The Threat of Silent Earthquakes

A LACK OF RUMBLING DOES NOT NECESSARILY MAKE AN EARTHQUAKE HARMLESS. SOME OF THE QUIET TYPES COULD PRESAGE DEVASTATING TSUNAMIS OR LARGER, GROUND-SHAKING SHOCKS

By Peter Cervelli

In early November 2000 the Big Island of Hawaii experienced its largest earthquake in more than a decade. Some 2,000 cubic kilometers of the southern slope of Kilauea volcano lurched toward the ocean, releasing the energy of a magnitude 5.7 shock. Part of that motion took place under an area where thousands of people stop every day to catch a glimpse of one of the island's most spectacular lava flows. Yet when the earthquake struck, no one noticed—not even seismologists.

How could such a notable event be overlooked? As it turns out, quaking is not an intrinsic part of all earthquakes. The event on Kilauea was one of the first unambiguous records of a so-called silent earthquake, a type of massive earth movement unknown to science until just a few years ago. Indeed, I would never have discovered this quake if my colleagues at the U.S. Geological Survey's Hawaiian Volcano Observatory had not already been using a network of sensitive instruments to monitor the volcano's activity. When I finally noticed that Kilauea's south flank had shifted 10 centimeters along an underground fault, I also saw that this movement had taken nearly 36 hours—a turtle's pace for an earthquake. In a typical tremor, opposite sides of the fault rocket past each other in a matter of seconds—quickly enough to create the seismic waves that cause the ground to rumble and shake.

But just because an earthquake happens slowly and quietly does not make it insignificant. My co-investigators and I realized immediately that Kilauea's silent earthquake could be a harbinger of disaster. If that same large body of rock and debris were to gain momentum and take the form of a gigantic landslide—separating itself from the rest of the volcano and sliding rapidly into the sea—the consequences would be devastating. The collapsing material would push seawater into towering tsunami waves that could threaten coastal cities along the entire Pacific Rim. Such catastrophic flank failure, as geologists call it, is a potential threat around many island volcanoes worldwide.

Unexpected Stir

FORTUNATELY, the discovery of silent earthquakes is revealing more good news than bad. The chances of catastrophic flank failure are slim, and the instruments that record silent earthquakes might make early warnings possible. New evidence for conditions that might trigger silent slip suggests bold strategies for preventing flank collapse. Occurrences of silent earthquakes are also being reported in areas where flank failure is not an issue. There silent earthquakes are inspiring ways to improve forecasts of their ground-shaking counterparts.

The discovery of silent earthquakes and their link to catastrophic flank collapse was a by-product of

GIANT LANDSLIDE (*upper left*) spawned by a silent earthquake could generate a fearsome tsunami hundreds of meters high (*below*).

efforts to study other potential natural hazards. Destructive earthquakes and volcanoes are a concern in Japan and the U.S. Pacific Northwest, where tectonic plates constantly plunge deep into the earth along what are called subduction zones. Beginning in the early 1990s, geologists began deploying large networks of continuously recording Global Positioning System (GPS) receivers in these regions and along the slopes of active volcanoes, such as Kilauea. By receiving signals from a constellation of more than 30 navigational satellites, these instruments can measure their own positions on the planet's surface at any given time to within a few millimeters.

The scientists who deployed these GPS receivers expected to see both the slow, relentless motion of the planet's shell of tectonic plates and the relatively quick movements that earthquakes and volcanoes trigger. It came as some surprise when these instruments detected small ground movements that were not associated with any known earthquake or eruption. When researchers plotted the ground movements on a map, the pattern that resulted very much resembled one characteristic of fault movement. In other words, all the GPS stations on one side of a given fault moved several centimeters in the same general direction. This pattern would have been no surprise if it had taken a year or longer to form. In that case, scientists would have known that a slow and steady process called fault creep was responsible. But at rates of up to centimeters a day, the mystery events were hundreds of times as fast as that. Beyond their relative speediness, these silent earthquakes shared another attribute with their noisy counterparts that distinguished them from fault creep: they are not steady processes but instead are discrete events that begin and end suddenly.

That sudden beginning, when it takes place on the slopes of a volcanic island, creates concern about a possible catastrophic flank event. Most typical earthquakes happen along faults that have built-in brakes: motion stops once the stress is relieved between the two chunks of earth that are trying to move past each other. But activity may not stop if gravity becomes the primary driver. In the worst-case scenario, the section of the volcano lying above the fault becomes so unstable that once slip starts, gravity pulls the entire mountainside downhill until it disintegrates into a pile of debris on the ocean floor.

The slopes of volcanoes such as Kilauea become steep and vulnerable to this kind of collapse when the lava from repeated eruptions builds them up more rapidly than they can erode away. Discovering the silent earthquake on Kilauea suggests that the volcano's south flank is on the move—perhaps on its way to eventual obliteration.

For now, friction along the fault is acting like an emergency brake. But gravity has won out in many other instances in the past. Scientists have long seen evidence of ancient collapses in sonar images of giant debris fields in the shallow waters surrounding volcanic islands around the world, including Majorca in the Mediterranean Sea and the Canary Islands in the Atlantic Ocean. In the Hawaiian Islands, geologists have found more than 25 individual collapses that have occurred over the past five million years—the blink of an eye in geologic time.

In a typical slide, the volume of material that enters the ocean is hundreds of times as great as the section of Mount St. Helens that blew apart during the 1980 eruption—more than enough to have triggered immense tsunamis. On the Hawaiian island of Lanai, for instance, geologists discovered evidence of wave action, including abundant marine shell fragments, at elevations of 325 meters. Gary M. McMurtry of the University of Hawaii at Manoa and his colleagues conclude that the most likely way the shells could have reached such a lofty location was within the waves of a tsunami that attained the astonishing height of 300 meters along some Hawaiian coastlines. Most of the tallest waves recorded in modern times were no more than one tenth that size.

> Tsunami-generating VOLCANIC COLLAPSES may occur once every 10,000 years.

Overview/*Slippery Slope*

- Not all earthquakes shake the ground, it turns out. The so-called silent types are forcing scientists to rethink their understanding of the way quake-prone faults behave.
- In rare instances, silent earthquakes that occur along the flanks of seaside volcanoes may cascade into monstrous landslides that crash into the sea and trigger towering tsunamis.
- Silent earthquakes that take place within fault zones created by one tectonic plate diving under another may increase the chance of ground-shaking shocks.
- In other locations, however, silent slip may decrease the likelihood of destructive quakes, because they release stress along faults that might otherwise seem ready to snap.

Preparing for the Worst

AS FRIGHTENING AS such an event may sound, this hazard must be understood in the proper context. Catastrophic failure of volcanic slopes is very rare on a human timescale—though far more common than the potential for a large asteroid or comet to have a damaging col-

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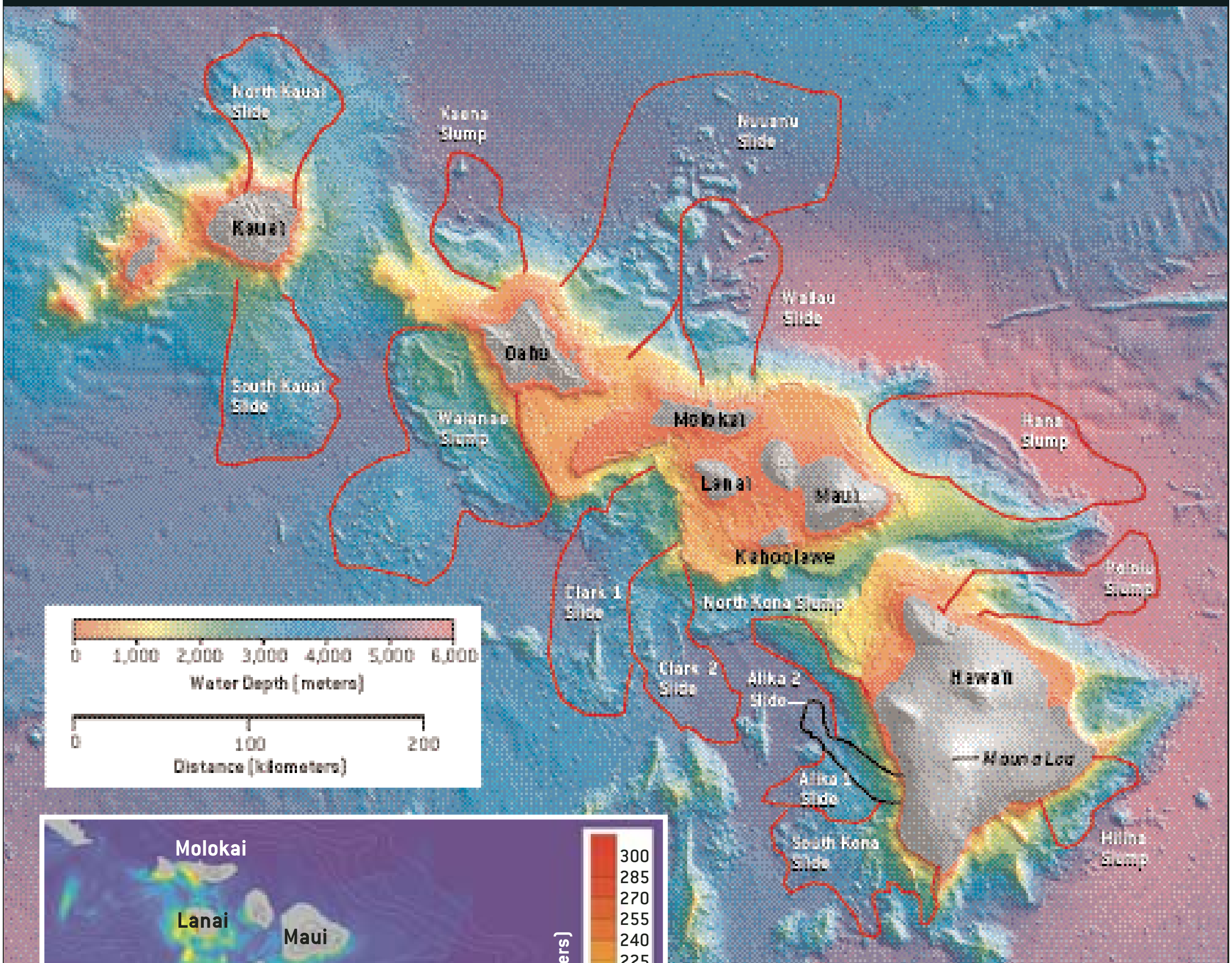
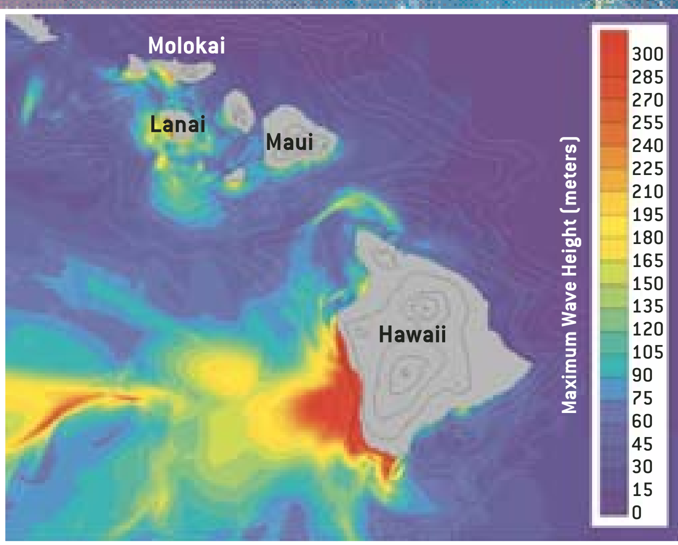
GIANT LANDSLIDES AND TERRIFYING TSUNAMIS





UNDERWATER FIELDS of rock and debris (*examples outlined in red*) reveal that massive sections of Hawaiian volcanoes have crumbled into the ocean many times in the past. Some geologists suspect that one collapse (*black outline*) off the western flank of Mauna Loa volcano kicked up a gigantic tsunami that deposited shattered shell and rock as high as 800 meters along the nearby coast. A computer simulation (*left*) reveals that the same landslide may have produced waves up to 300 meters high. For a brief time, Maui could have been divided in two and the ocean floor west of Molokai could have been exposed.

USGS, WITH JAPAN MARINE SCIENCE AND TECHNOLOGY CENTER, UNIVERSITY OF HAWAII AND MONTEREY BAY AQUARIUM RESEARCH INSTITUTE (*top*); REPRINTED FROM GARY M. MCMURTRY IN *MARINE GEOLOGY*, VOL. 202, © 2002, WITH PERMISSION FROM ELSEVIER (*bottom*)

lision with the earth. Collapses large enough to generate a tsunami occur somewhere in the Hawaiian Islands only about once every 100,000 years. Some scientists estimate that such events occur worldwide once every 10,000 years. Because the hazard is extremely destructive when it does happen, many scientists agree that it is worth preparing for.

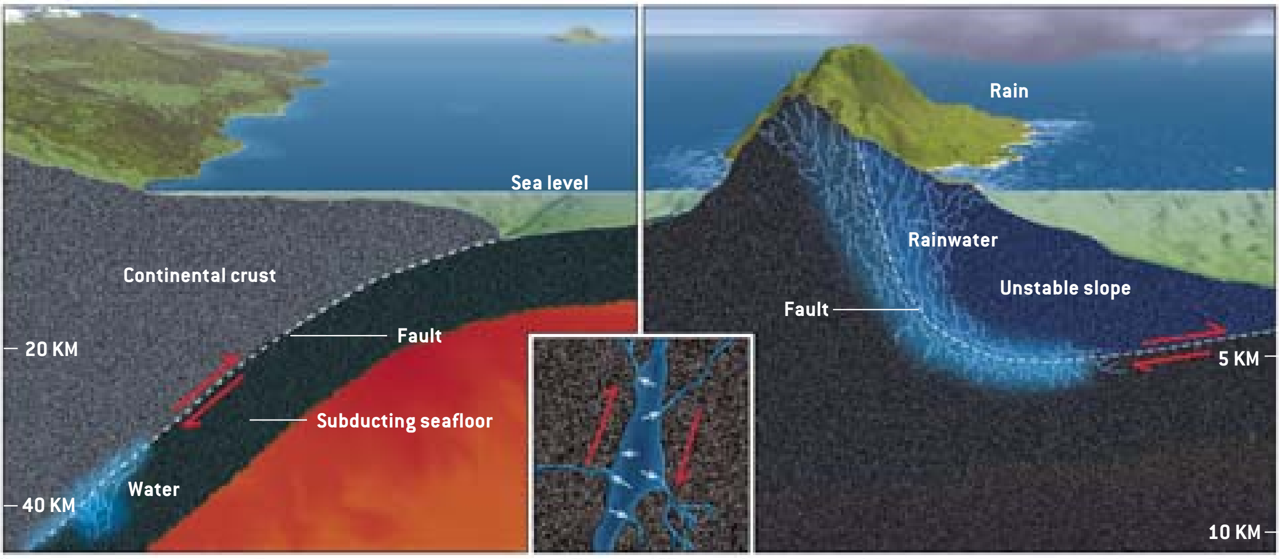
To detect deformation within unstable volcanic islands, networks of continuous GPS receivers are beginning to be deployed on Réunion Island in the Indian Ocean, on Fogo in the Cape Verde Islands, and throughout the Galápagos archipelago, among others. Kilauea's network of more than 20 GPS stations, for example, has already revealed that the volcano experiences creep, silent earthquakes as well as large, destructive typical earthquakes. Some scientists propose,

THE MECHANICS OF SILENT EARTHQUAKES

PERCOLATING WATER may trigger silent earthquakes if it finds a way into a vulnerable fault. Highly pressurized by the burden of overlying rock, water can push apart the two sides of the fault (*inset*), making it easier for them to slip past each other (*red arrows*). This kind of silent slip can occur within subduction zones and volcanic islands.

SUBDUCTION ZONE

VOLCANIC ISLAND



WATER squeezed out of hydrous minerals in a slab of ancient seafloor may enter faults created as the slab dives underneath another tectonic plate.

WATER-FILLED fault

RAINWATER may seep down from the earth's surface into shallow faults, such as those that separate an unstable slope from the rest of a volcano.

however, that Kilauea may currently be protected from catastrophic collapse by several underwater piles of mud and rock—probably debris from old flank collapses—that are buttressing its south flank. New discoveries about the way Kilauea is slipping can be easily generalized to other island volcanoes that may not have similar buttressing structures.

Whatever the specific circumstances for an island, the transition from silent slip to abrupt collapse would involve a sudden acceleration of the mobile slope. In the worst case, this acceleration would proceed immediately to breakneck velocities, leaving no chance for early detection and warning. In the best case, the acceleration would occur in fits and starts, in a cascade of silent earthquakes slowly escalating into regular earthquakes, and then on to catastrophe. A continuous GPS network could easily detect this fitful acceleration, well before ground-shaking earthquakes began to occur and, with luck, in plenty of time for a useful tsunami warning.

If the collapse were big enough, however, a few hours' or even days' warning might come as little comfort because it would be so difficult at that point to evacuate everyone. This problem raises the question of whether authorities might ever implement preventive measures. The problem of stabilizing the teetering flanks of oceanic volcanoes is solvable—in principle. In practice, however, the effort required would be immense. Consider simple brute force. If enough rock were removed from the upper reaches of an unstable volcanic flank, then the gravitational potential energy that is driving the system toward collapse would disappear for at least several hundred thousand years. A second possible method—lowering an unstable flank slowly through a series of small earthquakes—would be much cheaper but fraught with geologic unknowns and potential dangers. To do so, scientists could conceivably harness as a tool to prevent collapse the very thing that may be currently driving silent earthquakes on Kilauea.

Nine days before the most recent silent earthquake on Kilauea, a torrential rainstorm dropped nearly a meter of water on the volcano in less than 36 hours. Geologists have long known that water leaking into faults can trigger earthquakes, and nine days is about the same amount of time that they estimate it takes water to work its way down through cracks and pores in Kilauea's fractured basaltic rock to a depth of five kilometers—where the silent earthquake occurred. My colleagues and I suspect that

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the burden of the overlying rock pressurized the rainwater, forcing the sides of the fault apart and making it much easier for them to slip past each other.

This discovery lends credence to the controversial idea of forcefully injecting water or steam into faults at the base of an unstable flank to trigger the stress-relieving earthquakes needed to let it down slowly. This kind of human-induced slip happens at very small scales all the time at geothermal plants and other locations where water is pumped into the earth. But when it comes to volcanoes, the extreme difficulty lies in putting the right amount of fluid in the right place so as not to inadvertently generate the very collapse that is meant to be avoided. Some geophysicists considered this strategy as a way to relieve stress along California's infamous San Andreas fault, but they ultimately abandoned the idea for fear that it would create more problems than it would solve.

Wedges of Water

APART FROM CALLING attention to the phenomenon of catastrophic collapse of the flank of a volcano, the discovery of silent earthquakes is forcing scientists to reconsider various aspects of fault motion—including seismic hazard assessments. In the U.S. Pacific Northwest, investigators have observed many silent earthquakes along the enormous Cascadia fault zone between the North American plate and the subducting Juan de Fuca plate. One curious feature of these silent earthquakes is that they happen at regular intervals—so regular, in fact, that scientists are now predicting their occurrence successfully.

This predictability most likely stems from the fact that water flowing from below subduction zones may exert significant control over when and where these faults slip silently. As the subducting plate sinks deeper into the earth, it encounters higher and higher temperatures and pressures, which release the significant amount of water trapped in water-rich minerals that exist within the slab. The silent earthquakes may then take place when a batch of fluid from the slab is working its way up—as the fluid passes, it will unclamp the fault zone a little bit, perhaps allowing some slow slip.

What is more, Garry Rogers and Herb Dragert of the Geological Survey of Canada reported last June that these silent tremors might even serve as precursors to some of the region's large, ground-shaking shocks. Because the slow slips occur deep and at discrete intervals, they regulate the rate at which stress accumulates on the shallower part of the fault zone, which moves in fits and starts. In this shallow, locked segment of the fault, it usually takes years or even centuries to amass the stress required to set off a major shock. Rogers and Dragert suggest, however, that silent slip may dramatically hasten this stress buildup, thereby increasing the risk of a regular earthquake in the weeks and months after a silent one.

Silent earthquakes are forcing scientists to rethink seismic forecasts in other parts of the world as well. Regions of Japan near several so-called seismic gaps—areas where fewer than expected regular earthquakes occur in an otherwise seismically active region—are thought to be overdue for a destructive shock. But if silent slip has been relieving stress along these faults without scientists realizing it, then the degree of danger may actually be less than they think. Likewise, if silent slip is discovered along faults that were considered inactive up to now, these structures will need careful evaluation to determine whether they are also capable of destructive earthquakes.

If future study reveals silent earthquakes to be a common feature of most large faults, then scientists will be forced to revisit long-held doctrines about all earthquakes. The observation of many different speeds of fault slip poses a real challenge to theorists trying to explain the faulting process with fundamental physical laws, for example. It is now believed that the number and sizes of observed earthquakes can be explained with a fairly simple friction law. But can this law also account for silent earthquakes? So far no definitive answer has been found, but research continues.

Silent earthquakes are only just beginning to enter the public lexicon. These subtle events portend an exponential increase in our understanding of the how and why of fault slip. The importance of deciphering fault slip is difficult to overstate because when faults slip quickly, they can cause immense damage, sometimes at a great distance from the source. The existence of silent earthquakes gives scientists a completely new angle on the slip process by permitting the detailed study of fault zones through every stage of their movement. SA

Some SILENT EARTHQUAKES HAPPEN at such regular intervals that they can be predicted successfully.

MORE TO EXPLORE

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Visit the U.S. Geological Survey Hawaiian Volcano Observatory at **http://hvo.wr.usgs.gov**