When Kilauea Crumbles

Hawaii trembles as a mountain slowly collapses

By RICHARD MONASTERSKY

From the smell of seared rubber, geologist Carl Thornber knew his boots had caught fire again. It upset him, not because he feared for his feet, but because his new shoes had failed to live up to expectations. This was only their maiden trek onto the lava flows seeping out of Hawaii's Kilauea volcano. At this rate, the boots wouldn't last the month.

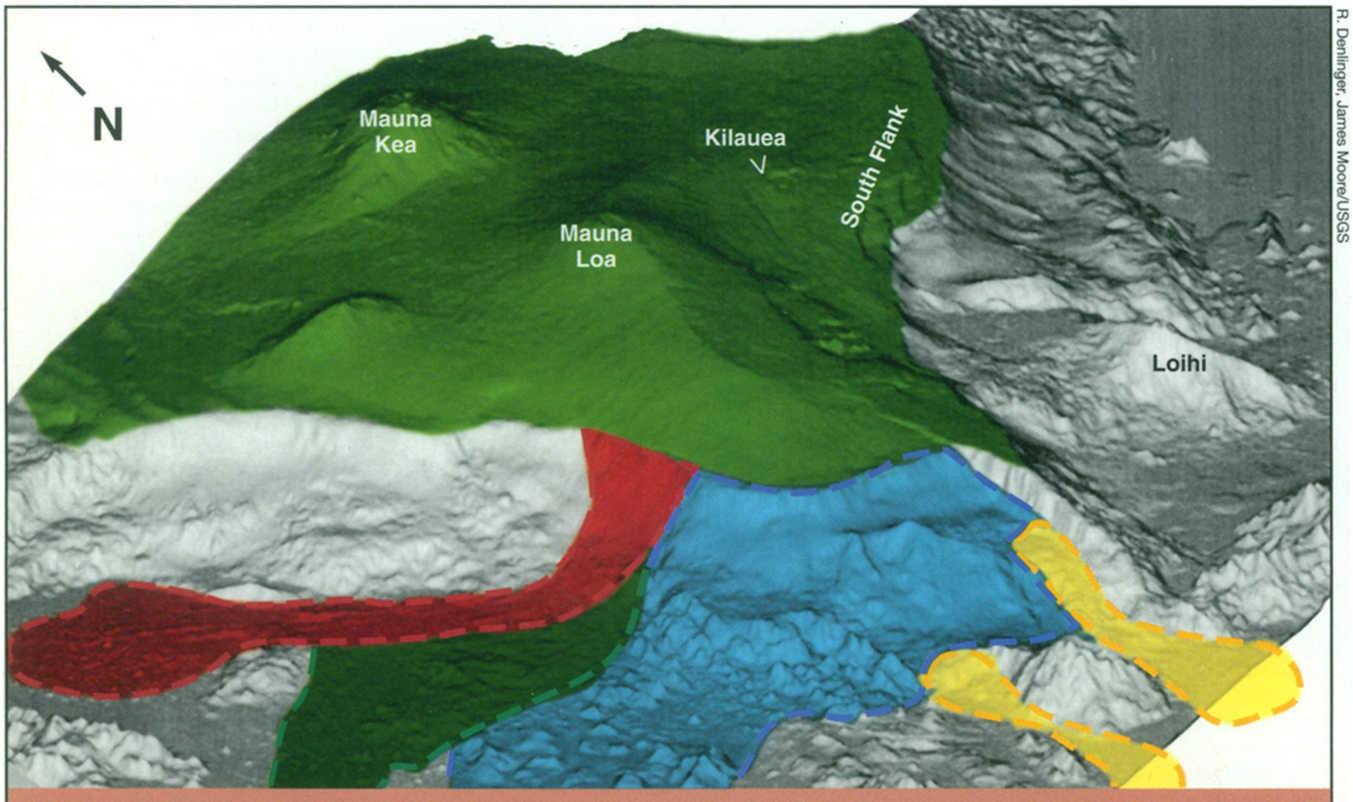
Thornber's truck might not either. His employer, the Hawaiian Volcano Observatory, acquired the aging vehicle from Clark Air Force Base in the Philippines, which evacuated in 1991 just before nearby Mount Pinatubo erupted. Although the truck, dubbed "the Battlewagon" for its camouflage colors, escaped death by volcano then, Kilauea (pronounced "kill-a-way-a") is finishing the job.

Like the boots and the Battlewagon, Kilauea volcano itself is falling apart. Even as geologists map its surface lava flows, the mountain beneath them is tearing away from the rest of the island of Hawaii and sliding toward the ocean at 10 centimeters a year, a sprint by geologic standards. This is the fastest-moving parcel of real estate on Earth.

That fact unsettles researchers at the volcano observatory, a U.S. Geological Survey facility perched next to Kilauea's summit crater. A look at bathymetric charts tacked up inside the observatory explains the scientists' concern. The maps reveal that the seafloor around the Hawaiian Islands is littered with debris from landslides of mythic proportions.

Gigantic slices of volcanoes have broken off the islands in millennia past and skidded across the ocean bottom, splintering into smaller blocks that finally ground to a halt as much as 200 kilometers from their starting point. One stranded fragment rivals Manhattan in size. Another avalanche triggered a tsunami that reached as high as the Empire State Building.

No one knows whether the southern section of Kilauea will take a dive anytime soon. But scientists say that even minor shifts of the mountain's mass can cause damaging earthquakes, which may represent a greater hazard to the



R. Denlinger, James Moore/USGS

Lost pieces of Hawaii, remnants of giant landslides, blanket the seafloor around the island. Normally hidden beneath the waves, the avalanche debris shows up on this relief map, which has stripped away the water to expose the seafloor. Shaded regions in the foreground mark individual landslides that have broken off Mauna Loa. Kilauea volcano appears in the upper right area of the island. Still an infant by geologic standards, Kilauea has yet to build itself into a true mountain. It is really a plateau perched on the slope of Mauna Loa. Rift zones define the boundaries of Kilauea's south flank, which is currently sliding seaward and will eventually give way in a major landslide. The seamount named Loihi is Hawaii's newest volcano, although it will take millennia for it to reach above sea level.

island than the much more obvious threat from lava flows.

To illustrate Kilauea's current wounds, geophysicist Roger Denlinger scrambles down a fissure big enough to swallow a bus. The crack has opened as land to the south edges seaward, pulling away from the rest of the island.

Denlinger hails originally from the mainland. But like the other USGS scientists, he came to the Hawaiian Volcano Observatory for the chance to study a mountain in action. The facility serves as a training ground for volcanologists from around the world.

To explain the processes tearing apart Kilauea, Denlinger and his colleagues have constructed a basic theoretical model of the volcano. The model consists of two main elements, a magma reservoir a few kilometers beneath the volcano's summit and a fault under the mountain's south flank. Resembling a flexible bladder, the reservoir expands when molten rock fills it from below.

"It seems the same basic model from other volcanoes applies here," says Denlinger. "You have a magma system that inflates like a balloon and pushes on the flank. The flank detaches along a basal fault and destabilizes and forms a big landslide. That's what happened at St. Helens in 1980 and it's happening here now and we're studying the process."

The Mount St. Helens eruption taught volcanologists a deadly lesson about landslides. Although USGS researchers in early 1980 predicted the upcoming blast, they failed to anticipate that it would start with a rock avalanche.

Scientists monitoring St. Helens expected a vertical eruption. But when the mountain's northern slope collapsed, the landslide triggered a sideways explosion that swept away geologist David Johnston, stationed 9 km to the north. Since then, researchers have recognized that many volcanoes have a habit of falling apart, including those on Hawaii.

At Kilauea, observatory scientists have used recent earthquakes to map the hidden fault threatening to shear the volcano. Many tremors originate about 9 km below the surface, on a plane interpreted to be a nearly horizontal fault.

This flat structure separates the upper part of Kilauea from the seafloor foundation on which the volcano has built itself over the last 100,000 years. Land seaward of Kilauea's summit — a region called the south flank — slides south along the basal fault like a wooden wedge being pushed across a table.

Denlinger works with colleagues at the volcano observatory and at Stanford University to monitor the flank's movement using the Global Positioning System (GPS). By regularly measuring the position of benchmarks around the volcano, they find that spots between the summit and coast creep quietly and continuously toward the ocean. The land moves as much as 10 cm per year at the surface and up to 20 cm per year at the depth of the fault. That's about four times the slip rate along California's infamous San Andreas fault, the scientists report in the March 3 SCIENCE.

Not all portions of the flank cruise along so smoothly, however. From GPS measurements, researchers know that the coast moves at only three-quarters of the speed of locations inland. Beyond the coast, submerged parts of the flank appear even less mobile. Bathymetric profiles of this region show a raised bench offshore that may result from land piling up behind a stuck portion of Kilauea's outer flank.

"It's like a bulldozer pushing on a pile of debris or a shovel pushing on snow," Denlinger says. "If you push on snow, it will pile up right in front of the blade. It works that way here. The resistance is right at the end of the flank's toe. Basically, this material is piling up as the flank is being pushed seaward."

In fact, the GPS measurements show the coastline currently bulging upward because lower reaches of the flank remain stuck. The pushing match can't continue forever, though. As the volcano's southern edge buckles, it stores up strain energy like a compressed spring. Squeeze the flank too much and it will eventually break free.

Denlinger and his colleagues are now struggling to understand what forces control the flank's behavior, allowing some parts to move continuously while other parts stick. "The big question is, at what point do we go from just having a portion of the fault slip to having a catastrophic event that causes the entire base to decouple from the island," he wonders.

Judging from recent events, Kilauea's south side appears sensitively poised. In early 1994, researchers noticed that the flank stopped moving after pressure in the magma reservoir dropped slightly. When the pressure increased again in March 1994, the flank resumed sliding.

"One of the things that's really scary about what happened last year is that the apparent pressure change that caused the flank to stop was small," says Denlinger. "So you have a fairly large piece of real estate that started and stopped and started again with very small changes in pressure. That means it has to be pretty delicately balanced and fairly slippery along the base."

When the flank eventually gives way, Hawaii will certainly not suffer alone. "The risk is very, very large because the tsunami that would be generated would be a Pacific-wide tsunami. It will hit every coastal city on the entire Pacific Rim," says David A. Clague, scientist-in-charge at

The Enduring Eruption

Lava oozes out of a gash in the ground with the consistency of molten mozzarella. Glowing bright orange, the 1,100°C blob advances a few centimeters and then hardens into a glassy gray mass. Instant rock, only seconds old.

In terms of drama, the lava flows currently issuing from Kilauea volcano can't compare to the explosive blasts served up by Mount Pinatubo or Mount St. Helens. But while these better-known volcanoes flashed briefly, hard-working Kilauea has poured out lava almost continuously for more than 12 years. Still going strong, this eruption is the longest known on Earth.

Since Jan. 3, 1983, Kilauea has quietly pumped out roughly 1.3 cubic kilometers of rock, more than the volume of the 1980 blast at Mount St. Helens. The eruption has destroyed 181 homes and a new visitor's center at Hawaii Volcanoes National Park. Losses now total $61 million. The lava flows have claimed no lives directly, but several sightseers died by venturing past warning signs into unsafe areas.

Usually peaceful, Kilauea does have the potential to erupt explosively. In 1790, a major blast killed a troop of Hawaiian soldiers who were marching across the island to fight King Kamehameha. Aided by Kilauea, the famous chief went on to conquer all the Hawaiian Islands. — *R. Monastersky*

R. Monastersky

USGS geologist Carl Thornber collects a sample of lava from one of the many active flows on Kilauea.

the volcano observatory.

To give a sense of the expected wave, Clague points out the tiny island of Lanai on a nearby map of the Hawaiian archipelago. One mountain on Lanai has fragments of coral sitting at an elevation of 365 meters above sea level — an unusual spot for an ocean-dwelling creature. Clague explains that the coral reached this height because of a giant tsunami, triggered by a landslide off the west coast of Hawaii.

Just how likely is one of these landslides? While scientists can't say for sure, they think that time is on their side. From the number of debris piles sitting on the seafloor, researchers calculate that giant sections of Hawaiian volcanoes peel off only once every 100,000 to 200,000 years. Chances are extremely slim, therefore, that one will occur during the next decade or even the next millennium.

But while landslides might not represent a major hazard in their own right, Clague believes that they illuminate a much greater threat to life on the islands: earthquakes. Almost all of the large tremors on the island emanate from the flat fault underneath Kilauea and similar faults beneath Mauna Loa, the same geologic structures that can give way and cause landslides.

"We're trying to understand how the volcano works. I think the landslides explain the mechanism behind the biggest earthquakes that occur here," Clague says. "They point out that those earthquakes are not flukes, that they are part of the regular history of the volcano. During anyone's lifetime [on Hawaii], they will almost certainly experience at least one large earthquake, actually more than one. We don't know enough about the earthquake mechanisms here on Hawaii, and the landslides are a key to understanding that."

Although most people do not view Hawaii as a seismic center, its earthquake record over the last 150 years actually rivals that of Southern California. On Nov. 29, 1975, a large patch of the south flank suddenly lurched seaward, generating a magnitude 7.2 earthquake — a tremor bigger than the one that hit Kobe, Japan, earlier this year.

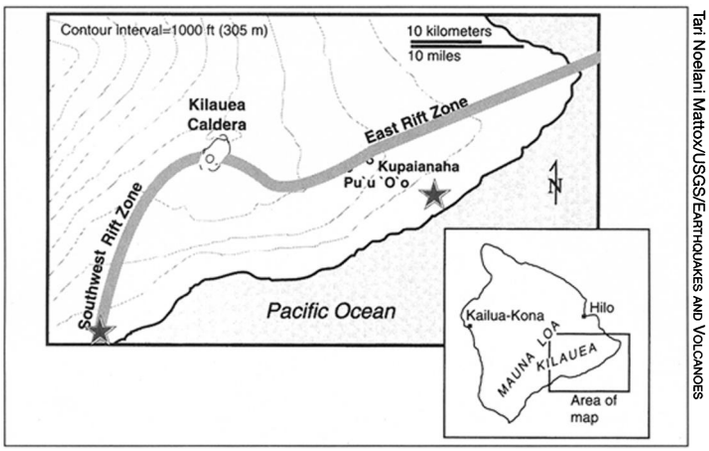
In 1868, Kilauea's south flank and parts of Mauna Loa slipped on the basal fault under the two volcanoes, causing damage across the entire island, even as far away as Honolulu. Scientists estimate this earthquake at magnitude 8.0. Meanwhile, strong earthquakes of magnitude 6.0 strike every 6 years or so.

The 1975 jolt caused significant damage but only two deaths, largely because few people lived nearby. Since then, development on the southern and eastern sides of Hawaii has brought tens of thousands of people closer to the earthquake region.

The city of Hilo, only 40 km away, has swelled since 1980 to a population of 60,000. Some of Hilo's new construction has sprouted directly atop thick ash deposits from Mauna Kea volcano, which tend to amplify ground shaking during earthquakes.

Scientists have seen evidence of enhanced vibrations in Hilo even during the small earthquakes that commonly jiggle the south flank. "We get reports of damage from Hilo — pictures falling off walls and glass figurines tumbling off shelves — from earthquakes out here as small as magnitude 3.2, which usually are right at the threshold that people can feel," Clague says.

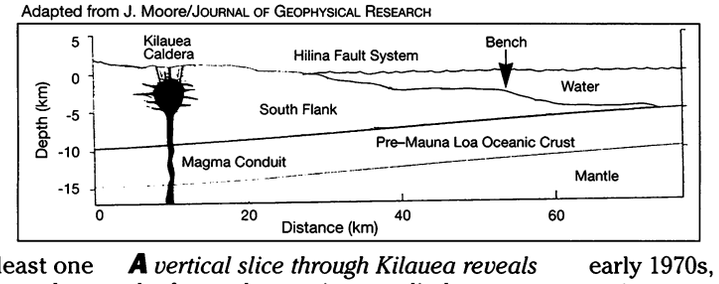
Kilauea's earthquakes are doubly dangerous because they generate tsunamis. When the south flank jumps forward, its submerged portions displace ocean water, sending destructive waves heading out toward other parts of the Hawaiian islands and potentially the entire Pacific Rim.



Tari Noelani Mattox/USGS/Earthquakes and Volcanoes

Rifts on either side of Kilauea separate its south flank from the rest of the island of Hawaii. The ongoing eruption since 1983 has come from Pu`u `O`o and from Kupaianaha. Stars mark the location of large earthquakes in 1975 and 1868.

Adapted from J. Moore/Journal of Geophysical Research



A vertical slice through Kilauea reveals the forces threatening to split the volcano. As the summit's magma reservoir expands, the southern part of the mountain edges seaward, sliding along an almost horizontal fault. The movement has built up a submarine bench near the flank's outer margin.

"The biggest [likely] risk associated with the volcano would be an earthquake that would cause a tsunami that would obviously cause death and destruction," says Harry Kim, head of the Civil Defense Agency on the island of Hawaii. "That is such a concern because this office will not be able to get advance warning to anyone [on the island]; the sequence of events would be very similar to what occurred in 1975."

During that tremor, a tsunami lashed the south coast almost immediately, killing two boy scouts camped with their troop along the water at Halape. Within 12 minutes, the tsunami hit Hilo, causing damage to boats and piers but no other deaths. The 1868 quake generated even larger waves that broke over the tops of palm trees along the south coast, according to eyewitness accounts from the time.

"Halape [in 1975] could be looked at as a forerunner of even bigger events of a similar nature," Kim says. "We as mankind must remember that the huge earthquake of 1868, which caused a huge tsunami, is a very real threat to this island."

Knowing that earthquakes and tsunamis will eventually strike, Kim and scientists at the volcano observatory have battled to inform Hawaiians about the hazards they face. Last year, they convinced the county to strengthen contruction codes to reduce damage during the next earthquake.

Kilauea has helped in its own way by doing some natural rezoning. In the early 1970s, developers planned to put a major resort along Kilauea's south flank. In preparation for golf courses, teahouses, hotels, and housing subdivisions, the state constructed roads and laid utility lines heading south out of the town of Pahoa. But the 1975 earthquake, which dropped the coastline by almost 3 m, upended the resort plans.

Despite the warning, a housing development blossomed in the 1980s on the south flank in a region called Kalapana. The Hawaiian goddess of fire, Pele, took care of Kalapana. Lava from Kilauea paved over the subdivision in 1990, destroying its homes but killing no one. In this way, the volcano's growing pains have effectively banished all people from the highest-risk seismic zone.

"Nature — others would say Pele — has solved a problem for us by removing the concentration of people," says Kim. "So even if we had the worst-case scenario, the death and destruction would be very limited compared to what it would have been." □