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QnAs with Thorne Lay

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In April 2016, a magnitude 7.8 earthquake struck Ecuador near the coastal town of Muisne. The tremor caused widespread destruction, set off tsunami warnings, killed nearly 700 people, and injured thousands more. This event followed a global surge of 19 great earthquakes from 2004 to 2015 that occurred at nearly three times the annual rate of the previous century. These and other earthquakes provided University of California Santa Cruz professor of earth and planetary sciences Thorne Lay ample data to investigate how devastating earthquakes develop. Lay began studying this phenomenon in graduate school. Aided by advances in observational and computational capabilities, his work is aimed at identifying areas at high risk of great earthquakes, besides probing other seismic phenomena. Lay was elected to the National Academy of Sciences in 2014. PNAS recently spoke to him about his current research.

PNAS: Your Inaugural Article (IA) examines earthquakes that occurred in South America over the past two decades (1). Why did you choose this region?

Lay: The Inaugural Article is a summary synthesis that applies updated versions of two major conceptual models in seismology—seismic gap and asperity models—to interpret data from recent very large earthquakes and compare them to historical ruptures along the west coast of South America. We use this analysis to identify where great earthquakes are most likely to happen next in the region.

Western South America has been an intensive focus of the international earthquake research community for many years. Here, a subduction zone extends for about 6,500 km where the Nazca tectonic plate, overlain by the Pacific Ocean, thrusts under the continental margin of the South American plate. This subduction zone produced the Andean mountains and has hosted six very large megathrust earthquakes during the past 21 y as well as many others in the last 500 y, including the largest recorded event, the 1960 M_W 9.5 Chile earthquake.

The National Science Foundation and the US Geological Survey are developing initiatives to study earthquakes in subduction zones to help anticipate when great ruptures may strike the United States in Alaska or in the heavily populated Cascades region of Oregon and Washington. South America has similar environments with more numerous events to study. Sensitive seismic and geodetic instrumentation can be deployed both on- and off-shore along the South American subduction zone to accumulate data late in the earthquake cycle. Previous efforts have captured several recent great earthquakes there.

PNAS: How was your recent research informed by developments in seismology?

Thorne Lay. Image credit: UCSC PBSCI Faculty Photos.

Lay: This work relies on theoretical frameworks in seismology that have been developing since the observational validation of plate tectonics in the 1960s. Plate tectonics reconciled the distribution of earthquakes and volcanoes around the world by determining that such activity primarily occurs near plate margins, such as the South American subduction zone. Long-term relative plate motions produce cycles of strain accumulation around plate boundary faults. Rock deforms until it overcomes frictional resistance, producing abrupt slip in an earthquake and reducing strain in the rock. However, due to the complexity of the fault system, earthquakes do not occur like clockwork.

Two key ideas introduced in the 1970s and 1980s address this behavior. The first, seismic gap theory, demonstrated that once a large earthquake occurred, it would take between

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30 and more than 100 y for plate tectonic motions to rebuild comparable strain on the same fault segment. This is why we do not observe large earthquakes rerupturing the same place without decades passing. Seismic gap theory does not precisely predict when the next event will happen, but it provides guidance on plate boundary segments where strain has built up since prior large events.

The second idea, the asperity model, is one that, as a student, I participated in developing by analyzing seismic waves produced by very large earthquakes. Seismic waves do not radiate uniformly from the rupture because slip varies over the fault surface. The distribution of fault slip is patchy, with some areas slipping a lot and releasing strong seismic waves from the elastic strain reduction, while the surrounding regions have little slip and weak seismic waves. There can be multiple large-slip patches or asperities within a single event that give rise to very complex seismic waves. We analyze seismic and geodetic recordings to determine space–time distribution of slip on the fault.

PNAS: Do the two theories complement each other?

Lay: Asperity theory accounts for what had been a limitation of seismic gap theory—that not every large earthquake ruptures exactly the same fault segment as a previous earthquake. Individual segments can fail, or they can fail together in a cascade, yielding a really huge earthquake. Asperities provide an understanding of how local segmentation occurs. Dynamic interactions between asperities indicate how cascade triggering occurs.

Asperities may be the result of geometric complexity of the fault surface, rock, and sediment variations, and/or the presence of pressurized fluids. Frictional properties are depth dependent, with the shallower plate boundary generally dominated by aseismic sliding, the mid-plate boundary dominated by patchy earthquake-producing asperities, and deeper depths having increasingly ductile deformation. As we can now routinely determine slip heterogeneity for individual earthquakes, our accumulated observations provide a context for examining the history of large earthquakes along the South American subduction zone.

PNAS: What did you uncover about these South American earthquakes?

Lay: The 2016 Ecuador earthquake is one of the six recent events considered in the Inaugural Article. Going back 110 y, in 1906, Ecuador experienced an even larger 8.6 M_W earthquake that ruptured along the entire coast. Over the next century, the boundary failed in three different smaller events—1942, 1958, and 1979—that spanned the same length of coastline as the 1906 earthquake. But, they did not trigger together as in 1906. By comparing seismic records, the 2016 earthquake is seen to basically be a repeat of the 1942 rupture.

PNAS: What did you determine about future earthquakes in South America?

Lay: Seismic records, geodetic data, and tsunami modeling of recent events allowed us to identify four areas along the South American subduction zone where very large-magnitude earthquakes can be expected. For example, the region in Ecuador that ruptured in 1958 has been building up almost as long as the adjacent region in 1942 that ruptured in 2016. GPS observations show that strain is accumulating. A future big earthquake will inevitably occur, and there is always the possibility that it will cascade and rupture the 1979 zone as well.

Other areas of concern include southeasternmost Peru, northern Chile, and north central Chile along the Atacama Desert where the last very large earthquake happened 100 y ago. We cannot specify exactly when future earthquakes will occur, but geodesy shows that the faults are locked because the coastline is being dragged toward the land. These are regions late in the seismic cycle.

PNAS: How have advancements in instrumentation changed seismology during your career?

Lay: It's been an amazing transition in the past 40 y. When I first started working on earthquakes, the seismograms were analog signals on paper and had to be manually digitized and then entered into a computer on punch cards. Current students cannot even imagine this.

For any recent earthquake, we can now download thousands of high-quality digital broadband seismic recordings in real time from around the world. Totally, new technologies, such as GPS, including seafloor observations, satellite ground motion measurements, and deep ocean tsunami recordings, have emerged. We now analyze earthquakes and determine their slip and asperity distributions within a couple of hours, whereas it used to take months.

1. T. Lay, S. P Nishenko, Updated concepts of seismic gaps and asperities to assess great earthquake hazard along South Americ. *Proc. Nat. Acad. Sci.*, **119** (51), 10.1073/pnas.2216843119.