Slow slip: A new kind of earthquake

John E. Vidale and Heidi Houston

Sandwiched between the shallow region of sudden, infrequent earthquakes and the deeper home to continuous viscous motion lies an intermediate realm of intermittent sliding and rumbling. Discovered in recent years, it still harbors many secrets.

Earthquakes have been understood conceptually for about 100 years. Strain and stress build until the rock fractures, sliding along a fault surface, with the fracture propagation moderated by elastic waves. Although some details about friction and the ensemble behavior of evolving fault networks still have to be worked out, the earthquake cycle follows an unchallenged master paradigm with an uneven two-step of rapid sliding and slow reloading.[1] Or so we thought 10 years ago.

Earthquakes mark the relative motion between tectonic plates, large and small. Since the 1960s, the theory of plate tectonics has recognized that Earth's lithosphere is broken into pieces of various sizes, ranging from much of the vast area under the Pacific Ocean down to as small a rock mass as one is able to consider. The definition of lithosphere—the shallower volume of rock that behaves in a plastic manner compared with the underlying viscous flow of the so-called asthenosphere—sets the stage for the dichotomy, now recognized as overly simplistic, of shallow, earthquake-ridden plate boundaries atop a deeper region of silent and steady deformation.

The discovery of episodic tremor and slip (ETS), which is thought to be tectonic fault slip many orders of magnitude slower, and generally just a bit deeper, than regular earthquakes, has added a new dimension to that picture. It has injected new ideas about tectonic plate boundaries and even raised the possibility of greater predictability of large earthquakes.

"Slow slip" is a more accurate name than ETS. Still widely used, the term "ETS" refers to the initial observation of large episodes that radiate high-frequency energy (1–10 Hz, tremor), show low-frequency motion (movement over days to weeks, slip), and sometimes recur like clockwork (episodic). But closer observation revealed that ETS motion spans a continuum from frequencies of 20 Hz to periods of years and that the events are often aperiodic. Furthermore, numerous smaller and shorter episodes have been observed along with the large ones. What the new phenomena all have in common is that slip advances much more slowly than in regular earthquakes,[2,3] so we use the term "slow slip" throughout the rest of this article.

The tremor in slow-slip events has been termed "nonvolcanic" tremor to distinguish it from tremor signals generated by magmatic fluids in volcanoes. Several results suggest that as in regular earthquakes, the tremor is directly generated by shear slip on or near the plate interface. But high-pressure fluids (water and carbon dioxide) are widely thought to be present in slow-slip regions and may play a yet unknown role.

Many other aspects of slow slip remain unexplained. For example, it's not yet known why slow-slip earthquakes are orders of magnitude more prolonged than traditional earthquakes. In this article we examine their many observed differences and offer speculation about the underlying geology and physics.

Tectonic setting

Slow slip has been seen most clearly in subduction zones, where pairs of tectonic plates converge. (For a brief introduction to plate tectonics, see the box on page 39.) To be more specific, we'll consider the part of the Cascadia subduction zone near our hometown of Seattle, Washington. Slow slip in Cascadia is similar to that seen in other subduction zones in Japan, Mexico, Alaska, and Costa Rica. We could have told this story with details from several regions—observations in Japan are now impressively detailed, for example—but we'll cite the studies with which we are most familiar. The subduction zone's geometry is shown in figure 1.

John Vidale and **Heidi Houston** are professors of Earth and space sciences at the University of Washington in Seattle.

Slow slip appears at intermediate depths, roughly 35–55 km beneath the Puget Sound, between the shallow regular earthquakes and deeper, more continuous motion. Down to 35 km, the plate boundary generally obeys the traditional expectations, locking for decades to millennia before sliding rapidly. Slip over a 1000-km length of fault can reach tens of meters in the greatest earthquakes. Plenty of smaller earthquakes also pepper the interface and the surrounding deforming volume. At depths below 55 km, motion is still thought to be smooth and constant.

Tremor, probably accompanied by slow slip, has also been observed at shallower depths on so-called crustal transform fault zones such as the San Andreas Fault in California, but most slow slip detected so far occurs on the subduction interface.

The motion in slow-slip episodes seems to fall mainly or entirely on the primary fault plane in the region. The relative motion on the fault is in the direction of expected plate motions based on regular earthquakes and geodetic measurements in the region. Some controversy remains whether significant off-fault activity is also present.

Seconds to weeks and beyond

Slow slip in Cascadia is some of the loudest, most periodic in recurrence, and best studied in the world. The average rate of motion along the plate boundary is 4 cm/yr, but as GPS measurements of surface deformation revealed, rather than sliding steadily at that rate, the plate boundary from 35 to 55 km is stuck for 11–15 months, then moves relatively quickly for several weeks.[4] The cycle is remarkably close to periodic: Twenty or so documented repetitions show only 10% variance in recurrence interval.[5]

In the early 2000s, at the same time that slow slip was coming into view in Cascadia, an even more surprising phenomenon was noticed in Japan. Sections of the plate interface beneath the locked boundary in several subduction zones were radiating intermittent prolonged bursts of tremor.[6] Tremor is high-frequency vibration that continues for minutes to days, fluctuating in amplitude, without the abrupt onset characteristic of normal earthquakes. It's most clearly observed in the frequency range 2–10 Hz, but observing it at all requires a dense, high-quality network of seismometers. Japan had recently installed the Hi-net network, comprising hundreds of seismometers emplaced in boreholes 100–2000 m deep. With Hi-net's station density and quiet surroundings, scientists could see the tremor signals previously obscured by such Earth noise as the pounding of ocean waves and wind in the trees. From the common amplitude modulations seen across many stations, it was evident that the tremor was generated deep beneath Earth's surface.

Guided by the GPS observations from Cascadia, scientists in Japan quickly noticed slow deformation in the same time and place as their tremor. Likewise, researchers in North America found tremor accompanying their slow deformation. It became clear that tremor and slip often occur together on the same patch of fault. Figure 2a shows the particularly well-resolved area of tremor for Cascadian events, and figure 2b shows the slip that was observed in the same place at the same time.

When the instrumentation and noise are most favorable, motion on a slow-slip patch can be seen with periods of 0.03 s (for 30-Hz tremor) to weeks. Tremor detected on seismometers and slip so slow it is only visible with geodetic techniques such as GPS turn out to represent the end members of a single slow-slip process. Tidal records, GPS, strainmeters, tiltmeters, and seismometers of various types, because of their individual sensor designs and noise peculiarities, each glimpse slow slip only in a limited passband. The overall shape and variability of the slow-slip spectra remain subjects of study.

Sometimes only tremor or slow slip is detectable, and sometimes both are detectable simultaneously in overlapping but not identical areas. Sometimes tremor appears in scattered patches that appear to be part of a more steadily moving underlying disturbance. Part of the difference is that tremor can be detected with much greater spatial and temporal resolution than slow slip can, but there also appear to be differences in the relative amounts of the two happening between various places on the fault. Recent observations demonstrate that slow slip also sometimes occurs at depths similar to those of regular earthquakes—and even in the region of subduction zones between regular earthquakes and the surface—and that a single slow-slip event can span a wide depth range.

More unique features

To recap the story so far, slow-slip episodes are news because they strike the deeper portion of faults previously thought to move boringly steadily, they take a long time to complete, and they can recur almost like clockwork. Traditional earthquakes share none of those characteristics.

Slow-slip events differ from regular earthquakes in several other ways. The stress released is orders of magnitude smaller, and small changes in

Plate tectonics, faults, and subduction zones

The upper 100 km or so of Earth's crust and mantle are broken into tectonic plates. Within each plate, the rock is relatively strong and does not deform much. The relative motion of the two rubbing plates, averaged over thousands of years, ranges from a few to 20 cm/yr.

Boundaries between plates are divided into three types, according to the plates' relative motion. Subduction zones are the geological boundaries at which tectonic plates converge, with one plate overriding and the other diving deep into Earth's mantle. At mid-ocean ridges, the plates move apart, with new rock upwelling in between. And at transform boundaries, plates shift laterally relative to each other.

Subduction zones are of great scientific and societal interest because they harbor a host of valuable landscapes and geophysical threats. The downwelling of cold crust and mantle creates large volumes of brittle rock that pave the way for the largest earthquakes. Big earthquakes near coastlines spawn tsunamis. The dragging of water-saturated crust into the fiery depths leads to magma upwelling through volcanic edifices. The high mountains near many subduction zones are susceptible to landslides.

The majority of global subduction occurs around the aptly named Pacific Ring of Fire.

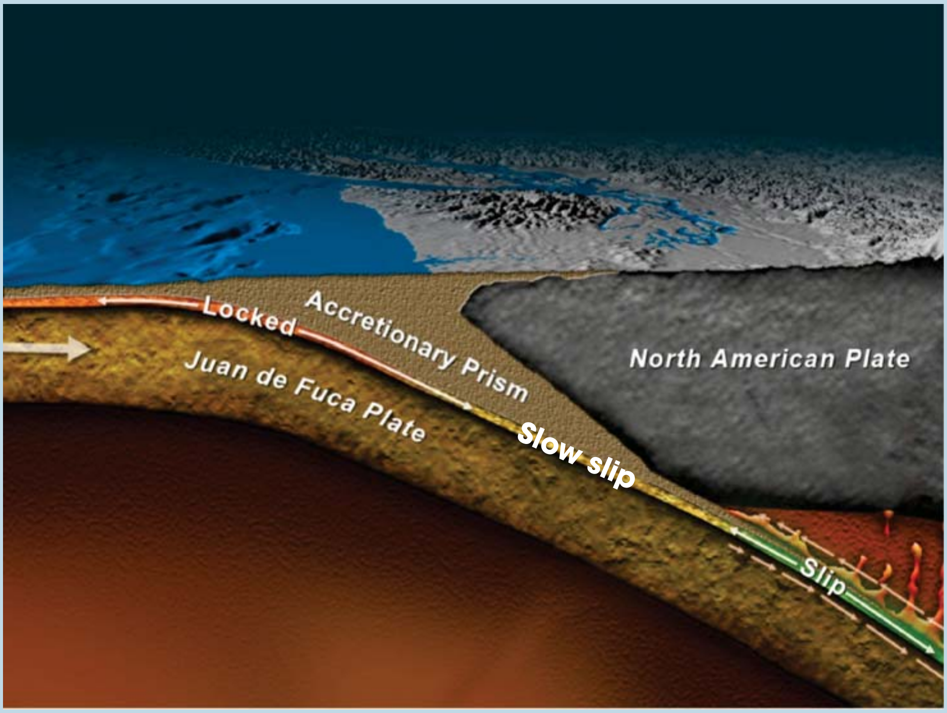

Figure 1. Slow slip appears most prominently in subduction zones, on the plate boundary between the shallow, locked section and the deeper, freely slipping section. The illustration shows an east–west cross section beneath Seattle, Washington, and Vancouver, British Columbia, Canada, in the Cascadia subduction zone. The Juan de Fuca Plate is pushed under the North American Plate as the two plates move together. Marine sediments scraped off the subducting plate build up in the accretionary prism.

stress become important. The speed and direction of slow-slip propagation follows its own distinct pattern, as does the relationship between event duration and total fault motion. Clearly, different physics is involved.

The small stress release for slow-slip episodes is apparent in several ways. Most directly, the motion is small and spreads out over a large area. For example, each of the four slow-slip events summed to produce figure 2b involved only 1–2 cm of slip, but that motion was enough to make the fault lock up again. A normal earthquake with a 100-km-long rupture would show meters of slip, hundreds of times the drop in shear stress.

Slow slip is so sensitive to small stress changes that it can be triggered by tidal stresses and by surface waves from distant earthquakes.[2] Slow-slip tremor amplitude ebbs and wanes with tidal stressing, whereas normal earthquakes show almost no correlation with the tides. Strong earthquake surface waves have been observed to incite bursts of tremor in phase with the arrival of stresses that would encourage slip on the tremoring faults. Figure 3 shows an example in the case of some extraordinarily strong surface waves. Regular earthquakes are sometimes also triggered by such stressing, but they are generally delayed from the stressing pulses.

An intriguing feature is the variety of speeds and directions in which tremor migrates over the course of a slow-slip episode. Major episodes, such as the one shown in figure 4, migrate along the plate boundary at about 10 km/day. The progress is fitful hour by hour, but fairly steady day by day. That progress is punctuated, however, by periods of rapid reversal, during which the activity jets backwards at about 200 km/day.[7] On the time scale of minutes, tremor tends to streak along a nearly perpendicular path, in the direction of the plates' relative motion, at about 50 km/hour.[8] In contrast, the rupture in a regular earthquake generally propagates at about 2–3 km/second, the speed at which stresses travel through the rock.

Like regular earthquakes, slow-slip events can be small or large. They can last anywhere from a fraction of a second for slow microearthquakes to several weeks for full-blown ETS events. And as with regular earthquakes, slow-slip episodes are more likely to be small than large, even sharing the Gutenberg–Richter log-linear distribution, developed for regular earthquakes, of number of events as a function of magnitude. The relationship between duration and moment, however, is dramatically different for the two types of events. (Seismic moment is the product of the area of faulting and the amount of slip.) Slow-slip activity radiates energy and accumulates slip at a fairly steady rate, both during individual events and between events of dramatically different duration. As a result, the duration is directly proportional to the moment. In contrast, for regular earthquakes the affected fault length is proportional to the event duration, the ruptured area is proportional to the square of fault length, and the amount of slip is proportional to length, so the duration is proportional to the cube root of the moment.[9] Slow-slip events and regular earthquakes therefore form two distinct continua of events.

Figuring out the physics

Conceptually, the simplest view of the physics of a slow-slip event is that the overriding and downward-plunging plates rub against each other along a well-defined interface, with their motion gov-

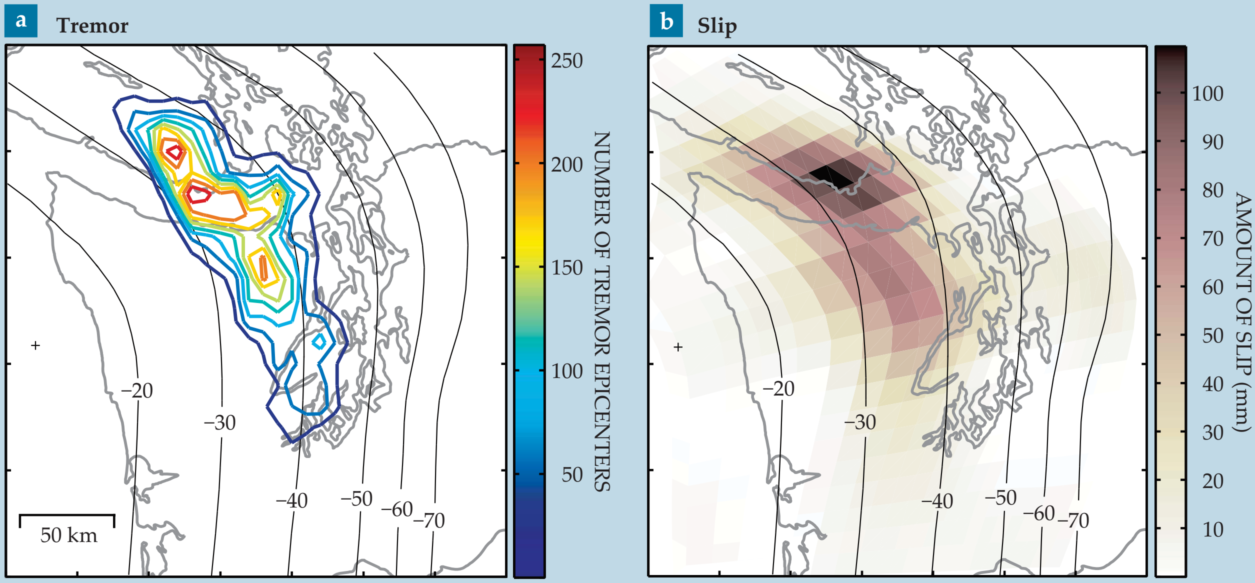

Figure 2. Tremor and slip are usually observed on the same patch of fault during a slow-slip episode. **(a)** Tremor, observed by seismometers and quantified as the number of tremor epicenters per 0.1° × 0.1° bin, summed over four slow-slip episodes in the Cascadia subduction zone from 2004 to 2008. **(b)** Total slip, measured by GPS, for the same four episodes. The contours in both panels show the depth of the plate interface. (Adapted from ref. 15.)

erned by frictional forces between their brittle surfaces. However, the physical and chemical environment at the subduction zone interface is not known in detail and may differ between subduction zones. The "interface" may actually broaden with the higher pressures and temperatures at greater depths, and it may behave ductilely rather than brittlely, in a so-called subduction channel. The minerals present undergo several poorly understood phase transitions at slow-slip depths. Fluids (H_2O or CO_2) are probably present and may be important. Any of these conditions could greatly complicate the physics of slow slip, so much remains to be understood.

Rate-and-state friction laws are empirical laws designed to account for the full range of behavior observed during regular earthquakes. They describe how friction varies with material properties, slip speed, and the history of the state of the contact surface. To describe slow slip as well, the friction laws would need to include mechanisms to keep the slip speed in check so that it doesn't accelerate to that of a regular earthquake. The effective normal stress must be very low, consistent with the presence of pressurized fluids, and the stress release involved must be several orders of magnitude smaller than for regular earthquakes. It appears that suitably designed rate-and-state friction laws can describe slow-slip pulses, such as those in Cascadia, and can reproduce the faster propagation of tremor on shorter time scales.[10] But what is still lacking is a clear connection between the empirical laws and the actual physics and chemistry—for example, the phase transitions in the source region, which can't be easily studied due to rock heterogeneity and the inaccessible location.

Healing due to mineral precipitation on time scales of months could moderate the periodic breaking in slow slip.[10] Alternatively, accelerating slip may lead to a competition between two opposing effects: Heating of the rock reduces friction, and dilatancy—expansion of fluid-filled pores as the rock is sheared—increases it.[11] In that model, fluid-mediated changes in friction control whether slip is slow or fast.

Further evidence for the key role of fluids is the diffusion-like migration of slow-slip activity. In the propagation of some slow-slip events, as determined by tremor measurements, the distance traveled is

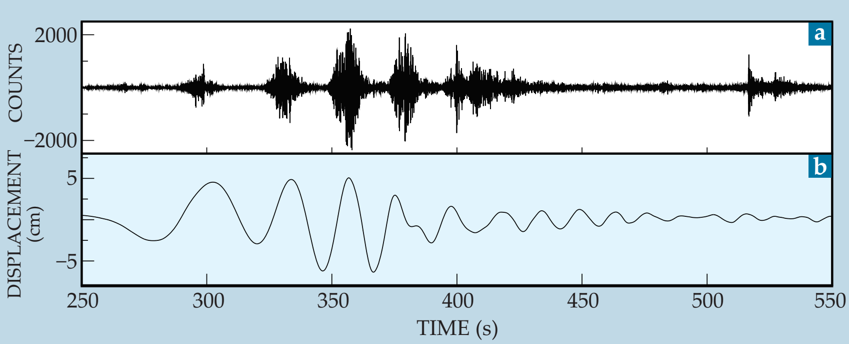

Figure 3. Seismic waves from distant earthquakes can trigger slow slip. **(a)** High-frequency tremor under Vancouver Island in southwestern Canada in the wake of the 2002 Denali earthquake in Alaska. **(b)** Low-frequency seismic record showing the surface waves that triggered the tremor. (Adapted from ref. 16.)

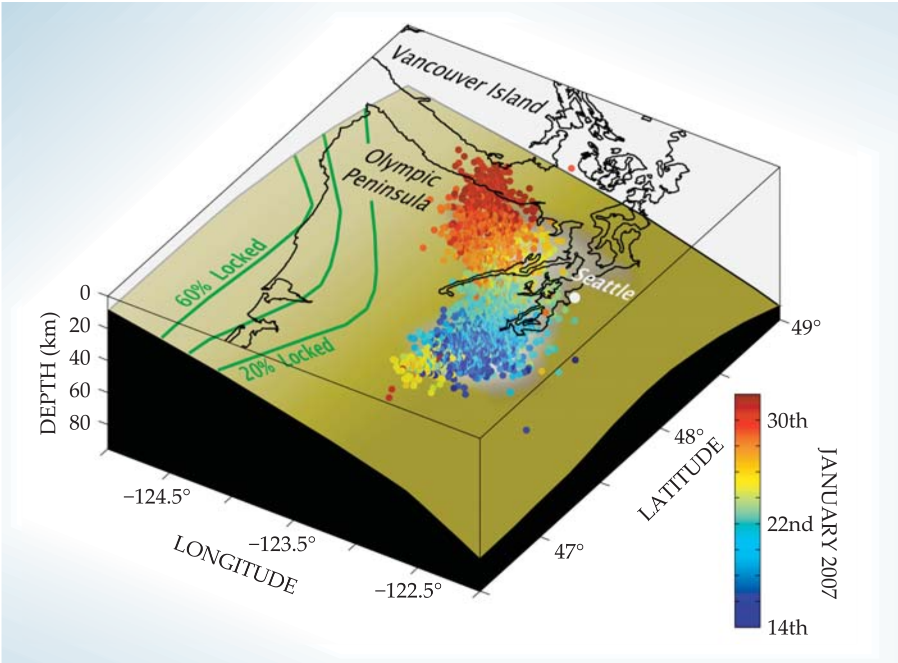

Figure 4. Evolution of a single slow-slip episode in the Cascadia subduction zone. The episode started with the deep blue dots near the southern end, spread bilaterally for a few days, and continued to the north for the rest of the 2 weeks shown. (Courtesy of Aaron Wech.)

proportional to the square root of time. It appears that something, perhaps fluid or shear stress, may diffuse during slow slip.[12]

An anomalously high Poisson's ratio in the underlying subducting crust and high conductivity, consistent with ample fluid content, are observed in several slow-slip regions. That the expected depths of dewatering reactions in subducting rocks coincide with zones of slow slip—and the tendency of slow slip to appear above younger slabs, which are most likely to still be losing water—strengthens this argument.

Open questions

Not every plate boundary that's been monitored with good instrumentation shows signs of slow slip, and it's not known why. Looking for patterns among observations may help to reveal the geological features that enable slow slip. But it's not clear whether the physical properties below, above, or at the interface are most important.

Several lines of evidence, as described above, suggest that fluids play a role in slow slip. Fluids may also be important in weakening rock to allow regular earthquakes, and they could be even more critical to the creation of the weaker conditions postulated for slow slip. A key result is that tremor streaks and lines of concentrated tremor tend to align with the direction of relative fault motion. That coincidence suggests that smearing of favorable geological units or corrugations in the plate interface contributes to the pattern of slow-slip behavior.

Can slow slip be helpful in assessing the threat of great earthquakes? It's possible, and that possibility is one of the motivations for the current studies. But no one has yet systematically monitored slow-slip-prone zones before and after great earthquakes, so the postulated patterns remain unconfirmed.

If slow-slip zones are releasing most of their stress, as many researchers assume, the locations of slow slip may mark the edges of an area of fault that is stressed enough to break. But we don't yet know whether tremor locations, long-term geodetic measurements, or other measurements best outline the edge of the dangerously locked zone.

A simple pattern would be if great earthquakes are most likely to occur when nearby slow slip is active. Slow slip on a given patch is generally active less than 10% of the time, so a correlation could narrow the time of greatest earthquake threat. But in Cascadia, for example, the zone that could break in a great earthquake is adjacent to several slow-slip patches that are all active at different times. So establishing a correlation between slow slip and nearby great earthquakes would require long-term observation over at least decades.

More powerful but more speculative possibilities involve the idea that slow-slip patterns may evolve during the cycle of stress recharge before a nearby great earthquake. Some numerical models indicate that great earthquakes might nucleate in slow-slip zones as normal slow slip that runs away over the course of minutes to months. An example is shown in figure 5. Or slow-slip episodes leading up to a great earthquake might cover larger or smaller areas, recur more frequently, or have more vigor with a recognizably accelerating pattern.

Most unconstrained, and perhaps most unlikely, is the possibility that we can directly observe geophysical changes revealing lubrication or stress building between events, and they can tell us when the next magnitude 9 event is imminent.

Two recent observations are tantalizing. Close observation of the time before the Izmit earthquake, which killed approximately 20 000 people in Turkey in 1999, showed an hour of accelerating seismic activity beneath where the fault ruptured,[13] a finding consistent with triggering by a slow-slip episode. Similarly, in the month and especially two days just before the Tohoku-oki earthquake, which killed about 20 000 people in Japan in 2011 (see the article by Thorne Lay and Hiroo Kanamori in PHYSICS TODAY, December 2011, page 33), slow slip and other seismic activity were observed near the main-shock hypocenter.[14] Just how often such slow-slip precursors appear, and how often they are followed by destructive earthquakes, remains to be seen. But those results may indicate progress in the supremely frustrating challenge of earthquake prediction.

The discovery of slow slip has inspired geophysicists and remains the focus of intense attention. Dense arrays of seismometers are being planted in several places, which we hope will resolve many of the questions framed above. As Yogi Berra said, "You can observe a lot by watching".

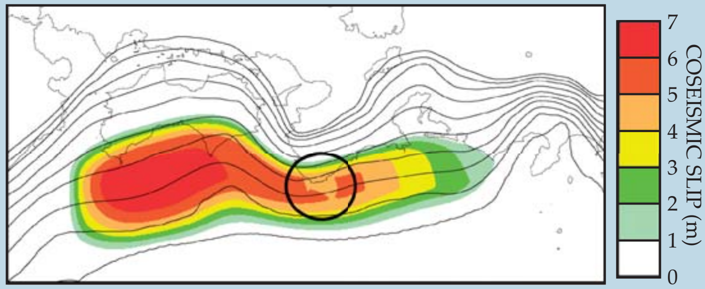

Figure 5. Numerical simulation of possible slow-slip nucleation in Japan's Tokai region, southwest of Tokyo. Slow slip in the area marked by the circle grows into meters of coseismic slip—that is, a large earthquake. The cabled 25-element DONET array is now installed in the region to monitor deformation in real time.[17] (Figure adapted from ref. 18.)

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