How earthquake swarms arise

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Earthquakes can be abrupt bursts of home-crumbling, ground-buckling energy when slices of the planet's crust long held in place by friction suddenly slip and lurch.

"We typically think of the plates on either side of a fault moving, deforming, building up stresses and then: Boom, an earthquake happens," said Stanford University geophysicist Eric Dunham.

But deeper down, these blocks of rock can slide steadily past one another, creeping along cracks in Earth's crust at about the rate that your fingernails grow.

A boundary exists between the lower, creeping part of the fault, and the upper portion that may stand locked for centuries at a stretch. For decades, scientists have puzzled over what controls this boundary, its movements and its relationship with big earthquakes. Chief among the unknowns is how fluid and pressure migrate along faults, and how that causes faults to slip.

A new physics-based fault simulator developed by Dunham and colleagues provides some answers. The model shows how fluids ascending by fits and starts gradually weaken the fault. In the decades leading up to big earthquakes, they seem to propel the boundary, or locking depth, a mile or two upward.

Migrating swarms

The research, published Sept. 24 in *Nature Communications*, also suggests that as pulses of high-pressure fluids draw closer to the surface, they can trigger earthquake swarms—strings of quakes clustered in a local area, usually over a week or so. Shaking from these seismic swarms is often too subtle for people to notice, but not always: A swarm near the southern end of the San Andreas Fault in California in August 2020, for example, produced a magnitude-4.6 quake strong enough to rattle surrounding cities.

Each of the earthquakes in a swarm has its own aftershock sequence, as opposed to one large mainshock followed by many aftershocks. "An earthquake swarm often involves migration of these events along a fault in some direction, horizontally or vertically," explained Dunham, senior author of the paper and an associate professor of geophysics at

Stanford's School of Earth, Energy & Environmental Sciences (Stanford Earth).

The simulator maps out how this migration works. Whereas much of the advanced earthquake modeling of the last 20 years has focused on the role of friction in unlocking faults, the new work accounts for interactions between fluid and pressure in the fault zone using a simplified, two-dimensional model of a fault that cuts vertically through Earth's entire crust, similar to the San Andreas Fault in California.

"Through computational modeling, we were able to tease out some of the root causes for fault behavior," said lead author Weiqiang Zhu, a graduate student in geophysics at Stanford. "We found the ebb and flow of pressure around a fault may play an even bigger role than friction in dictating its strength."

Underground valves

Faults in Earth's crust are always saturated with fluids—mostly water, but water in a state that blurs distinctions between liquid and gas. Some of these fluids originate in Earth's belly and migrate upwards; some come from above when rainfall seeps in or energy developers inject fluids as part of oil, gas or geothermal projects. "Increases in the pressure of that fluid can push out on the walls of the fault, and make it easier for the fault to slide," Dunham said. "Or, if the pressure decreases, that creates a suction that pulls the walls together and inhibits sliding."

For decades, studies of rocks unearthed from fault zones have revealed telltale cracks, mineral-filled veins and other signs that pressure can fluctuate wildly during and between big quakes, leading geologists to theorize that water and other fluids play an important role in triggering earthquakes and influencing when the biggest temblors strike. "The rocks themselves are telling us this is an important process," Dunham said.

More recently, scientists have documented that fluid injection related to energy operations can lead to earthquake swarms. Seismologists have linked oil and gas wastewater disposal wells, for example, to a dramatic increase in earthquakes in parts of Oklahoma starting around 2009. And they've found that earthquake swarms migrate along faults faster or slower in different environments, whether it's underneath a volcano, around a geothermal operation or within oil and gas reservoirs, possibly because of wide variation in fluid production rates, Dunham explained. But modeling had yet to untangle the web of physical mechanisms behind the observed patterns.

Dunham and Zhu's work builds on a concept of faults as valves, which geologists first put forth in the 1990s. "The idea is that fluids ascend along faults intermittently, even if those fluids are being released or injected at a steady, constant rate," Dunham explained. In the decades to thousands of years between large earthquakes, mineral deposition and other chemical processes seal the fault zone.

With the fault valve closed, fluid accumulates and pressure builds, weakening the fault and forcing it to slip. Sometimes this movement is too slight to generate ground shaking, but it's enough to fracture the rock and open the valve, allowing fluids to resume their ascent.

The new modeling shows for the first time that as these pulses travel upward along the fault, they can create earthquake swarms. "The concept of a fault valve, and intermittent release of fluids, is an old idea," Dunham said. "But the occurrence of earthquake swarms in our simulations of fault valving was completely unexpected."

Predictions, and their limits

The model makes quantitative predictions about how quickly a pulse of high-pressure fluids migrates along the fault, opens up pores, causes the fault to slip and triggers certain phenomena: changes in the locking depth, in some cases, and imperceptibly slow fault movements or clusters of small earthquakes in others. Those predictions can then be tested against the actual seismicity along a fault—in other words, when and where small or slow-motion earthquakes end up occurring.

For instance, one set of simulations, in which the fault was set to seal up and halt fluid migration within three or four months, predicted a little more than an inch of slip along the fault right around the locking depth over the course of a year, with the cycle repeating every few years. This particular simulation closely matches patterns of so-called slow-slip events observed in New Zealand and Japan—a sign that the underlying processes and mathematical relationships built into the algorithm are on target. Meanwhile, simulations with sealing dragged out over years caused the locking depth to rise as pressure pulses climbed upward.

Changes in the locking depth can be estimated from GPS measurements of the deformation of Earth's surface. Yet the technology is not an earthquake predictor, Dunham said. That would require more complete knowledge of the processes that influence fault slip, as well as information about the particular fault's geometry, stress, rock composition and fluid pressure, he explained, "at a level of detail that is simply impossible, given that most of the action is happening many miles underground."

Rather, the model offers a way to understand processes: how changes in fluid pressure cause faults to slip; how sliding and slip of a fault breaks up the rock and makes it more permeable; and how that increased porosity allows fluids to flow more easily.

In the future, this understanding could help to inform assessments of risk related to injecting fluids into the Earth. According to Dunham, "The lessons that we learn about how fluid flow couples with frictional sliding are applicable to naturally occurring earthquakes as well as induced earthquakes that are happening in oil and gas reservoirs."

More information: Weiqiang Zhu et al, Fault valving and pore pressure evolution in simulations of earthquake sequences and aseismic slip, *Nature Communications* (2020). DOI: 10.1038/s41467-020-18598-z

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