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Of Landslides, Couch Potatoes, and Pocket Tsunamis

by Douglas L. Smith

A fifteen-year-old boy from Arop No. 2 village points out the palm tree he climbed to escape the wave, which came up to just below the fronds. (When villages adjoin one another, they frequently have the same name and are distinguished by numbers.)

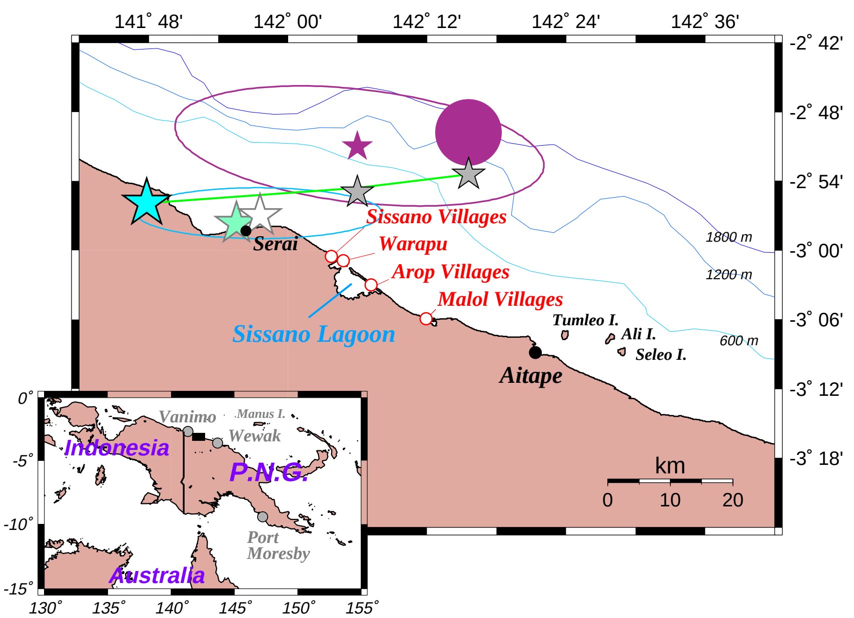
Sometime after seven o'clock in the evening on Friday, July 17, 1998, a wall of water three stories high wiped out a 25-kilometer stretch of tropical paradise on the north shore of Papua New Guinea. Hardest hit was the Sissano Lagoon region, where three villages of thatched huts sat on the spit of sand that divided the ocean from the lagoon. The tsunami, which penetrated as much as three kilometers inland in other places, washed over this glorified sandbar like it wasn't even there. All three villages were completely destroyed, and several more up and down the coast were heavily damaged. At least 2,200 people died, and some 12,000 souls were left homeless as buildings were swept away like yesterday's sand castles—even substantial structures, such as churches and schools, were reduced to their concrete-pad foundations. This tsunami, which actually consisted of three separate waves, is making waves in the scientific community as well, as it bolsters a theory advanced by a group of Caltech alumni that some of the largest localized tsunamis are caused by underwater landslides instead of by the motion of the seafloor during an earthquake.

The tsunami followed a magnitude 7 earthquake at 6:49 p.m., and earthquakes frequently *do* generate tsunamis. Such tsunamis are called tectonic, and their size is related to the energy released by the quake, which is readily derivable from seismograms. Tsunamis also travel at known speeds, so their arrival time at any location can be calculated. And that was the problem with this one—like a typical Hollywood disaster movie, it was late (by a full 10 minutes) and waaaay over budget. The standard tectonic-generation models predicted that the wave should have been, at most, 1.3 meters high on arrival—about average for the surf there. So what happened? How did this two-bit tsunami become a killer wave, and what took it the extra 10 minutes? As Chief Engineer Montgomery Scott is fond of saying, "You canna change the laws of physics," so unless there's some sort of time-dilation effect worthy of a *Star Trek* episode going on here, whatever caused the tsunami must have happened after the earthquake.

Well, earthquakes also unleash landslides—sometimes hours after the shaking stops. In a 1982 study of the 1980 Mount St. Helens eruption, Hiroo Kanamori, the Smits Professor of Geophysics, and Jeffrey Given (PhD '84) concluded that the massive landslide that uncorked the eruption had a distinctive seismic signature. Then, in 1987, Kanamori and H. S. Hasegawa of the Geological Survey of Canada examined seismograms from the 1929 Grand Banks earthquake (magnitude 7.2), which caused a tsunami that killed 27 people on the south coast of Newfoundland, and found the same signature. A landslide had been suspected there long before Kanamori's time, because the spiderweb of transatlantic telegraph cables had snapped in 28 places. The breaks' timing helped map the slide's path—there were 14 "instantaneous" ones within 100 kilometers of the epicenter, followed by a series that rolled downslope and across the abyssal plain, with the final one coming some 560 kilometers away and 13 hours 17 minutes later. Since then, a half-dozen or so other tsunamis have been convincingly linked to landslides as well. This notion sloshed over to Caltech's engineering and applied science division, where Philip Watts (PhD '97), working with Fred Raichlen, professor of civil engineering and mechanical engineering, derived a computer model of waves generated by a submerged landslide. This model, based on wave-propagation code developed by Stéphan Grilli of the University of Rhode Island, was the first to take a user-defined motion of the landslide's center of mass to represent the motion of the landslide as a whole, a feature that would eventually prove to be crucial.

Most tsunami models start with a source motion on the seabed. The most common is an earthquake that instantaneously dislocates the

Just an average day in paradise. The house in the background is typical of local construction methods. The posts on which it rests are driven two or three feet into the ground. This photo is of a resettlement village built for the survivors from the Arop villages. In the foreground, USGS geologist Jocelyn Davies swims with some village kids.

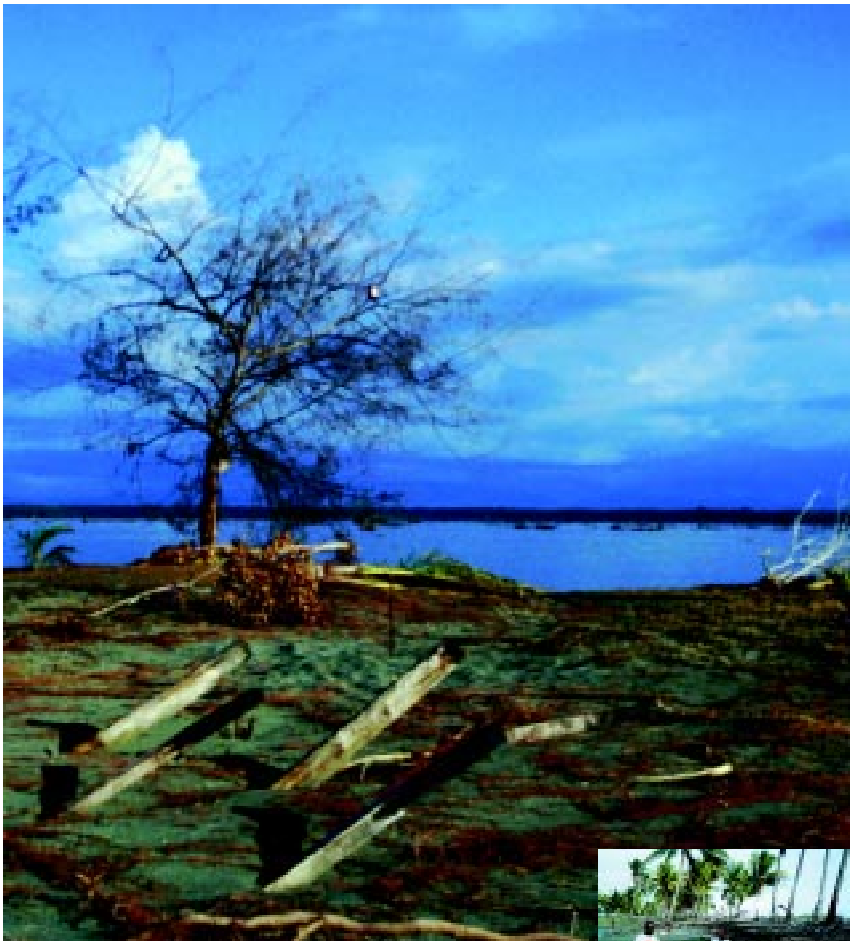


The large map shows the tsunami area (the black rectangle in the inset map). The villages labeled in red were devastated or partially destroyed, while the ones in black escaped serious damage. Stars indicate the epicenters of some significant earthquakes. Papua New Guinea doesn't have many seismographs so the locations are imprecise—the three large stars in the blue error ellipse are all putative main shock locations, with the white star being the one the Caltech group calculated. The two gray stars are the pair of aftershocks, and the green line behind them is the fault. The purple star is the mysterious 7:02 seismic event; its error ellipse, also in purple, includes the landslide (purple circle).

water above it to create a wave. This is why tsunamis pack such a wallop: in deep water, all the kinetic energy of a wind-generated wave lies within a few wave heights of the surface, but a tsunami goes all the way down—the entire water column is in motion. When all this energy gets squeezed into a few meters of shallow water, all hell breaks loose. Conventional tsunami models assume a tectonic source—a block of seafloor is thrust up, in the Papua New Guinea case by about 40 centimeters, and the tsunami is born as the water collapses back on itself. But a landslide on the move leaves a void behind itself that the ocean instantly fills, creating a wave.

A computerized tsunami is really three separate models: source, propagation, and arrival. Once the wave has been generated, by whatever means, it spreads through the high seas according to the laws of fluid mechanics, which were translated into a form appropriate to tsunamis by Joseph Hammack (PhD '72) and Jiin Jen Lee (PhD '70). Then, as it nears the coast, the wave's detailed behavior depends on the topography, both above and below the shoreline. The tsunami's run-up, as it's called, is the province of Costas Synolakis (BS '78, MS '79, PhD '86), who first suggested the approximations needed for computer simulations while modeling run-up under Raichlen and is now a professor of civil and environmental engineering at USC and director of the tsunami center there.

But neither the tectonic nor the landslide models' predictions of wave heights and arrival times matched the maps and measurements made by the International Tsunami Survey Team. The team was cosponsored by the National Science Foundation, the Japan Science Foundation, and the Ministry of Science and Culture and co-led by Synolakis, who has been on nine such teams in seven years, and Yoshiaki Kawata of the Disaster Prevention Research Institute at Kyoto University. The survey found that the wave height fell off very rapidly outside the zone of inundation, leaving



Paradise leveled: This was a small, unnamed hamlet east of the lagoon mouth. The angled logs in the foreground used to be house posts. The silver object high in the tree is a bucket left there by the wave. At right, survivors from Arop No. 1 stand in the scour left by the wave—note the scarp in the background.

Left: Some survey team members set out for the next village. In the bow are Costas Synolakis (wearing vest); seismologist Emile Okal, PhD '78 (with hat); and José L. Borrero, a field surgeon and father of Synolakis's grad student José C. Borrero, who was also on the team.

villages just a little further up or down the coast completely untouched. But a tectonic source takes impetus from the entire length of the rupture (about 35 kilometers for a magnitude 7 quake), so its effects are felt along a very broad front. And as this quake is believed to have started about a kilometer or two offshore and headed out to sea at a shallow angle, a tectonic tsunami should have trashed a much larger area if it trashed anything at all. Even stranger, the shore closest to the epicenter got a wave only a couple of meters tall. (The epicenter's location is not very precise, as that part of the world isn't heavily instrumented—we're spoiled here in Southern California.) The landslide model fared better in that a landslide is a more concentrated source, so its effects are highly localized and an intense "pocket" tsunami, if you will, is a likely outcome. But still, the numbers just wouldn't come out right. If this was indeed a pocket tsunami generated by a landslide, the computer models were missing an essential feature.

The survey team visited the area two weeks after the disaster. It's important to get there fast, Synolakis explains, especially during the rainy season—one good storm can wash away the high-water marks, and obliterate the debris paths that tell you the wave's angle of approach. There were no buildings left on which to measure lines of discoloration from the flooding, but the trees told their own eloquent story: some were stripped clean of branches to a height of 12 meters; others had household goods and wreckage lodged in their tops. "If you have a severe wind, that bucket in the tree would just fly away," he says. "And people scavenge things. The lagoon villages are inaccessible by road. They can't just go to the store and get another bucket, so if you wait too long they will have combed the area and picked up everything that they can reuse. And eyewitness accounts change: as time passes, people start hearing the story from the local authorities or the shortwave radio, and it contaminates their memories. They are more likely to give you the official number than what they actually saw. They hear, for example, that 'it was a 40-foot wave and it came from the north,' and that's what they'll tell you. But then when you ask them to point to where they saw it go, you get different results."

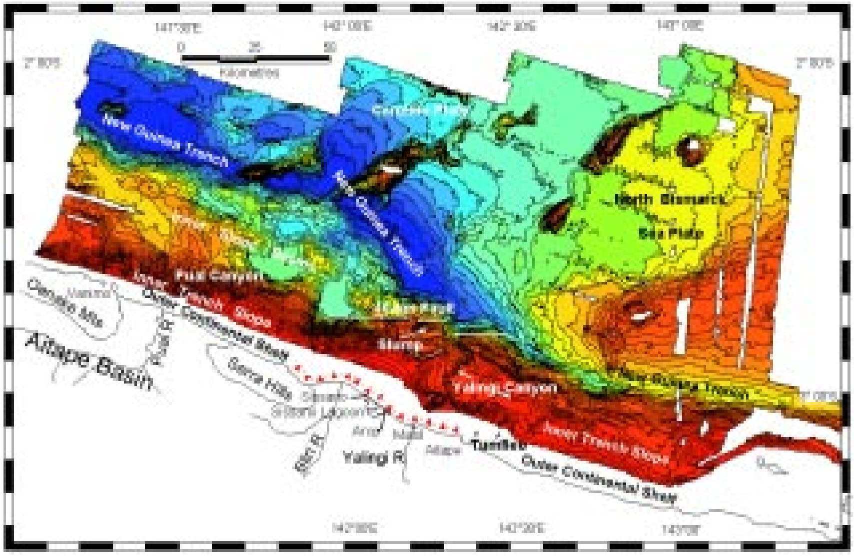
In more built-up areas, automatic tide gauges—rugged instruments mounted in concrete—would have recorded the waves' arrival times. (If nothing else, you could at least note the time when the recording stopped.) Here, the team had to rely on people's memories. Hugh Davies, professor of geology at the University of Papua New Guinea, in Port Moresby, spent every weekend for six months afterward interviewing survivors, many of whom had been dispersed to hospitals or resettled in new villages farther inland. When he quizzed people about the time of arrival of the wave he was given many different answers. "That's what you

Above: Launched in 1997, the RV *Kairei* is designed to stay at sea for months at a time. She's 105 meters long overall, displaces 4,628 gross tons, and has a crew of 29—not counting up to 31 scientists. The big blue thing is an A-frame designed to lower corers, sonar arrays, or even robot submarines. Below, left: Pirates are a big problem in the South Pacific, so the *Kairei* sported a barbed-wire girdle when not in port. Fire hoses and stacks of bamboo staves were kept ready at all times to repel boarders. Below: These guys weren't exactly pirates, but they may have been smugglers—they approached the ship expectantly, says Watts, but eventually left when nothing was thrown overboard for them to retrieve. Whatever they were, they were bold seafarers—the *Kairei* was roughly 100 kilometers from the nearest land at the time.

expect when people mostly measure the time of day by the sun," says Jocelyn Davies, a physical science technician at the United States Geological Survey's Pasadena office. Davies, who lived in Papua New Guinea until she was nine, flew back twice after the disaster and assisted her dad with follow-up interviews. "In Aitape [a larger town at the fringe of the devastation, where the wave was only three meters tall], they could at least tell us that the wave came ashore a few minutes after the seven o'clock news started on TV." Otherwise, the best one could hope for was to get information on the sequence of events: Did the wave hit before or after the big aftershock? If the interviewee said, "What aftershock?" it was presumed that the tsunami arrived at the same time or earlier, monopolizing the person's attention. (The aftershock, which was widely felt, occurred 20 minutes after the main shock and was actually two shocks—a 5.6 and a 5.9 within 30 seconds of each other.)

The survey team noted many landslides on shore, and speculation arose that the tsunami might have been triggered by an offshore one. But the critical geology was under water, so the Papua New Guinea government issued an international request that a marine survey be done. It was a matter of some urgency—Papua New Guinea lies on an active subduction zone, where the Australian plate is riding up over oceanic crust. Earthquakes and their resulting landslides are frequent, so if the tsunami had in fact been triggered by a slide, were there other undiscovered hazards lurking offshore? Such programs usually take a year and a half to mount, but this one was organized in record time by close collaboration between the Japan Center for Marine Science and Technology (JAMSTEC), the South Pacific Applied Geoscience Commission (SOPAC), and the government of Papua New Guinea. The cochief scientists were Takeshi Matsumoto of JAMSTEC and David Tappin of the British Geological Survey, acting for SOPAC. (If you're wondering why an Englishman from Nottingham was representing SOPAC, it's because Tappin has been a marine geologist for 27 years, 17 of them in the South Pacific, including a five-year stint as the chief geologist for the Kingdom of Tonga.) In December 1998, JAMSTEC's RV (research vessel, not recreational vehicle) *Kairei* arrived, carrying an international team of 22 scientists from assorted disciplines, to try to get to the bottom of things.

There have now been four cruises on different vessels, and a fifth is planned—the first time that an undersea earthquake has ever been studied so intensively. Still, you can imagine what a disadvantage seismologists working on, say, the Landers quake would have labored under if they had been confined to an airplane flying a mile overhead while trying to figure out how much and which way the fault moved, and what kind of material it cut through. And we have better maps of the moon, Mars, and Venus than we do of much of



Left: The seafloor as surveyed by the *Kairei*. The Yalingi River's submarine canyon is shown, as is the slump (white arrow), which lies on the eastern side of the amphitheater (white arc). The amphitheater lies at the edge of a shallow shelf that extends out to sea from the lagoon. The colors indicate depth, from 200 meters (dark red) to 4400 meters (dark blue). The white zone just offshore is water less than 200 meters deep—too shallow for an oceangoing vessel as big as the *Kairei* to navigate safely in this ill-charted region. The red triangles show the stretch of coast where the tsunami was observed. The "40-km fault" was not the source of the magnitude-seven quake, but had been favored as a source of the tsunami. Bathymetry data courtesy of JAMSTEC.

Earth's ocean bottoms, so there was precious little prequake data to go on. But the *Kairei*, a spanking new ship with state-of-the-art multibeam sonar arrays accurate to half a percent of the water depth, (10 meters in two kilometers of seawater), provided great postquake data. Watts and several Japanese tectonic-source colleagues went along to provide modeling support. While the geologists were looking for faults and landslides, the modelers were compiling a comprehensive depth profile—bathymetry data, it's called—to feed into their various tsunami models.

A tsunami's height and arrival time are profoundly influenced by the water's depth. As the bottom shoals, the water piles up and the wave slows down, so an uneven seafloor will refract and reflect the wave, occasionally aiming it at a piece of shoreline like a lens focusing a searchlight's beam. The depth at which the bottom begins steering the wave depends on its wavelength, so for wind-driven waves a few meters apart, only the shallows count. Tsunamis, however, have wavelengths of tens to hundreds of kilometers, so it's *all* shallow water to them—the midocean abyssal plains average about four kilometers deep. The *Kairei* discovered a shallow shelf and a submarine canyon that helped focus the wave's energy toward the lagoon, but this boost still left the tectonic models severalfold short of delivering the observed run-up.

To trace the tsunami's point of origin, you run the model backward, and Watts recalls that on one mapping leg "I realized we'd be passing over what seemed like the most promising site at about 1:00 a.m. So I got up and watched the bathymetry come in—a 3-D color image being plotted in real time on the control console. And suddenly, amid the geologically old features—rolling hillsides and ancient reefs covered in sediment—we had a very sharp, several-hundred-meter-high cut, which turned out to be the scar from a slump." The slump proved to be about four kilometers wide by five kilometers long. It's part of a much larger amphitheater some 10 kilometers wide, the sum of many slumps over the eons. "That tells us that this is a very vulnerable area," says Watts. "We know there's enough sediment to fail again at the next earthquake. This is an important observation. Should the people move back into their old village sites? And the answer is an emphatic *no!* This is a very dangerous chunk of shoreline."

But what was down there? What kind of material gave way so catastrophically? All a dry-land geologist needs for sample collection is a rock hammer. But when your sample is at the wrong end of 1.5 kilometers of salt water, you need something more—in this case, a 10-meter length of pipe called a corer. Inside the pipe is a piston that starts out flush with the pipe's bottom end. The corer is lowered until the piston rests on the seafloor and a trip line releases the lead-weighted pipe, driving it down around the piston and cutting free a core. The effect is the same as sucking liquid into a straw, except that the straw moves instead of the liquid. The piston, now at the top of the pipe, acts like a thumb over the top of the straw and keeps the sample—even loose sand!—from falling out en route to the surface. And just to be sure, there's a "core catcher" at the end, which closes like the iris of a camera.

"And so on the fourth-to-last day of the science phase of the cruise Toshi Kanamatsu dropped our first core, and pulled out seven meters of really stiff clay. But all the models, including ours, assumed that underwater landslides were happening in a relatively thin layer of sand or silt. Sand moves. It's known to liquefy during earthquakes, and it's known to move hundreds of kilometers out onto the ocean floor when it lets go." In the nightly meeting of all the scientists to discuss the day's results, Tappin pointed out that clay would behave much differently. So upon returning Stateside, Watts asked soil mechanician Jean-Pierre Bardet (MS '79, PhD '84), now also a

Above: Somewhere at the end of that cable is the corer.

Right: Retrieving it is an all-hands operation.

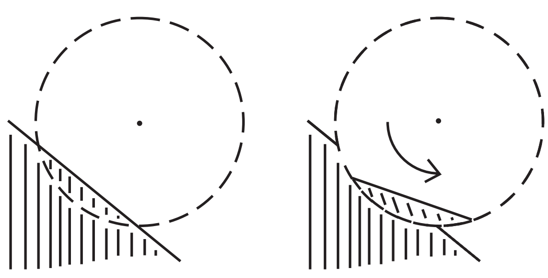
Far right: Once it's safely on its dolly, principal JAMSTEC sedimentologist Kanamatsu (in profile) detaches the weighted piston before extracting the core from the pipe in an on-board lab. Wilfred Lus, who was born in nearby Wewak and is now a grad student in geology at the University of Papua New Guinea, looks on.

professor of civil and environmental engineering at USC, to describe clay's behavior mathematically.

Says Bardet, "These hydrodynamic tools, these models, do marvelous things, making waves go all across the ocean, but the initial motion all depends on the mechanics of the source, which the models don't consider. It's just assumed. But when you are dealing with a local secondary rupture, like a soil failure, it's a much broader venue." In other words, there are a lot more possibilities to consider—a wider range of material strengths, more different types of failure modes—than just the snapping of pressurized rock deep underground. So Bardet analyzed a typical clay's shear strength to determine how much force it would take to set the slump in motion and how it was likely to move once under way.

It turns out that stiff clay moves in a "slump," not a "landslide," and this semantic nicety is of utmost importance. "A slump is like a couch potato," Watts explains. "When the slump fails, its butt slides a little farther forward on the sofa cushion, and its head sinks a little lower."

That is, the slump's center of mass moves down

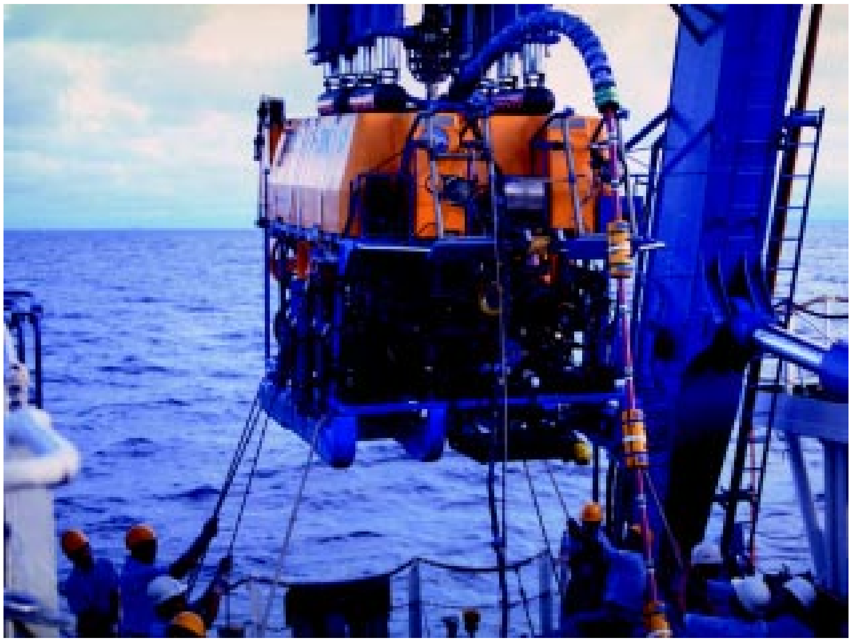


Above: A cross-section of a slump (not to scale).

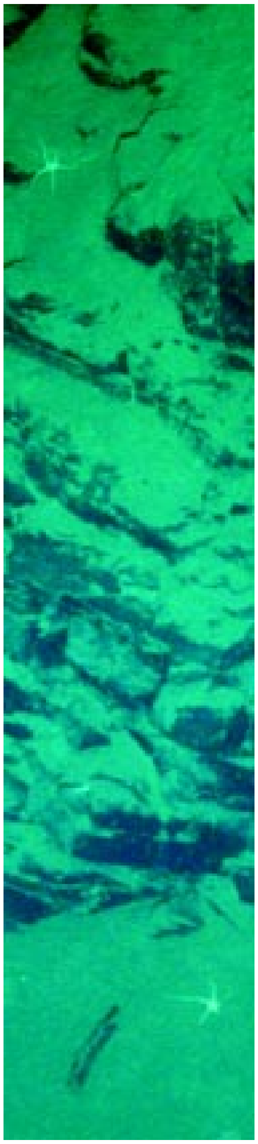
and forward in a short arc. This motion is modeled by rotating a cylinder that lies on its side on the seabed like one of the fallen columns of Atlantis. The cylinder penetrates the hillside (shaded) to a depth equal to the maximum thickness of the slump, and the buried portion of the cylinder's curved surface is the failure plane along which the slump will move. If you rotate the cylinder maybe six degrees, the embedded portion travels downslope a ways, and that's the slump. The degree and speed of the rotation, the diameter of the cylinder, and the depth to which it is embedded, all depend on the clay's shear strength.

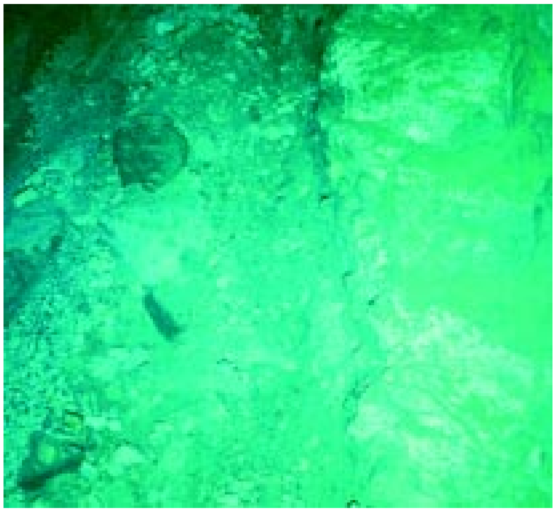
Says Watts, "The key difference between a landslide and a slump is the center-of-mass motion. A slump starts and stops—if you plot position as a function of time, it accelerates, achieves some maximum velocity, and then decelerates. Whereas a landslide is like your umbrella getting whipped away by the wind and carried down the street—there's nothing to stop it. It experiences a relatively rapid acceleration, and then just keeps on going. *Nothing* stops a landslide."

In January 1999, another JAMSTEC ship, the RV *Natsushima*, took over. *Natsushima* carries an unmanned submersible named *Dolphin*, whose cameras confirmed that the clay was stiff—there were knife-sharp fractures in the clay deep and wide enough to stand in—and that the slump was fresh, because the chunks that had detached themselves from the headwall at the top of the slump and tumbled downslope had not yet accumulated a blanket of sediment. The *Dolphin* also visited the stretch of fault that the tectonic modelers favored, hoping to find similar evidence of fresh activity. Recalls Watts, "We got an hour of what looked like a helicopter ride through the snow-



Right: The *Dolphin*.





Above: This fissure is about two meters deep, three meters wide, and 50 meters long. Right: The debris flow on the left side of this photo is fresh, free of the sediment that covers the limestone cliff on the right. Left: A couple of starfish go about their business along an old, sediment-draped portion of the 40-kilometer fault scarp west of the amphitheater. Seafloor photos courtesy of JAMSTEC.

covered Alps. It was beautiful. It was stunning. Nobody moved, everything came to a halt. There were video monitors all over the place, and the ship was nothing but full of people staring in awe at these underwater mountains." But the snow was actually sediment, indicating that nothing had moved there in quite a while. Other *Dolphin* excursions found fresh faulting, but only off to the west, away from the tsunami's calculated point of origin. Says Tappin, "This is how mapping the seabed with multibeam bathymetry, and direct observations from remotely operated vehicles allow you to discriminate between tsunami source mechanisms."

A third cruise, sponsored by the National Science Foundation, took place in September 1999 (a more usual time lag for marine geology) aboard the Lamont-Doherty Earth Observatory's RV *Maurice Ewing*. On this voyage, seismic reflection studies by Eli Silver and Suzanne Sweet of UC Santa Cruz confirmed that the clay had moved cohesively, and gave the slump's maximum thickness as 700 meters. Reflection studies bounce shock waves (in this case, from an air gun) off the seabed and the sedimentary layers and fault planes that lie beneath it. The echoes are picked up by an array of hydrophones and processed by computer to give a cross-sectional view of the sea bottom.

But finding a fresh slump wasn't enough—did it cut loose at the right time? There were no undersea cables to sever—no smoking gun, in other words, but it turns out there *was* a gunshot. A U.S. Navy hydrophone near Wake Island, 3,600 kilometers away, picked up an unusual rumble at 7:42 p.m. Papua New Guinea time, or about 13 minutes after the quake, allowing 40 minutes for the sound to propagate through the ocean. The amphitheater proved to be a speaker pointing at Wake Island, which is a tiny pimple in the middle of the Pacific.

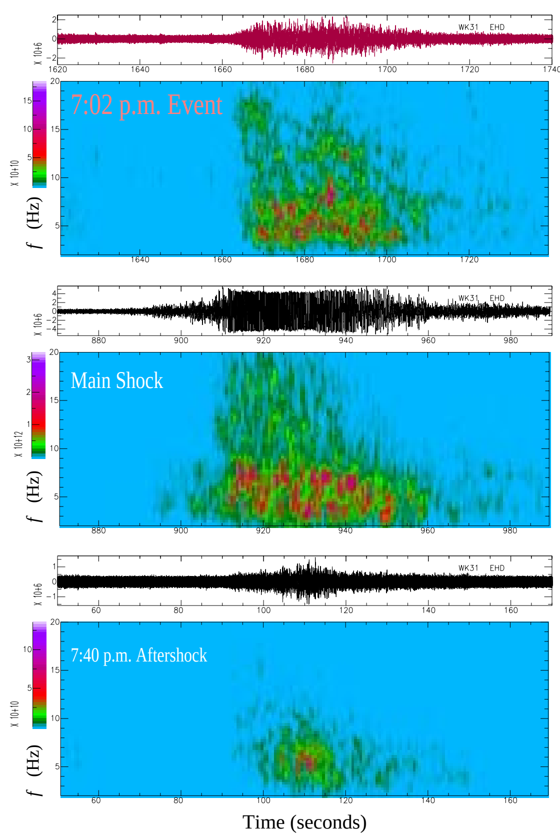
Seismologist Emile Okal (PhD '78), now a professor of geological sciences at Northwestern University, initiated the hunt for the vital recording. "I've been working with T waves for a long time, so when it became obvious that this event didn't fit any of the tectonic models, it was natural for me to look at the T-wave records. T waves provide sensitive detections of very faint sounds at extreme ranges: the Navy hunts subs, biologists listen to the love songs of whales, and geologists discover underwater volcanoes—I've found several, myself." T waves are trapped in a natural waveguide: as you go deeper, the pressure increases, which increases the speed of sound. But at the same time, the temperature decreases, which slows sound propagation, and the tug-of-war between the two means that there is some depth at which the speed bottoms out. Sounds entering this zone are trapped there, refracted back into it by the faster-conducting layers above and below. It's fiber optics for sound waves, basically. The depth of the SOFAR channel, as it's called, varies with latitude, but in the mid-Pacific it's about 600 to 1,800 meters down. At 1,500 meters, the slump lay at just the right depth to be heard.

Although the rumble coincided with an event listed as a magnitude 4.4 aftershock, it didn't look like any ordinary earthquake. Quake T waves fit a very standard pattern: they start abruptly and rapidly die off, with the signal's duration related to the earthquake's magnitude. A magnitude 4.5 aftershock at 7:40 lasted about 15 seconds; the 7:02 event went on for a good 45—almost as long as the main shock. And the 7:02 event gradually crescendoed, then even more slowly faded away—quite reasonable behavior for a slump that gathered momentum before petering out. When Okal did a spectral analysis—breaking down the signal to see how much energy was being carried at each frequency—things got even less earthquake-like. He explains, "Normally, you find the high frequencies, which correspond to fast energy release—ground motion at high velocity—at the beginning. But here, the frequency rose with time, indicating that the source was accelerating. The largest burst of energy is halfway through the signal, which is exactly what a slump does. Kanamori and Given first described this acceleration-peaking-deceleration behavior in their Mount St. Helens paper, and Kanamori and Hasegawa described it again later in their Grand Banks paper."

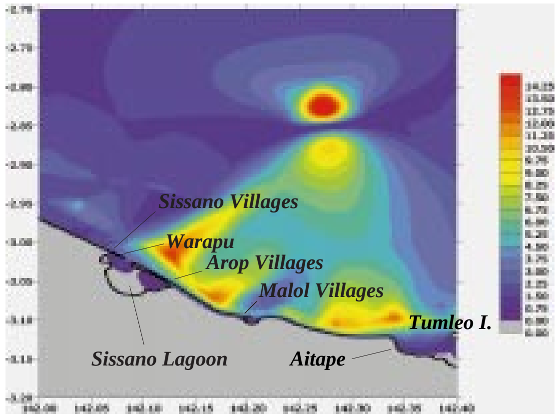
Hydrophones are submerged buoys containing microphones, anchored to float in the SOFAR layer. They're complicated and expensive pieces of equipment, and most of them belong to the world's navies. Thus their data are routinely classified. (The Wake Island records had been declassified as part of the prototype monitoring system for the Comprehensive Nuclear Test-Ban Treaty, and were at that point directly accessible from a Web site.) Fortunately, when T waves hit shore, they become easily recorded seismic waves. Says Okal, "seismometers near the seacoast will pick them up, and even humans will if the waves are strong enough. The Alaskan Panhandle quake of 1958 and the Bolivian earthquake of '94 were both felt by people in Hawaii."

So Okal turned to T-wave seismograms from stations scattered around the Pacific, and found something else unusual—a station in Taiwan picked up the main shock loud and clear, but the 7:02 event didn't register. Taiwan is roughly perpendicular to the speaker's beam line, in the acoustic shadow of the amphitheater's western wall, and apparently was out of earshot. In fact, the 7:02 event's T waves only showed up at a handful of stations.

Intrigued, Okal then reexamined the actual seismic-wave (not T-wave) records for the 7:02 event. There weren't that many, because a



The Wake Island T waves and their spectra (blue backgrounds) of the suspected slump (top), the main shock (middle) and a magnitude 4.5 aftershock (bottom). In the spectral plots, the redder the color at any point, the more energy is being carried at that frequency at that moment. The slump signal's high frequencies reach maximum redness toward the middle of the event, which lasts much longer than an aftershock of comparable magnitude.



Above: The slump model's predicted maximum wave heights in meters, time-averaged until just before impact. Waves are refracted toward shallow water and away from the deeps, so the shelf focuses the wave on Sissano, creating the large red region aimed at the lagoon. The Yalingi River canyon comes ashore at Malol and also steers the wave toward the lagoon, helping protect Malol, which was only partially destroyed.

A couple of concrete slabs and a cistern are all that remain of the Arop No. 1 village church, now a makeshift graveyard.

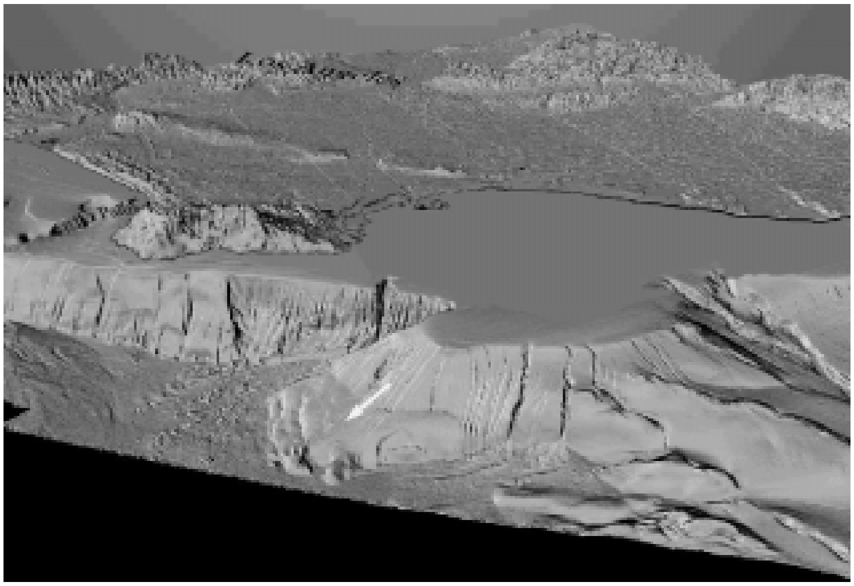
magnitude 4.4 isn't that big, and there were very few seismic stations close enough to catch it. Even so, he says, "I've derived a location ellipse from those few records, and it includes the amphitheater. Here was the proof that some activity took place 13 minutes after the main shock, at the exact location of the slump mapped by the *Dolphin*."

Run-up modeler Synolakis says the survey team's fieldwork adds one final tidbit in support of the slump model. "For many years, it's been standard, in fact universal, to model tsunamis as leading elevation waves—the crest in front of the trough. People thought that leading depression waves, trough before crest, were hydrodynamically unstable. Everyone was looking at the effects of tsunamis far from their sources, and it was thought that leading depression waves wouldn't propagate that far. But the Nicaraguan tsunami of '92 showed that subduction zones can produce tectonic tsunamis with depression waves, and if you look at the coastal manifestation of a tsunami close to its source, they turn out to be quite important. The slump model automatically provides the sense of the leading wave, which in most cases turns out to be a depression wave." The slump creates a void behind itself that the water rushes into, so that if it's moving toward deeper water the depression wave points toward land. "So finally we have a model that corroborates eyewitness accounts. In every tsunami in the past eight years, people always say the sea withdrew first, and then the wave came. Before Papua New Guinea, we could only try to explain this in terms of tectonic tsunamis, but now we know why. Unfortunately, the model shows that if you put the trough first, you get double the run-up than if you put the crest first." Adds Watts, "The other thing is, you have a bit of warning. If you see the sea receding, get out and stay out!"

This last bit of knowledge is paying off, says Synolakis. Last December, another pocket tsunami wiped out the village of Bai Martele in Vanuatu, formerly the New Hebrides. "The wave was eight to nine meters high, and in a village of that size there could easily have been two or three hundred people killed. But only three people died. Why? The magic of television. They have no electricity, no water, no nothing, but last summer the Vanuatu authorities went around with a portable generator and a TV and a brand-new UNESCO video about volcanoes, earthquakes, and tsunamis. They showed it in every village. The video described the Papua New Guinea disaster and warned, 'If you feel the ground shaking, or you see the water receding, run for high ground!' As it happened, the ground shaking in Vanuatu was not very strong, but they saw the water receding. There was a nearby hill, and they all ran up it. And stayed there. That's the big lesson—slumps can happen quite some time after the main shock, so we tell them to stay away for half an hour to an hour. It has happened in the past that a wave comes in and people run; then they return to look for loved ones or survey the damage, and they get hit by the second wave. Or the third wave. So for only three people to die in Bai Martele was amazing—spectacular! Of the people who died, two were very old, and the other one was high on kava, which is a local cognac. Of all the science we did, that was the best part. It really did save lives." A just-completed French bathymetric cruise has found a scarp off Bai Martele that has been interpreted as evidence for a landslide, but the jury is still out.

"This is a very exciting time," Synolakis says. "Tools developed over 40 years in diverse fields—classic long-wave theory, fluid mechanics, geophysics, soil science, oceanography, and seismology—are suddenly coming together. We have Fred Raichlen and his wave lab at Caltech to thank for this. He kept the field alive in the lean years of the '70s and '80s, when very few people were interested in tsunamis."

As you might have guessed by now, California is not immune to pocket tsunamis. We have as many faults offshore as onshore, and they're just



Above: At least three submarine landslides contributed to the arrowed region in this view of the seafloor south of Palos Verdes. The vertical scale is exaggerated tenfold. Unpublished composite image of high-resolution multibeam bathymetry courtesy of James V. Gardner, U.S. Geological Survey, Menlo Park, CA.

as active. Says Watts, “The geology and seafloor mapping off California is pretty complete in several key places, including San Pedro and Santa Monica Bays, largely due to the oil industry and the ports. The evidence would suggest there was a slump off Santa Barbara about 100 to 150 years ago—it’s hard to be sure when—and another one 10 kilometers farther east about 300 years ago. Both of these are about an order of magnitude smaller than the one off Papua New Guinea, but they would be tsunamigenic because they occurred in much shallower water—at 100 meters’ depth, rather than 1.5 kilometers. There are also slumps off Palos Verdes. This is a huge point: Northridge had thousands of documented landslides; Vanuatu had 2,000 documented landslides following the earthquake, so it’s not unreasonable to expect a number to occur underwater as well.”

In fact, Kuo-Fong Ma (PhD ’93), postdoc Kenji Satake, now with the Geological Survey of Japan, and Kanamori found that the Loma Prieta earthquake of October 17, 1989, set off submarine landslides that created a small tsunami, 0.7 meters high, in Monterey Bay. The wave was recorded by tide gauges and, of all things, the video camera of a tourist who happened to pick that day to tape the sunset at Moss Landing.

As *E&S* was going to press, the Governor’s Office of Emergency Services of the State of California was releasing the first-ever set of tsunami inundation maps for the most populous locales along the California coast, analogous to the earthquake-hazard maps previously released. The maps, a joint effort with the Seismic Safety and State Lands Commissions, took two years to prepare. Synolakis, grad student José C. Borrero, and grad-student-turned-postdoc Utku Kanoglu did the modeling, which generated inundation scenarios for the San Diego, Los Angeles, and Santa Barbara areas, and from Half Moon Bay north to San Francisco. The flooding could be extensive, covering many low-lying areas and affecting port and harbor facilities, but there are other urban consequences. Paved surfaces don’t dissipate wave energy, so roads become conduits. When the roads lead to underpasses, as they do in Santa Barbara where Highway 101 parallels the beach, you have a set of fire hoses aimed at downtown. And cars in beach-access parking lots become torpedoes. It’s too late to unbuild along California’s coastline, but knowing what’s vulnerable and what will survive allows response teams to plan in advance how best to restore services and what kinds of relief supplies to bring in—you’ll know where a railroad spur can be run over uneroded ground to bring in heavy cranes, for example, and you won’t need so much diesel fuel if the tank farm is above the maximum run-up line. Issuing evacuation alerts is being considered as a means of saving lives—if the seismometers already affixed to offshore drilling platforms were tied into a computerized early-warning system, there could be about 10 minutes’ notice of an incoming wave triggered by a slump in the Santa Barbara Channel. The best hope is to try to educate people not to hop in their cars and jam the freeways, but to simply run for high ground, including the upper floors of sturdy buildings. After all, the people on Vanuatu had even less warning, and if they could do the right thing, so can we. □

Left: In this day and age, you’re never out of touch—Synolakis talks to colleagues in the National Oceanic and Atmospheric Administration in Seattle as José C. Borrero (center) and Okal look on. Right: The survey teams bade farewell at Madang International Airport. That’s “Air New Guinea” in pidgin over the door.