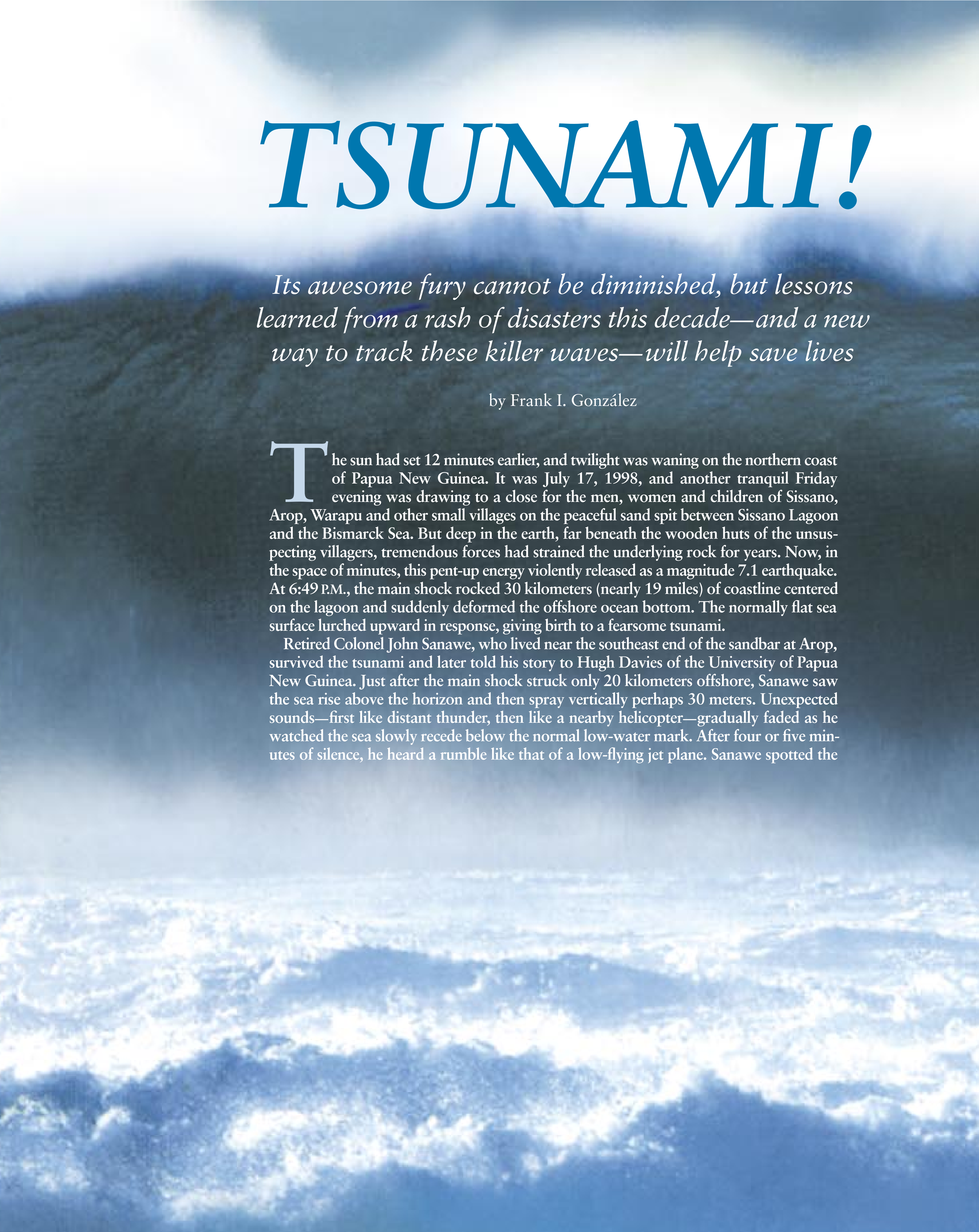


TSUNAMI!

Its awesome fury cannot be diminished, but lessons learned from a rash of disasters this decade—and a new way to track these killer waves—will help save lives

by Frank I. González

The sun had set 12 minutes earlier, and twilight was waning on the northern coast of Papua New Guinea. It was July 17, 1998, and another tranquil Friday evening was drawing to a close for the men, women and children of Sissano, Arop, Warapu and other small villages on the peaceful sand spit between Sissano Lagoon and the Bismarck Sea. But deep in the earth, far beneath the wooden huts of the unsuspecting villagers, tremendous forces had strained the underlying rock for years. Now, in the space of minutes, this pent-up energy violently released as a magnitude 7.1 earthquake. At 6:49 P.M., the main shock rocked 30 kilometers (nearly 19 miles) of coastline centered on the lagoon and suddenly deformed the offshore ocean bottom. The normally flat sea surface lurched upward in response, giving birth to a fearsome tsunami.

Retired Colonel John Sanawe, who lived near the southeast end of the sandbar at Arop, survived the tsunami and later told his story to Hugh Davies of the University of Papua New Guinea. Just after the main shock struck only 20 kilometers offshore, Sanawe saw the sea rise above the horizon and then spray vertically perhaps 30 meters. Unexpected sounds—first like distant thunder, then like a nearby helicopter—gradually faded as he watched the sea slowly recede below the normal low-water mark. After four or five minutes of silence, he heard a rumble like that of a low-flying jet plane. Sanawe spotted the

HISTORY'S MOST TERRIFYING TSUNAMIS could have dwarfed a lighthouse, as in this artist's conception. At heights of 30 meters and speeds of 15 meters per second (35 miles per hour), waves already this close to shore would be impossible to outrun.

PHOTOILLUSTRATION BY JANA BRENNING;
PHOTOGRAPHS BY ROBERT BECK AND KATHLEEN NORRIS COOK

first tsunami wave, perhaps three or four meters high. He tried to run home, but the wave overtook him. A second, larger wave flattened the village and swept him a kilometer into a mangrove forest on the inland shore of the lagoon.

Other villagers were not so fortunate as Sanawe. Some were swept across the lagoon and impaled on the broken mangrove branches. Many more were viciously battered by debris. At least 30 survivors would lose injured limbs to gangrene. Saltwater crocodiles and wild dogs preyed on the dead before help could arrive, making it more difficult to arrive at an exact death toll. It now appears that the tsunami killed more than 2,200 villagers, including more than 230 children. Waves up to 15 meters high, which struck within 15 minutes of the main shock, had caught many coastal inhabitants unawares. Of the few villagers who knew of the tsunami hazard, those trapped on the sandbar simply had no safe place to flee.

Tsunamis such as those that pounded Papua New Guinea are the world's most powerful waves. Historical patterns of their occurrence are revealed in large databases developed by James F. Lander, Patricia A. Lockridge and their colleagues at the National Geophysical Data Center in Boulder, Colo., and Viacheslav K. Gusiakov and his associates at the Tsunami Laboratory in Novosibirsk, Russia. Most tsunamis afflict the Pacific Ocean, and 86 percent of those are the products of undersea earthquakes around the Pacific Rim, where powerful collisions of tectonic plates form highly seismic subduction zones.

Since 1990, 10 tsunamis have taken more than 4,000 lives. In all, 82 were reported worldwide—a rate much higher than the historical average of 57 a decade. The increase in tsunamis reported is due to improved global communications; the high death tolls are partly due to increases in coastal populations. My colleagues and I at the National Oceanic and Atmospheric Administration Pacific Marine Environmental Laboratory in Seattle set up an electronic-mail network as a way for researchers in distant parts of the world to help one another make faster and more accurate tsunami surveys. This Tsunami Bulletin Board, now managed by the International Tsunami Information Center, has facilitated communication among tsunami scientists since shortly after the 1992 Nicaragua tsunami [*see box on page 60*].

Disasters similar to those in Nicaragua

Larger Wave than Expected

Papua New Guinea

July 17, 1998
Maximum wave height: 15 meters
Fatalities: More than 2,200

PALANI MOHAHN *Sipa Press*

Sissano area four days after the tsunami.
Bare spots mark locations of structures swept away.

Swept clean by three monstrous waves, this now barren sandbar along Papua New Guinea's north coast once was crowded with houses and villages. Surprisingly, a relatively small earthquake (magnitude 7.1) spawned waves usually limited to much larger quakes. This apparent discrepancy between earthquake strength and tsunami intensity has prompted speculation among scientists that the seismic vibrations may have triggered other seafloor disturbances, such as an underwater landslide or an explosion of gas hydrates, that helped to create a much larger tsunami.

Unexpectedly high tsunami waves have caused other disasters, such as that in Nicaragua in 1992, but intensive surveys of the seafloor to investigate the mystery have never been conducted until now. Two expeditions explored the seafloor off the ravaged coast of Papua New Guinea for signs of an undersea landslide earlier this year. The survey teams, jointly led by Takeshi Matsumoto of the Japan Marine Science and Technology Center and David Tappin of the South Pacific Applied Geoscience Commission, identified a small depression that could be a candidate landslide site. The next question is whether this feature is fresh or was created by another earthquake long ago. —*F.G.*

and Papua New Guinea have wreaked havoc in Hawaii and Alaska in the past, but most tsunami researchers had long believed that the U.S. West Coast was relatively safe from the most devastating events. New evidence now suggests that earthquakes may give birth to large tsunamis every 300 to 700 years along the Cascadia subduction zone, an area off the Pacific Northwest coast where a crustal plate carrying part of the Pacific Ocean is diving under North America. A clear reminder of this particular threat occurred in April 1992, when a magnitude 7.1 earthquake at the southern end of the subduction zone generated a small tsunami near Cape Mendocino, Calif. This event served as the wake-up call that has driven the development of the first systematic national effort to prepare for dangerous tsunamis before they strike. The Pacific Marine Environmental Laboratory is playing a key research and management role in this endeavor.

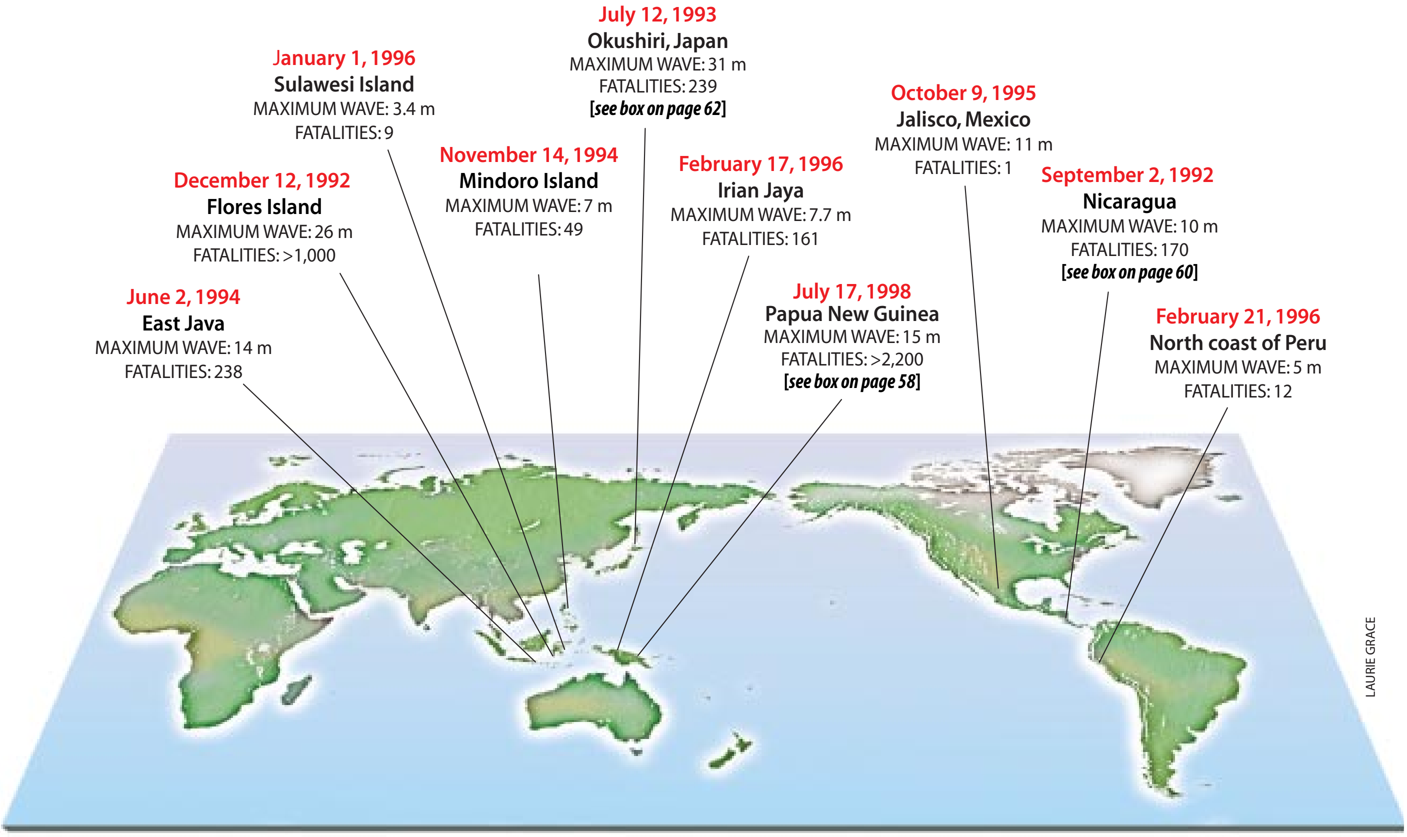
The Physics of Tsunamis

To understand tsunamis, it is first helpful to distinguish them from wind-generated waves or tides. Breezes blowing across the ocean crinkle the surface into relatively short waves that create currents restricted to a shallow layer; a scuba diver, for example, might easily swim deep enough to find calm water. Strong gales are able to whip up waves 30 meters or higher in the open ocean, but even these do not move deep water.

Tides, which sweep around the globe twice a day, do produce currents that reach the ocean bottom—just as tsunamis do. Unlike true tidal waves, however, tsunamis are not generated by the gravitational pull of the moon or sun. A tsunami is produced impulsively by an undersea earthquake or, much less frequently, by volcanic eruptions, meteorite impacts or underwater landslides. With speeds that can exceed 700 kilometers per hour in the deep ocean, a tsunami wave could easily keep pace with a Boeing 747. Despite its high speed, a tsunami is not dangerous in deep water. A single wave is less than a few meters high, and its length can extend more than 750 kilometers in the open ocean. This creates a sea-surface slope so gentle that the wave usually passes unnoticed in deep water. In fact, the Japanese word *tsu-nami* translates literally as "harbor wave," perhaps because a tsunami can speed silently and undetected across the ocean, then unexpectedly arise as destructively high waves in shallow coastal waters.

A powerful tsunami also has a very long reach: it can transport destructive energy from its source to coastlines thousands of kilometers away. Hawaii, because of its midocean location, is especially vulnerable to such Pacific-wide tsunamis. Twelve damaging tsunamis have struck Hawaii since 1895. In the most destructive, 159 people died there in 1946 from killer waves generated almost 3,700 kilometers away in Alaska's Aleutian Islands [*see box on page 64*]. Such remote-source tsunamis can strike unexpectedly, but local-source tsunamis—as in the case of last year's Papua New Guinea disaster—can be especially devastating. Lander has estimated that more than 90 percent of all fatalities occur within about 200 kilometers of the source. As an extreme example, it is believed that a tsunami killed more than 30,000 people within 120 kilometers of the catastrophic eruption of Krakatoa volcano in the Sunda Straits of Indonesia in 1883. That explosion generated waves as high as a 12-story building.

Regardless of their origin, tsunamis



LAURIE GRACE

TEN DESTRUCTIVE TSUNAMIS have claimed more than 4,000 lives since 1990. Last year's Papua New Guinea disaster is the most recent in this string of killer waves generated by earthquakes along colliding tectonic plates of the Pacific Rim.

evolve through three overlapping but quite distinct physical processes: generation by any force that disturbs the water column, propagation from deeper water near the source to shallow coastal areas and, finally, inundation of dry land. Of these, the propagation phase is best understood, whereas generation and inundation are more difficult to model with computer simulations. Accurate simulations are important in predicting where future remote-source tsunamis will strike and in guiding disaster surveys and rescue efforts, which must concentrate their resources on regions believed to be hardest hit.

Generation is the process by which a seafloor disturbance, such as movement along a fault, reshapes the sea surface into a tsunami. Modelers assume that this sea-surface displacement is identical to that of the ocean bottom, but direct measurements of seafloor motion have never been available (and may never be). Instead researchers use an idealized model of the quake: they assume that the crustal plates slip past one another along a simple, rectangular plane inside the earth. Even then, predicting the tsunami's initial height requires at least 10 descriptive parameters, including the amount of slip on each side of the imaginary plane and its length and width. As modelers scramble to guide tsunami survey teams immediately after an earthquake, only the orientation of the assumed fault plane and the quake's location, magnitude and depth can be interpreted from the seismic data alone. All other parameters must be estimated. As a consequence, this first simulation frequently underestimates inundation, sometimes by factors of 5 or 10.

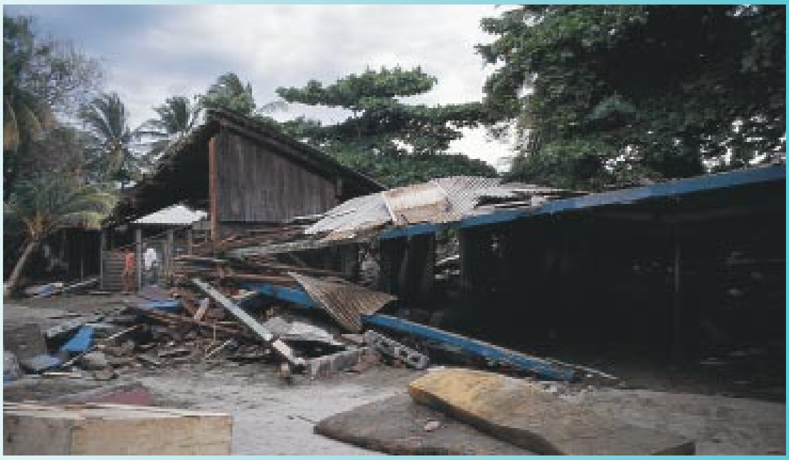
Low inundation estimates can signify that the initial tsunami height was also understated because the single-plane fault model distributes seismic energy over too large an area. Analyses of seismic data cannot resolve energy distribution patterns any shorter than the seismic waves themselves, which extend for several hundred kilometers. But long after the tsunami strikes land, modelers can work backward from records of run-up and additional earthquake data to refine the tsunami's initial height. For example, months of aftershocks eventually reveal patterns of seismic energy that are concentrated in regions much smaller than the original, single-plane fault model assumed. When seismic energy is focused in a smaller area, the vertical motion of the seafloor—and therefore

Slow, Silent, Deadly Quake

Nicaragua

September 2, 1992
Maximum wave height: 10 meters
Fatalities: 170

Survivors line up for emergency food supplies

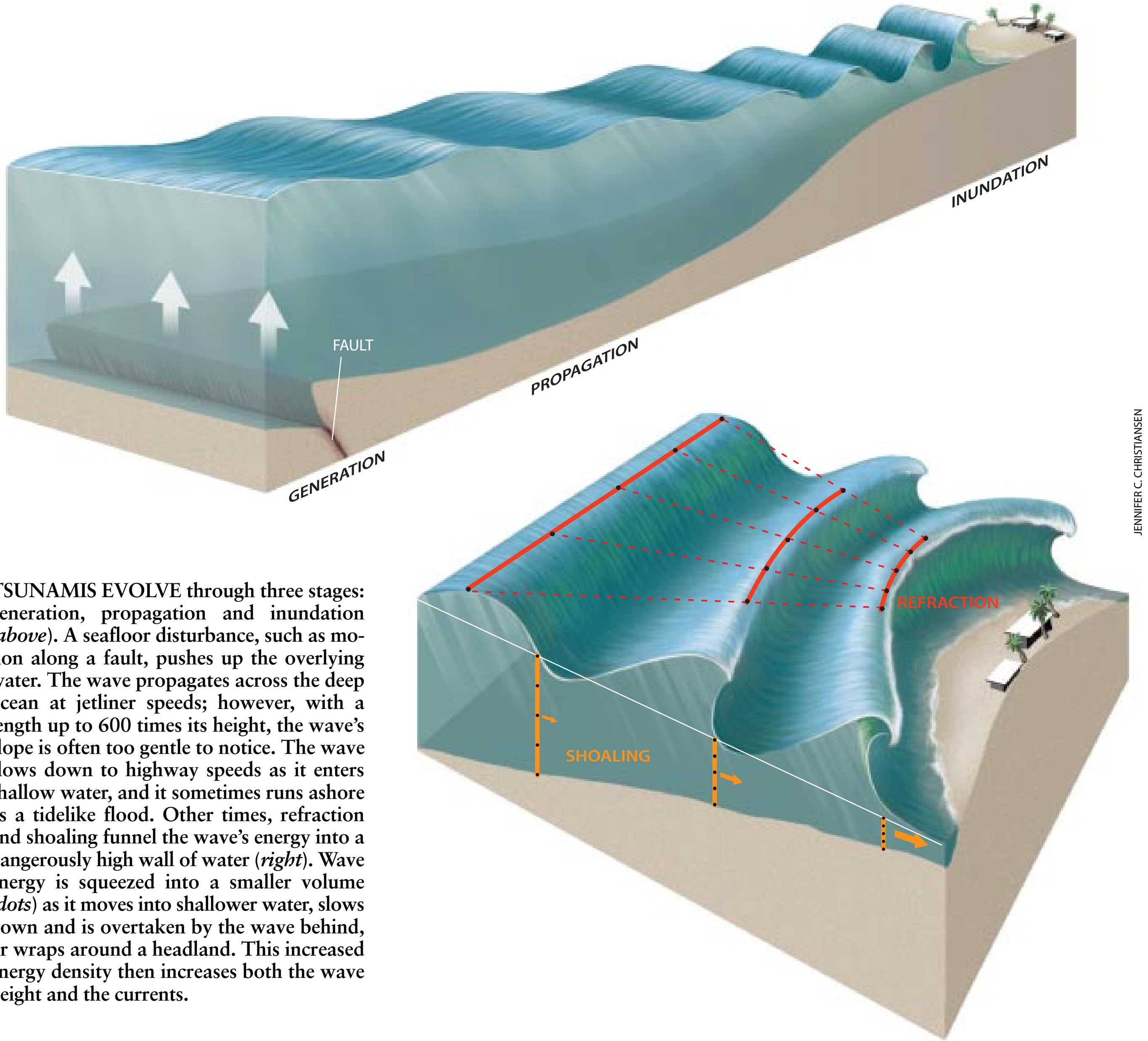


PHOTOGRAPHS BY PAOLO BOSIO *Gamma Liaison*

Coastal village the day after the tsunami

Coastal inhabitants can be educated to run to higher ground when they feel the land shake from an earthquake. But in certain tragic cases, such as the 1992 Nicaragua tsunami that killed 170 people and left 13,000 homeless, residents feel only a minor tremor, or even none at all, and assume there is no danger. An estimated 5 to 10 percent of tsunami-causing earthquakes are of this particularly hazardous breed—so-called silent earthquakes, first described by Hiroo Kanamori of the California Institute of Technology.

In the latest Nicaragua event, the short waves that produce the characteristic rumbling of an earthquake—and that die out quickly as they spread out from the epicenter—never made it from the quake's offshore origin to the mainland. Longer waves did reach the coast, but they hardly shook the ground. What is more, standard seismometers, which record only seismic waves with periods less than 20 seconds, missed most of these longer waves. Kanamori argued that the Nicaragua quake was actually five times greater than its assigned magnitude of 7.0 because these low-frequency waves had been ignored. The Nicaragua event made it abundantly clear that broadband seismometers sensitive to low-frequency waves must be linked to warning systems to forecast the true potential tsunami danger. *—F.G.*



TSUNAMIS EVOLVE through three stages: generation, propagation and inundation (*above*). A seafloor disturbance, such as motion along a fault, pushes up the overlying water. The wave propagates across the deep ocean at jetliner speeds; however, with a length up to 600 times its height, the wave's slope is often too gentle to notice. The wave slows down to highway speeds as it enters shallow water, and it sometimes runs ashore as a tidelike flood. Other times, refraction and shoaling funnel the wave's energy into a dangerously high wall of water (*right*). Wave energy is squeezed into a smaller volume (*dots*) as it moves into shallower water, slows down and is overtaken by the wave behind, or wraps around a headland. This increased energy density then increases both the wave height and the currents.

the initial tsunami height—is greater. Satisfactory simulations are achieved only after months of labor-intensive work, but every simulation that matches the real disaster improves scientists' ability to make better predictions.

Propagation of the tsunami transports seismic energy away from the earthquake site through undulations of the water, just as shaking moves the energy through the earth. At this point, the wave height is so small compared with both the wavelength and the water depth that researchers apply linear wave theory, which assumes that the height itself does not affect the wave's behavior. The theory predicts that the deeper the water and the longer the wave, the faster the tsunami. This dependence of wave speed on water depth means that refraction by bumps and grooves on the seafloor can shift the wave's direction, especially as it travels into shallow water. In particular, wave fronts tend to align parallel to the shoreline so that they wrap around a protruding headland before smashing into it with greatly focused incident energy. At the same time, each individual wave must also slow down because of the decreasing water depth, so they begin to overtake one another, decreasing the distance between them in a process called shoaling. Refraction and shoaling squeeze the same amount of energy into a smaller volume of water, creating higher waves and faster currents.

The last stage of evolution, inundation and run-up, in which a tsunami may run ashore as a breaking wave, a wall of water or a tidelike flood, is perhaps the most difficult to model. The wave height is now so large that linear theory fails to describe the complicated interaction between the water and the shoreline. Vertical run-up can reach tens of meters, but it typically takes only two to three meters to cause damage. Horizontal inundation, if unimpeded by coastal cliffs or other steep topography, can penetrate hundreds of meters inland. Both kinds of flooding are aided and abetted by the typical crustal displacement of a subduction zone earthquake, which lifts the offshore ocean bottom and lowers the land along the coast. This type of displacement propagates waves seaward with a leading crest and landward with a leading trough (the reason a receding sea sometimes precedes a tsunami). Not only does the near-shore subsidence facilitate tsunami penetration inland but, according to recent studies by Raissa Mazova of the Nizhny Novgorod State Technical

Education Saves Lives

Okushiri, Japan

July 12, 1993
Maximum wave height: 31 meters
Fatalities: 239

Fires burned across the ravaged shores of Aonae, a small fishing village on Okushiri's southern peninsula, in the wake of the 1993 tsunami. Waves ranging from 5 to 10 meters had crashed ashore less than five minutes after the magnitude 7.8 earthquake struck perhaps 15 to 30 kilometers offshore in the Sea of Japan. The waves washed over seawalls erected after past tsunami disasters. High currents swept up buildings, vehicles, docked vessels and heavy material at coastal storage areas, transforming them into waterborne battering rams that obliterated all in their path. Collisions sparked electrical and propane gas fires, but access by fire engines was blocked by debris.

The loss of lives in this event was a great tragedy, but it is clear that both warning technology and community education greatly reduced the number of casualties. The Japan Meteorological Agency issued timely and accurate warnings, and many residents saved themselves by fleeing to high ground immediately after the main shock—even before the warning. Okushiri clearly demonstrated that the impact of tsunamis can be reduced. This event has also become the best-documented tsunami disaster in history. Detailed damage assessments of transportation and telecommunications networks, interviews with survivors and local officials, run-up and inundation measurements, and extensive aerial photography produced a database especially valuable to the U.S.: this urban township is a better analogue of U.S. coastal communities than the other, less developed areas destroyed by tsunamis this decade. *—F.G.*


KYOTO NEWS SERVICE

Fires and denuded peninsula in wake of the tsunami


NOAA

Damaged fire truck amid the debris

University in Russia and by Costas Synolakis of the University of Southern California, both theoretical predictions and field surveys indicate that coastal run-up and inundation will be greater if the trough of the leading wave precedes the crest.

Tsunami Threats

Predicting where a tsunami may strike helps to save lives and property only if coastal inhabitants recognize the threat and respond appropriately. More than a quarter of all reliably reported Pacific tsunamis since 1895 originated near Japan. This is not surprising, because Japan is precariously situated near the colliding margins of four tectonic plates. Recognizing the recurring threat, the Japanese have invested heavily over the years in tsunami hazard mitigation, including comprehensive educational and public outreach programs, an effective warning system, shoreline barrier forests, seawalls and other coastal fortifications.

On the night of July 12, 1993, their preparations faced a brutal test. A magnitude 7.8 earthquake in the Sea of Japan generated a tsunami that struck various parts of the small island of Okushiri [*see box above*]. Five minutes after the main shock the Japan Meteorological Agency issued a warning over television and radio that a major tsunami was on its way. By then, 10- to 20-meter waves had struck the coastline nearest the source, claiming a number of victims before they could flee. In Aonae, a small fishing village on the island's southern peninsula, many of the 1,600 townspeople fled to high ground as soon as they felt the main shock. A few minutes later tsunami waves five to 10 meters high ravaged hundreds of their homes and businesses and swept them out to sea. More than 200 lives were lost in this disaster, but quick response saved many more.

Over the past century in Japan, approximately 15 percent of 150 tsunamis were damaging or fatal. That track record is much better than the tally in countries with few or no community education programs in place. For example, more than half of the 34 tsunamis that struck Indonesia in the past 100 years were damaging or fatal. Interviews conducted after the 1992 Flores Island tsunami that killed more than 1,000 people indicated that most coastal residents did not recognize the earthquake as the natural warning of a possible tsunami and did not flee inland. Similarly, Papua New Guinea residents were tragically uninformed, sending the number of casualties from last year's disaster higher than expected for a tsunami of that size. A large quake in 1907 evidently lowered the area that is now Sissano Lagoon, but any resulting tsunami was too small and too long ago to imprint a community memory. When the earthquake struck last year, some people actually walked to the coast to investigate the disturbance, thus sealing their fate.

Scientists have learned a great deal from recent tsunamis, but centuries-old waves continue to yield valuable insights. Lander and his colleagues have described more than 200 tsunamis known to have affected the U.S. since the time of the first written records in Alaska and the Caribbean during the early 1700s and in Hawaii and along the West Coast later that century. Total damage is estimated at half a billion dollars and 470 casualties, primarily in Alaska and Hawaii. An immediate threat to those states and the West Coast is the Alaska-Aleutian subduction zone. Included in this region's history of large, tsunami-generating earthquakes are two disasters that drove the establishment of the country's only two tsunami warning centers. The probability of a magnitude 7.4 or greater earthquake occurring somewhere in this zone before 2008 is estimated to be 84 percent.

Another major threat, unrevealed by the written records, lurks off the coasts of Washington State, Oregon and northern California—the Cascadia subduction zone. Brian F. Atwater of the U.S. Geological Survey has identified sand and gravel deposits that he hypothesized were carried inland from the Washington coast by tsunamis born of Cascadia quakes. Recent events support this theory. The Nicaragua tsunami was notable for the amount of sand it transported inland, and researchers have documented similar deposits at inundation sites in Flores, Okushiri, Papua New Guinea and elsewhere.

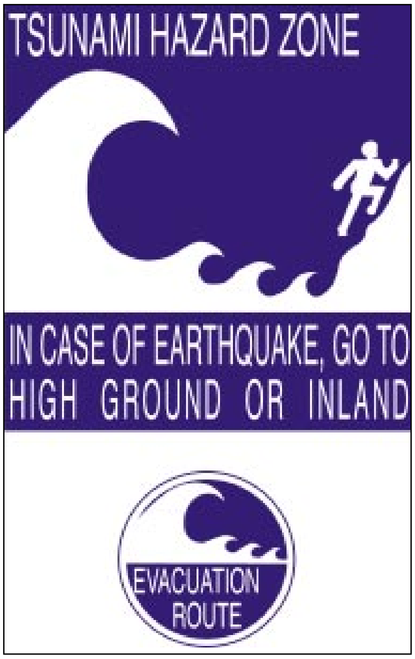
At least one segment of the Cascadia subduction zone may be approaching the end of a seismic cycle that culminates in an earthquake and destructive tsunami [see "Giant Earthquakes of the Pacific Northwest," by Roy D. Hyndman; Scientific American, December 1995]. The earthquake danger is believed to be comparable to that in southern California—about a 35 percent probability of occurrence before 2045. Finally, the 1992 Cape Mendocino earthquake and tsunami was a clear reminder that the Cascadia subduction zone can unleash local tsunamis that strike the coast within minutes.

Getting Ready in the U.S.

Hard on the heels of the surprising Cape Mendocino tsunami, the Federal Emergency Management Agency (FEMA) and NOAA funded an earthquake scenario study of northern California and the production of tsunami inundation maps for Eureka and Crescent City in that state. The resulting "all hazards" map was the first of its kind for the U.S. It delineates areas susceptible to tsunami flooding, earthquake-shaking intensity, liquefaction and landslides. Researchers then tackled the possible effects of a great Cascadia subduction zone earthquake and tsunami. About 300,000 people live or work in nearby coastal regions, and at least as many tourists travel through these areas every year. Local tsunami waves could strike communities within minutes of a big quake, leaving little or no time to issue formal warnings. What is more, a Cascadia-born tsunami disaster could cost the region between $1.25 billion and $6.25 billion, a conservative estimate considering the 1993 Okushiri disaster.

Clarification of the threat from the Cascadia subduction zone and the many well-reported tsunami disasters of this decade have stimulated a systematic effort to examine the tsunami hazard in the U.S. In 1997 Congress provided $2.3 million to establish the National Tsunami Hazard Mitigation Program. Alaska, California, Hawaii, Oregon and Washington formed a partnership with NOAA, FEMA and the USGS to tackle the threat of both local- and remote-source tsunamis. The partnership focuses on three interlocking activities: assessing the threat to specific coastal areas; improving early detection of tsunamis and their potential danger; and educating communities to ensure an appropriate response when a tsunami strikes.

The threat to specific coastal areas can be assessed by means of tsunami inundation maps such as those designed for Eureka and Crescent City using state-of-the-art computer modeling. These maps provide critical guidance to local emergency planners charged with identifying evacuation routes. Only Hawaii has systematically developed such maps over the years. To date, three Oregon communities have received maps, six additional maps are in progress in Oregon, Washington and California, and three maps are planned for Alaska.



OREGON DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES

COMMUNITY EDUCATION is crucial to the recent U.S. push to avoid future tsunami disasters. Signs, standardized for all Pacific states, now alert coastal dwellers and visitors to tsunami-prone areas.

Rapid, reliable confirmation of the existence of a potentially dangerous tsunami is essential to officials responsible for sounding alarms. Coastal tide gauges have been specially modified to measure tsunamis, and a major upgrade of the seismic network will soon provide more rapid and more complete reports on the nature of the earthquake. These instruments are essential to the warning system, but seismometers measure earthquakes, not tsunamis. And although tide gauges spot tsunamis close to shore, they cannot measure tsunami energy propagating toward a distant coastline. As a consequence, an unacceptable 75 percent false-alarm rate has prevailed since the 1950s. These incidents are expensive, undermine the credibility of the warning system, and place citizens at risk during the evacuation. A false alarm that triggered the evacuation of Honolulu on May 7, 1986, cost Hawaii more than $30 million in lost salaries and business revenues.

NOAA is therefore developing a network of six deep-ocean reporting stations that can track tsunamis and report them in real time, a project known as

Deep-Ocean Assessment and Reporting of Tsunamis (DART). Scientists have completed testing of prototype systems and expect the network to be operating reliably in two years. The rationale for this type of warning system is simple: if an earthquake strikes off the coast of Alaska while you're lying on a Hawaiian beach, what you really want to have between you and the quake's epicenter is a DART system. Here's why:

Seismometers staked out around the Pacific Rim can almost instantly pinpoint a big Alaskan quake's location. In the next moment, complex computer programs can predict how long a triggered tsunami would take to reach Hawaii, even though there is not yet evidence a wave exists. After some minutes, tide gauges scattered along the coastlines may detect a tsunami. But the only way to be sure whether a dangerous wave is headed toward a distant coast is to place tsunami detectors in its path and track it across the open ocean.

Conceptually, the idea of such a real-time reporting network is straightforward; however, formidable technological and logistical challenges have held up implementation until now. The DART systems depend on bottom pressure recorders that Hugh B. Milburn, Alex Nakamura, Eddie N. Bernard and I have been perfecting over the past decade at the Pacific Marine Environmental Laboratory. As the crest of a tsunami wave passes by, the bottom recorder detects the increased pressure from the additional volume of overlying water. Even 6,000 meters deep, the sensitive instrument can detect a tsunami no higher than a single centimeter. Ship and storm waves are not detected, because their length is short and, as with currents, changes in pressure are not transmitted all the way to the ocean bottom. We placed the first recorders on the north Pacific seafloor in 1986 and have been using them to record tsunamis ever since. The records cannot be accessed, however, until the instruments are retrieved.

Ideally, when the bottom recorders detect a tsunami, acoustic chirps will transmit the measurements to a car-size buoy at the ocean surface, which will then relay the information to a ground station via satellite. The surface buoy systems, the satellite relay technology and the bottom recorders have proved themselves at numerous deep-ocean stations, including an array of 70 weather buoys set up along the equator to track

Not the First, Not the Last

East Aleutian Islands

April 1, 1946
Maximum wave height: 35 meters
Fatalities: 165

A rash of tsunamis has struck the Pacific Rim this decade, but destructive waves have made their mark long before now. Earthquakes along a seismic subduction zone off Alaska's Aleutian Islands have stirred up the worst tsunamis in U.S. recorded history. On April 1, 1946, a magnitude 7.8 earthquake generated a tsunami that wiped out the Scotch Cap Lighthouse in Alaska and killed five Coast Guard employees. The same tsunami also made a surprise attack five hours later on residents of Hilo, Hawaii. There debris-laden waves up to eight meters high caught a number of schoolchildren before classes began and wiped out a hospital. Altogether the killer waves took the lives of 165 people, 159 of them in Hawaii, and caused more than $26 million in damage.

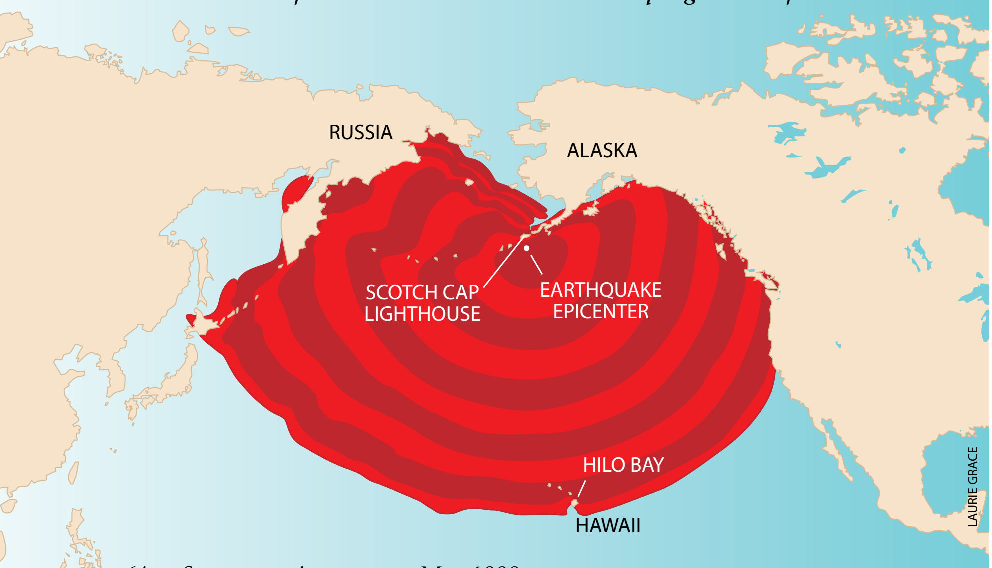
The U.S. reacted to this disaster by setting up the Pacific Tsunami Warning Center in Hawaii in 1948. Similarly, three years after the March 28, 1964, Alaskan tsunami that took more than 100 lives, the Alaska Regional Tsunami Warning System (now the West Coast and Alaska Tsunami Warning Center) was established. Today a newly recognized threat from a seismic zone off the West Coast has driven the U.S. to take action against a tsunami disaster *before* it occurs. This endeavor by state and federal partners features a systematic tsunami inundation mapping program, a state-of-the-art, deep-ocean tsunami detection network and educational campaigns to prepare coastal communities for a potential disaster. —*F.G.*

PHOTOGRAPHS BY CORBIS

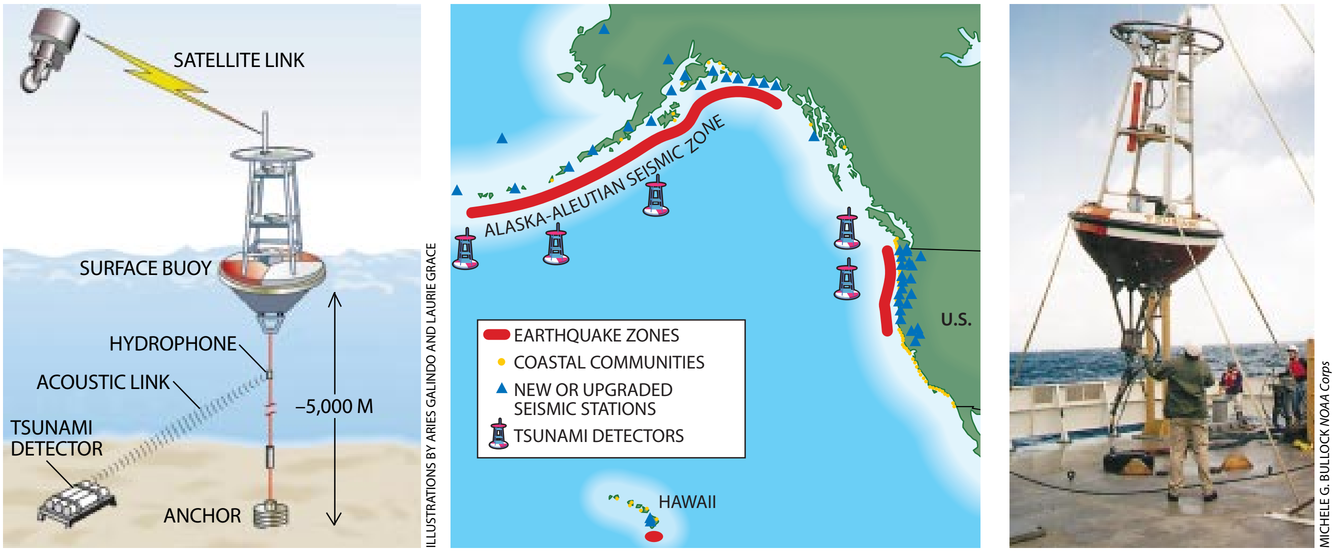
Flattened parking meters in Hilo, Hawaii

Scotch Cap Lighthouse before tsunami

Scotch Cap Lighthouse after tsunami



LAURIE GRACE



ILLUSTRATIONS BY ARIES GALINDO AND LAURIE GRACE

MICHELE G. BULLOCK *NOAA Corps*

DEEP-OCEAN TSUNAMI DETECTORS (*left*) and a major upgrade of existing earthquake monitoring networks (*blue triangles on map*)—both scheduled for installation within two years—lead the U.S. effort to take the surprise out of tsunami attacks. The deep-ocean detectors depend on high-tech sensors stationed on the seafloor. When one of these instruments senses a tsunami wave overhead, it will send acoustic signals to a buoy at the surface, such as the one being launched in the photograph, which will then relay the warning via satellite to the officials who are responsible for sounding an alarm.

El Niño, the oceanographic phenomenon so infamous for its effect on world climate. The biggest challenge has been developing a reliable acoustic transmission system. Over the past three years, four prototype DART systems have been deployed, worked for a time, then failed. Design improvements to a second-generation system have refined communication between the bottom recorders and the buoys.

In the next two years, our laboratory plans to establish five stations spread across the north Pacific from the west Aleutians to Oregon and a sixth sited on the equator to intercept tsunamis generated off South America. More buoys would reduce the possibility that tsunami waves might sneak between them, but the current budget limits the number that NOAA can afford. This is where detailed computer simulations become invaluable. Combined with the buoy measurements, the simulations will provide more accurate predictions to guide officials who may have only a few minutes to decide whether to sound an alarm.

Even the most reliable warning is ineffective if people do not respond appropriately. Community education is thus perhaps the most important aspect of the national mitigation program's threefold mission. Each state is identifying coordinators who will provide information and guidance to community emergency managers during tsunami disasters. Interstate coordination is also crucial to public safety because U.S. citizens are highly mobile, and procedures must be compatible from state to state. Standard tsunami signage has already been put in place along many coastlines.

Tsunami researchers and emergency response officials agree that future destructive tsunamis are inevitable and technology alone cannot save lives. Coastal inhabitants must be able to recognize the signs of a possible tsunami—such as strong, prolonged ground shaking—and know that they should seek higher ground immediately. Coastal communities need inundation maps that identify far in advance what areas are likely to be flooded so that they can lay out evacuation routes. The proactive enterprise now under way in the U.S. will surely upgrade tsunami prediction for a much larger region of the Pacific. All of these efforts are essential to the overriding goal of avoiding tragedies such as those in Papua New Guinea, Nicaragua and elsewhere. SA

The Author

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Further Reading

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Additional information on tsunamis can be found at http://www.pmel.noaa/tsunami/ on the World Wide Web.