New earthquake fault models show that 'stable' zones may contribute to the generation of massive earthquakes

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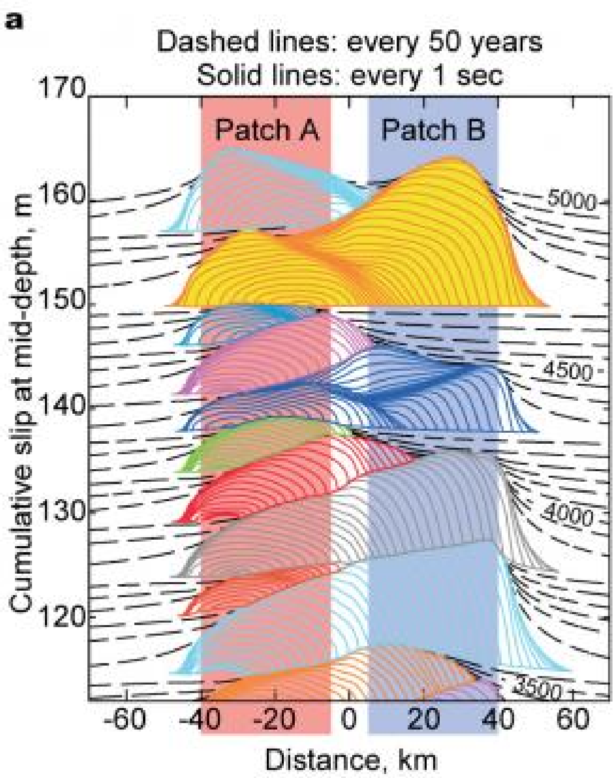

Numerical simulations illustrate that fault segments can move slowly and stably over long periods of time and later host large earthquakes. Dashed lines represent slow slip every 50 years along a cross-section of the fault, with the numbers indicating the simulated time in years. Earthquakes are shown by solid lines plotted every second. The area marked patch B can both slip slowly (e.g., dashed lines above the 4,500 year mark) and participate in large earthquakes (e.g., yellow event). Credit: Nadia Lapusta/Caltech

In an earthquake, ground motion is the result of waves emitted when the two sides of a fault move—or slip—rapidly past each other, with an average relative speed of about three feet per second. Not all fault segments move so quickly, however—some slip slowly, through a process called creep, and are considered to be "stable," or not capable of hosting rapid earthquake-producing slip. One common hypothesis suggests that such creeping fault behavior is persistent over time, with currently stable segments acting as barriers to fast-slipping, shake-producing earthquake ruptures. But a new study by researchers at the California Institute of Technology (Caltech) and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) shows that this might not be true.

"What we have found, based on laboratory data about rock behavior, is that such supposedly stable segments can behave differently when an earthquake rupture penetrates into them. Instead of arresting the rupture as expected, they can actually join in and hence make earthquakes much larger than anticipated," says Nadia Lapusta, professor of mechanical engineering and geophysics at Caltech and coauthor of the study, published January 9 in the journal *Nature*.

She and her coauthor, Hiroyuki Noda, a scientist at JAMSTEC and previously a postdoctoral scholar at Caltech, hypothesize that this is what occurred in the 2011 magnitude 9.0 Tohoku-Oki earthquake, which was unexpectedly large.

Fault slip, whether fast or slow, results from the interaction between the stresses acting on the fault and friction, or the fault's resistance to slip. Both the local stress and the resistance to slip depend on a number of factors such as the behavior of fluids permeating the rocks in the earth's crust. So, the research team formulated fault models that incorporate laboratory-based knowledge of complex friction laws and fluid behavior, and developed computational procedures that allow the scientists to numerically simulate how those model faults will behave under stress.

"The uniqueness of our approach is that we aim to reproduce the entire range of observed fault behaviors—earthquake nucleation, dynamic rupture, postseismic slip, interseismic deformation, patterns of large earthquakes—within the same physical model; other approaches typically focus only on some of these phenomena," says Lapusta.

In addition to reproducing a range of behaviors in one model, the team also assigned realistic fault properties to the model faults, based on previous laboratory experiments on rock materials from an actual fault zone—the site of the well-studied 1999 magnitude 7.6 Chi-Chi earthquake in Taiwan.

"In that experimental work, rock materials from boreholes cutting through two different parts of the fault were studied, and their properties were found to be conceptually different," says Lapusta. "One of them had so-called velocity-weakening friction properties, characteristic of earthquake-producing fault segments, and the other one had velocity-strengthening friction, the kind that tends to produce stable creeping behavior under tectonic loading. However, these 'stable' samples were found to be much more susceptible to dynamic weakening during rapid earthquake-type motions, due to shear heating."

Lapusta and Noda used their modeling techniques to explore the consequences of having two fault segments with such lab-determined fault-property combinations. They found that the ostensibly stable area would indeed occasionally creep, and often stop seismic events, but not always. From time to time, dynamic rupture would penetrate that area in just the right way to activate dynamic weakening, resulting in massive slip. They believe that this is what happened in the Chi-Chi earthquake; indeed, the quake's largest slip occurred in what was believed to be the "stable" zone.

"We find that the model qualitatively reproduces the behavior of the 2011 magnitude 9.0 Tohoku-Oki earthquake as well, with the largest slip occurring in a place that may have been creeping before the event," says Lapusta. "All of this suggests that the underlying physical model, although based on lab measurements from a different fault, may be qualitatively valid for the area of the great Tohoku-Oki earthquake, giving us a glimpse into the mechanics and physics of that extraordinary event."

If creeping segments can participate in large earthquakes, it would mean that much larger events than seismologists currently anticipate in many areas of the world are possible. That means, Lapusta says, that the seismic hazard in those areas may need to be reevaluated.

For example, a creeping segment separates the southern and northern parts of California's San Andreas Fault. Seismic hazard assessments assume that this segment would stop an earthquake from propagating from one region to the other, limiting the scope of a San Andreas quake. However, the team's findings imply that a much larger event may be possible than is now anticipated—one that might involve both the Los Angeles and San Francisco metropolitan areas.

"Lapusta and Noda's realistic earthquake fault models are critical to our understanding of earthquakes—knowledge that is essential to reducing the potential catastrophic consequences of seismic hazards," says Ares Rosakis, chair of Caltech's division of engineering and applied science. "This work beautifully illustrates the way that fundamental, interdisciplinary research in the mechanics of seismology at Caltech is having a positive impact on society."

Now that they've been proven to qualitatively reproduce the behavior of the Tohoku-Oki quake, the models may be useful for exploring future earthquake scenarios in a given region, "including extreme events," says

Lapusta. Such realistic fault models, she adds, may also be used to study how earthquakes may be affected by additional factors such as man-made disturbances resulting from geothermal energy harvesting and CO_2 sequestration. "We plan to further develop the modeling to incorporate realistic fault geometries of specific well-instrumented regions, like Southern California and Japan, to better understand their seismic hazard."

"Creeping fault segments can turn from stable to destructive due to dynamic weakening" appears in the January 9 issue of the journal *Nature*. Funding for this research was provided by the National Science Foundation; the Southern California Earthquake Center; the Gordon and Betty Moore Foundation; and the Ministry of Education, Culture, Sports, Science and Technology in Japan.

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