (tsunami-detecting) instruments on the ocean floor, provide continuous seismic and water level data.

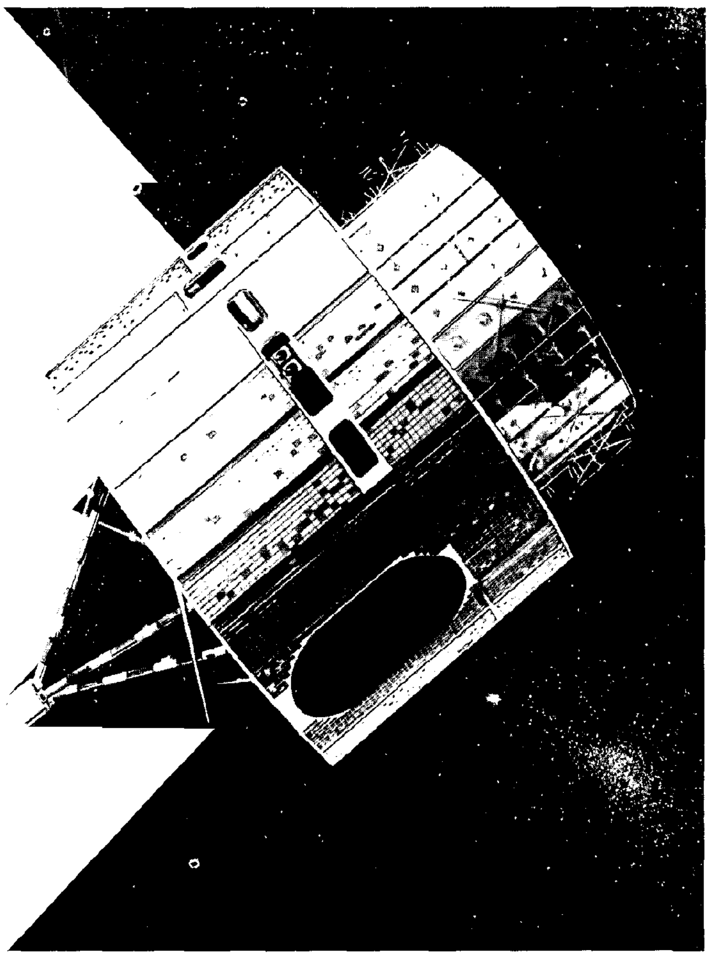
When an earthquake occurs in the Hawaiian region of a size and location that make tsunami generation possible, Honolulu Observatory issues warning messages to the threatened coastal areas through Hawaii Civil Defense. Meanwhile, observatory personnel monitor incoming tide gage data to determine whether a tsunami has been generated. If none has, the warning is quickly canceled.

The rule of thumb in both the regional systems is to get the warning out within minutes of an earthquake and to keep information flowing to emergency forces and the public until the danger is past.



Tsunami alarm sirens.

Into the Space Age



Later in the decade of the 1970's, the first Geostationary Operational Environmental Satellite will be lofted into an earth-synchronous orbit above the International Dateline. This spacecraft, like its geostationary predecessors, will seem to mark time 22,300 miles above a point on the equator; and, like its predecessors, it will provide a relay point for a wide spectrum of fast-moving environmental data, including tsunami watches and warnings.

The difference will be that the spacecraft in NOAA's operational series will be able to pass on the questions and answers between a computer at Honolulu Observatory and automated seismic and tide stations around the Pacific. This warning system of the not very distant future will dramatically slice the time between the occurrence of a tsunami-generating earthquake and the issuance of watches and warnings by Honolulu and the regional systems.

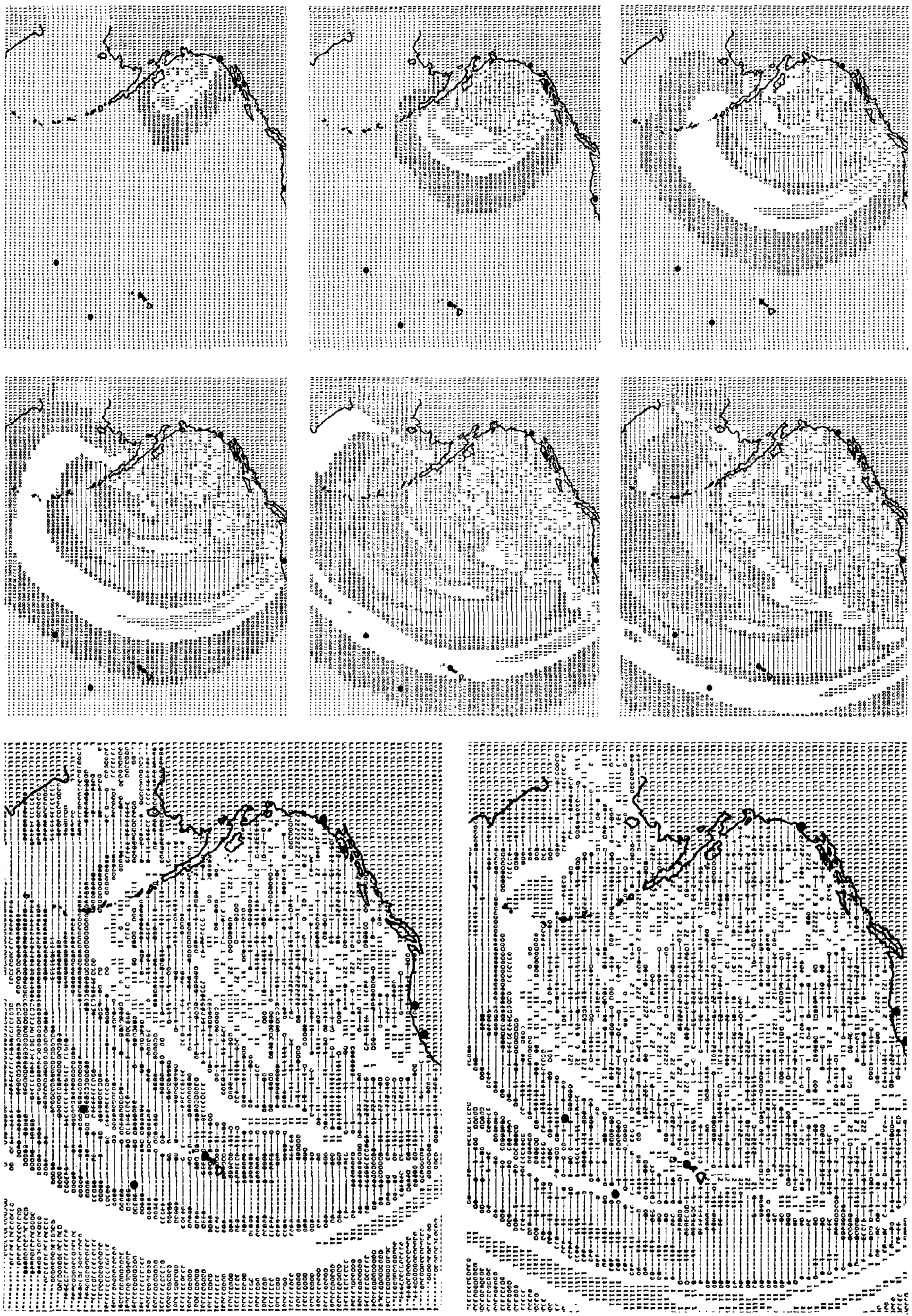
These and other uses of space age technology have been accompanied by a continuing effort to improve tsunami detection, predicton, and theory. The Joint Tsunami Research Effort, a cooperative venture of NOAA's Environmental Research Laboratories and the University of Hawaii, has been pursuing the legion unknowns of the great waves since the mid-1960's.

One reason there are still so many unanswered questions about tsunamis is that they are difficult to observe directly. They leave their tidal record and their mark on coastal communities, and that is about all. So that tsunami research has involved a good deal of detective work.

The researchers have set up a volunteer observer program, in an effort to get good time-lapse photography and measurements of tsunami water-levels and run-up. This observation program also tries to correlate ground deformation and other effects and eye-witness accounts in the event of a tsunami.

The group has fielded some new tsunami-sensing equipment, including the offshore pressure-sensors used in the Hawaiian regional warning system. These measure the changes in the height of the water column above the sensor caused by a passing tsunami or other wave of that amplitude and period. An electromagnetic wave-measuring technique developed there uses the interactions of ocean waves with an electromagnetic field to sense tsunami's wave action offshore; it has also been applied to measuring tides on the open ocean as part of the Mid-Ocean Dynamics Experiment.

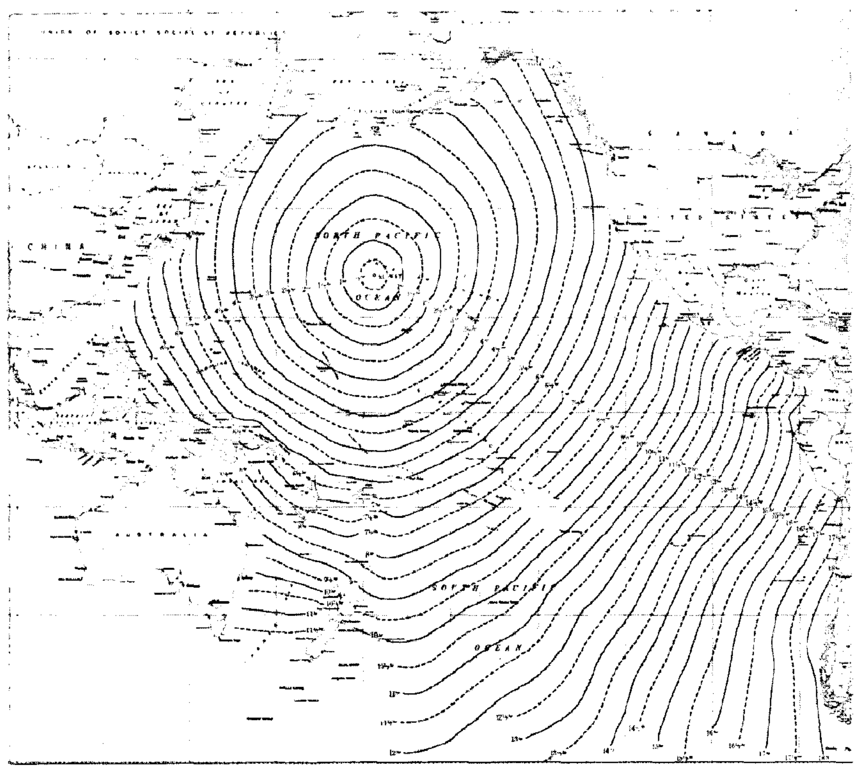
One of the key efforts at the laboratory involves the development of mathematical models which simulate the behavior of tsunamis. Using present models, the NOAA scientists are looking into such unseeable events as tsunami generation, deep-ocean propagation, and the relationship between the source of a tsunami and the shape taken by the mature wave series.

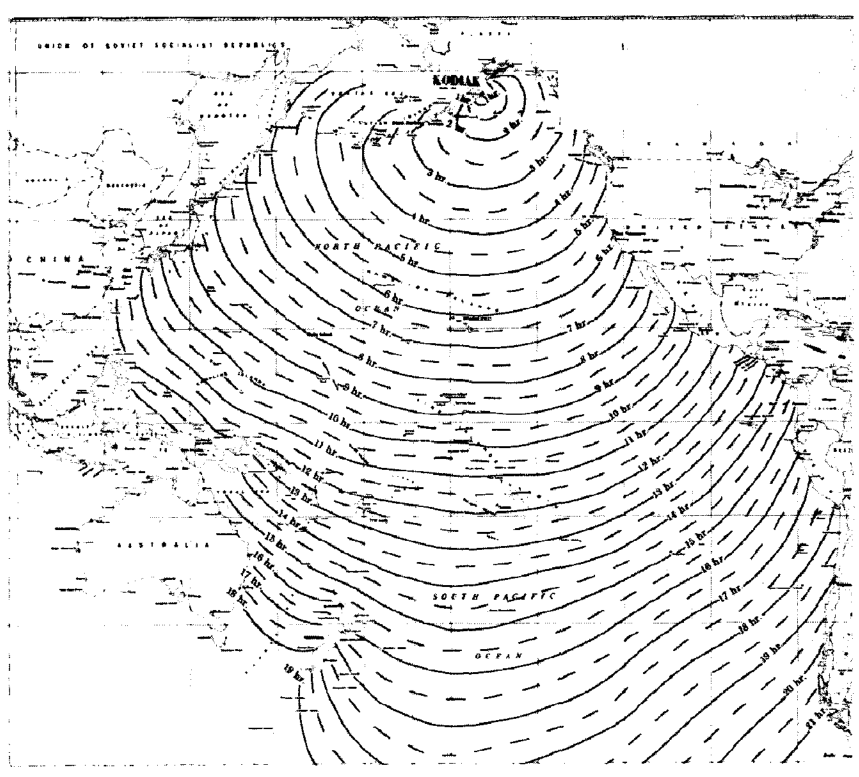


Computer models at NOAA's Joint Tsunami Research Effort (with the University of Hawaii) are being used to simulate tsunami generation, open-ocean propagation, run-up, and other characteristics. Here, a simulated tsunami spreads from the March 1964 Alaska epicenter.

Tsunami Travel Times

NOAA scientists have developed a series of tsunami travel-time charts, computed to provide wave travel-times from any Pacific earthquake epicenter to a number of selected coastal locations. In the charts reproduced here, for example, a tsunami generated by an earthquake near the Philippines would be felt at Midway Island in about seven and a half hours, and, at Kodiak, Alaska, in about fourteen and a half hours.





Tsunami SAFETY RULES

Tsunamis are the so-called "tidal waves" generated by some earthquakes. When you hear a tsunami warning, you must assume a dangerous wave is on its way. History shows that when the great waves finally strike, they claim those who have ignored the warning.

1. All earthquakes do not cause tsunamis, but many do. When you hear that an earthquake has occurred, stand by for a tsunami emergency.

2. An earthquake in your area is a natural tsunami warning. Do not stay in low-lying coastal areas after a local earthquake.

3. A tsunami is not a single wave, but a series of waves. Stay out of danger areas until an "all-clear" is issued by competent authority.

4. Approaching tsunamis are sometmes heralded by a noticeable rise or fall of coastal water. This is nature's tsunami warning and should be heeded.

5. A small tsunami at one beach can be a giant a few miles away. Don't let the modest size of one make you lose respect for all.

6. The Tsunami Warning System does not issue false alarms. When an ocean-wide warning is issued, a tsunami exists. When a regional warning is issued, a tsunami probably exists. The tsunami of May 1960 killed 61 in Hilo, Hawaii, who thought it was "just another false alarm."

7. All tsunamis—like hurricanes—are potentially dangerous, even though they may not damage every coastline they strike.

8. Never go down to the beach to watch for a tsunami. When you can see the wave you may be too close to escape it.

9. Sooner or later, tsunamis visit every coastline in the Pacific. Warnings apply to you if you live in any Pacific coastal area.

10. During a tsunami emergency, your local Civil Defense, police, and other emergency organizations will try to save your life. Give them your fullest cooperation.

Stay tuned to your radio or television stations during a tsunami emergency—bulletins issued through Civil Defense and NOAA offices can help you save your life!

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