QUAKES IN SLO-MO

Barely detectable tremors may portend major destruction

By Alexandra Witze

Herb Dragert didn't know what to make of his wayward station.

In the early days of GPS satellites, Dragert had set up four benchmarks in the bedrock of Vancouver Island, British Columbia, to watch how their positions changed over time. Maybe, he thought, he could capture the ground moving during the earthquakes that occasionally shake the Pacific Northwest.

But instead Dragert saw one of his stations, at Albert Head on the southern part of the island, throwing a slow-motion tantrum. Every year or two it would inch westward for a few weeks, then stop, then do it again. The movement was far too slow to be an earthquake, but too fast for the ordinary creep of tectonic plates.

Twenty years later, Dragert and his colleagues know that they were seeing something new and important at Albert Head. The phenomenon, known as "slow slip," happens when two sides of a geologic fault shift the same amount as in a large quake, but over weeks to months rather than seconds. "It's like an earthquake, only slower," says codiscoverer Kelin Wang, who, like Dragert, is a geophysicist at the Geological Survey of Canada in Sidney, British Columbia.

Geologists are now learning that slow slip happens in all sorts of places, from Japan to New Zealand to Costa Rica.

Geologists use GPS stations (one shown below on Mount Olympus in Washington state) to detect the gentle ground movements known as "slow slip."

PACIFIC NORTHWEST GEODETIC ARRAY/CENTRAL WASHINGTON UNIV.

New discoveries reveal how slow slip serves as a transition between ordinary quakes at the surface and those in deeper parts of the Earth where rocks flow like softened butter. And because periods of slow slip have heralded several large recent quakes, including Japan's 2011 Tohoku quake, studying slow-motion events could hint at new and better ways to anticipate the next big one.

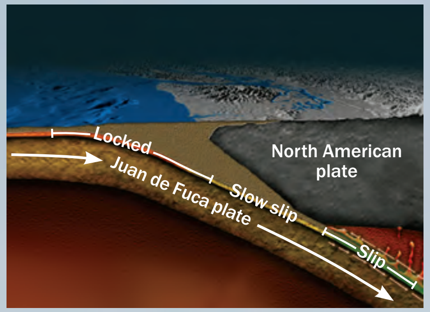
Balancing the books

Albert Head sits in a sprawling region of islands, peninsulas and waterways spanning the northwestern corner of the United States and southwestern British Columbia. This cross-border area is in a geological subduction zone known as Cascadia, where one huge plate of Earth's crust dives beneath another. Stress builds up where the Juan de Fuca plate slides beneath the North American plate, and that stress relieves itself occasionally in earthquakes. The last great "megathrust" quake shook the Cascadia coastline in the year 1700, as shown by drowned trees and other silent evidence along the water's edge.

Once the diving, or subducting, plate gets about 50 kilometers down, temperatures are warm enough that the brittle crust starts to flow more easily. Here, rocks move past each other in a sort of flowing motion, relieving accumulated stress so that it doesn't have a chance to build up. Between the upper, rigid part and the lower, flowing part is what scientists had long and unimaginatively called the transition zone. Now it is more accurately called the slow slip zone, because this is where slow slip events happen.

Slow slip helps scientists balance the books at subduction zones by explaining where all the motion of the subducting plate goes. A single slow slip event can account for as much ground movement as a magnitude 7.0 quake or greater. "For many, many years we were missing a lot," says Susan Schwartz, a seismologist at the University of California, Santa Cruz. "It's a very important component that we never knew was there before."

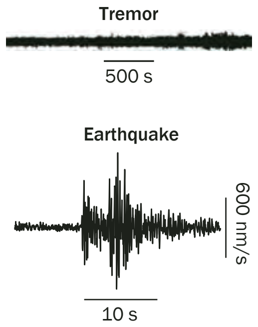
In some locations slow slip happens like clockwork — in Cascadia it appears about every 15 months — while in other places it comes more sporadically. A region can have more than one kind of slow slip; Japan, for instance, has both long-term events that happen every three to five years for several months, and briefer ones that crop up far more frequently.



Slip sliding away Off the Pacific Northwest coast, where one slab of crust plunges beneath another, plates are locked in place near the surface but slip slowly and regularly deep underground. SOURCE: UNIV. OF WASHINGTON

Along with Cascadia, Japan is the best-studied slow slip spot in the world. In large part that's thanks to sophisticated instruments placed across the country after the devastating 1995 Kobe earthquake. By the early 2000s, Kazushige Obara of the University of Tokyo found that the ground under southwestern Japan shook intermittently with a low seismological rattle. This “tremor” appeared on a seismic readout as squiggly lines, like background noise from a windstorm. But it, too, turned out to be a totally new phenomenon.

Seismic signatures



SOURCE: J. GOMBERG *ET AL*/ *GSA BULL*. 2010

Slow slip is often accompanied by tremor (top), which appears on a seismogram as a signal quite different from that of an ordinary quake (bottom).

Slow slip and tremor may represent two faces of the same thing happening deep underground. Usually, slow slip happens too slowly to generate seismic waves. But occasionally small patches along either side of the fault may slip rapidly enough to create seismic waves, just barely distinguishable above background noise. That's tremor.

Tremor often happens along with slow slip, although sometimes it crops up before or after slow slip, or not at all. Occasionally tremor reverses direction and speeds up dramatically for a little while. Why that happens remains a mystery. “There's a lot we don't know,” says John Vidale, a seismologist at the University of Washington in Seattle.

Seeds of destruction

Answering such questions is crucial because of the risk involved. Cascadia is either due or overdue for its next great megathrust quake, and building codes and earthquake preparedness in the region lag behind seismically active parts of California. A 2009 paper in *Geophysical Research Letters* reported that slow slip is happening so deep within Cascadia that when a really big earthquake does happen, its shaking could extend farther inland than once thought. That means it could hit people in much of western Washington and some of Canada, not just along the coast (*SN Online: 11/24/09*).

The biggest slow slip event ever, by some measures, took place last year in Cascadia. It began in late August, when seismometers picked up tremors in a patch beneath southern Vancouver Island. Over time the patch spread; defying national borders, it moved south into Washington and then beyond Seattle. In mid-October it faded, but by then it had lasted 42 days and included a total of 618 hours of tremor — the longest such episode yet detected. Slow slip events have been detected in this area at least six times before, but never for this long, Vidale says.

The big question is what this means for seismic hazards in Cascadia. Some scientists think that slow slip may increase stress on particular patches of the subducting plate. Studies of an August 2009 slow slip event in Cascadia found that the tremor was concentrated in areas where the fault was slipping most rapidly. So slow slip may be transferring stress and loading up patches that become more prone to rupture in a great quake.

Theoretical work backs this up. Paul Segall, a geophysicist at Stanford, uses computers to simulate what happens when factors like fluid pressure, heat transport and friction change at subduction zones. Some of his results suggest that slow slip events could lead to runaway slipping that culminates in a megathrust quake. But so far there's no way to tell in advance when the slip is going to run away and when it's not, Segall and Andrew Bradley reported in September in *Geophysical Research Letters*.

One scientific challenge is understanding whether big quakes are actually triggered by slow slip. The 1999 Izmit quake in Turkey may have been; so too the March 2011 Tohoku quake in Japan.

A team led by Aitaro Kato of the University of Tokyo has found that two sets of slow slip happened very near the epicenter of the Tohoku quake just before it happened. The first slow slip event ran from middle to late February 2011. After the slow slip came a magnitude 7.3 earthquake; this would turn out to be the largest of the foreshocks before the great quake.

Next, a second episode of slow slip began and shifted westward toward the place where the seafloor eventually ruptured in the massive 9.0 quake. Scientists still don't understand what all this means: whether the slow slip directly triggered the huge quake, or whether it was all simply associated seismic activity but not a direct cause.

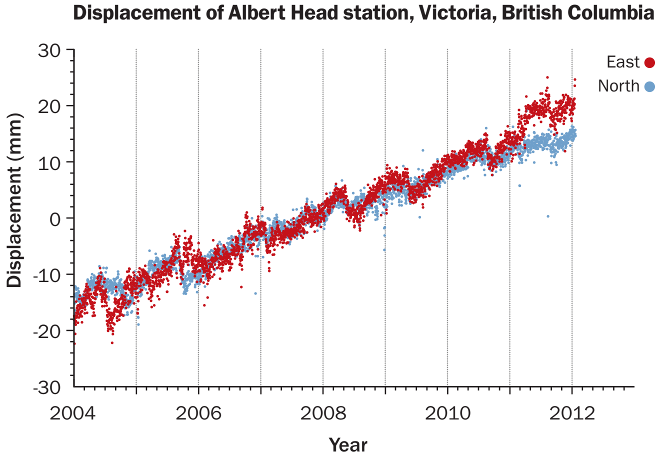
“We would love to understand how preparation for large earthquakes happens,” says Schwartz. “If slow slip is part of that preparation process, it's really important — but I don't think we can say that yet.”

Winning the lottery

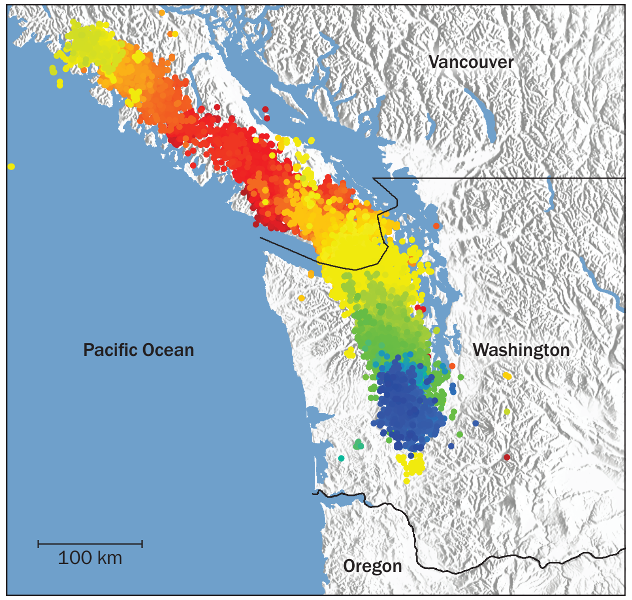
One approach is to look at places both before and after a big quake to see what role slow slip played, if any. That kind of measurement is tough in Japan, where much of the subducting plate is buried far offshore. It's a little easier in places like Costa Rica, where the Cocos crustal plate dives down quite close to the Nicoya peninsula. That means researchers can set up monitoring stations on land, much closer to the place where slow slip is happening — about 15 kilometers below the shoreline — than they can at other subduction zones. “In Costa Rica, we can really sense what's going on in the shallower part,” says Schwartz.

Repeat slip

Every 15 months or so the GPS station at Albert Head, British Columbia, makes a sharp westward movement, temporarily reversing its gradual eastward drift (red dots). These sudden reversals over the course of weeks to months signal slow slip deep underground. (Blue dots represent north-south motion.)



SOURCE: BEN WEBBER/ WIKIMEDIA COMMONS



Migrating quakes

Between August and October 2012, the Pacific Northwest experienced the longest slow slip event ever recorded. It started on Vancouver Island in Canada (red dots), and over several weeks migrated south into the Olympic Mountains and deeper into Washington state (blue dots).

SOURCE: A. WECH

Schwartz and her collaborators have studded the Nicoya peninsula with GPS stations and seismometers, and find that big slow slip events accompanied by tremor happen there about once every two years. The last was in summer 2011, so the next big slow slip event may begin this summer.

Catching that event would be interesting because Costa Rica had a magnitude 7.6 earthquake last September. There may have been some tremor in the weeks before that quake, Schwartz says. Her team originally set up their instruments because they knew the subduction zone there was getting ripe for a large quake, and they caught it right in the act. Her goal now is to keep monitoring the plate boundary to see how it heals after a great rupture. One major question, for instance, is whether future slow slip events will happen in the same place on the subducting plate as they did before the September earthquake.

Other scientists will be watching a little farther north along the same subduction zone, off the Mexican state of Oaxaca. There, in March 2012, a magnitude 7.4 quake hit after slow slip — but not tremor — increased in the months beforehand. The slow slip seemed to migrate over time, moving toward where the eventual main shock struck. “Large earthquakes don't occur during each slow slip event, but it does appear that chances of a large earthquake may increase during a slow slip event,” Stefany Sit of Miami University in Ohio reported at an American Geophysical Union meeting in December in San Francisco. In 2001–2002, seven months of slow slip in Mexico released the equivalent of a magnitude 7.5 quake — the biggest ever by that measure.

As seismologists gather more field data on how slow slip happens, other scientists are working to simulate the phenomenon using computers. One recent simulation seems to reproduce pretty well what's happening in places like Cascadia, Costa Rica and Oaxaca.

Harmony Colella of Miami University in Ohio crunches numbers to recreate what might happen for hundreds of thousands of slow slip events in real subduction zones. The model incorporates four important factors, including how much slip happens in each event and how long it lasts. Colella's results show that far more slip tends to happen toward the deepest part of the subducting plate, and far less at shallower depths.

Conceptually that finding sounds obvious, but “with the model we can say this is how it works, based on the physics,” says Colella. “We see a lot of really interesting things as well” — like the fact that the largest slow slip events are followed by a relatively quiet period. That may mean that it takes a while for stress to build up again to the level where it can trigger another slow slip event. “These things are so much more complex than traditional earthquakes,” Colella says.

For now, scientists are thinking about how to find out as much about slow slip as they can, as quickly as possible. One idea is to drill directly into a fault that experiences slow slip, to study properties like how fluid flows through slipping rock and how stress varies from place to place.

A group led by Laura Wallace of the University of Texas at Austin has its eye on the Japanese drill ship *Chikyu*, which can drill deeper into the seafloor than any other research vessel. The scientists are trying to drum up support to drill into the Hikurangi subduction zone off the coast of New Zealand, where slow slip happens every 18 to 24 months at depths of just five to 15 kilometers. “If we could do this it would be like winning the lottery,” Wallace said at the AGU meeting.

To some, scientists have already won the lottery merely by discovering slow slip. “Each passing year we're finding this phenomenon is more and more pervasive,” says Vidale. “It's not just a few places where we have our best networks — it's everywhere we know how to look.” ■

Explore more

- Pacific Northwest Seismic Network: www.pnsn.org
- Cascadia Hazards Institute: www.cascadiahazards.org