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Study of 2004 Tsunami Disaster Forces Rethinking of Theory of Massive Earthquakes

The Sumatra-Andaman earthquake of December 26, 2004, was one of the worst natural disasters in recent memory, mostly due to the devastating tsunami that followed it. A group of geologists, geodesists and geophysicists, including scientists at Scripps Institution of Oceanography at the University of California, San Diego, has delineated the full dimensions of the fault rupture that caused the earthquake.

Their findings, reported in the March 2 issue of the journal Nature, suggest that previous ideas about where large earthquakes are likely to occur need to be revised. Regions of the earth previously thought to be immune to such major events may actually be at high risk of experiencing them.

Local guides and BAKOSURTANAL surveyors inspect the site of a GPS monument in North Sumatra near Lake Toba. The site was surveyed by the Dutch colonial government in the1880s, and resurveyed by Scripps researchers and others approximately 100 years later.

Like all massive earthquakes, the 2004 event occurred on a subduction megathrust, in this case the Sunda megathrust, an earthquake fault along which the Indian and Australian tectonic plates are diving beneath the margin of Southeast Asia. The fault surface that ruptured cannot be seen directly because it lies several kilometers deep in Earth's crust, largely beneath the sea.

Nevertheless, the rupture of the fault caused movements at the surface as long-accumulating elastic strain was suddenly released. The researchers measured these surface motions by three different techniques based on geodesy, the area of science that deals with the measurement and representation of Earth. In one, Scripps scientists with their Indonesian counterparts at the National Coordination Agency for Surveys and Mapping (BAKOSURTANAL) in Cibinong, West Java, measured the shift in position of GPS stations whose locations had been accurately determined prior to the earthquake.

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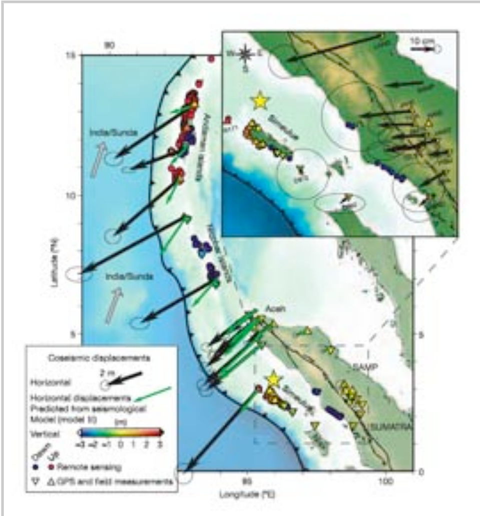

"We have been surveying GPS monuments in northern Sumatra and Aceh provinces with colleagues at BAKOSURTANAL and the Rensselaer Polytechnic Institute since 1989, with the last survey conducted in 2001," said Yehuda Bock, research geodesist and senior lecturer at Scripps and a coauthor of the paper. "These surveys to study the process of oblique plate subduction provided us with an invaluable record of observations prior to the great Sumatra-Andaman earthquake. We mobilized quickly after the earthquake to re-survey these monuments. The Indonesian surveys led by Cecep Subarya (first author of paper) of BAKOSURTANAL were completed under extremely difficult field conditions in the regions of greatest devastation within several weeks after the event."

In the second method, pioneered at the California Institute of Technology, the researchers studied giant coral heads on island reefs. The top surfaces of these corals normally lie right at the water surface, so the presence of corals with tops above or below the water level indicated that the earth's crust rose or fell by that amount during the earthquake.

Finally, the researchers compared satellite images of island lagoons and reefs taken before and after the earthquake: changes in the color of the seawater or reefs indicated a change in the water's depth and hence a rise or fall of the crust at that location.

On the basis of these measurements the researchers found that the 2004 earthquake was caused by rupture of a 1,600-kilometer-long stretch of the megathrust—by far the longest of any recorded earthquake. The breadth of the contact surface that ruptured ranged up to 150 kilometers.

Over this huge contact area, the surfaces of the two plates slid against each other by up to 18 meters._On the basis of these data, the researchers calculated that the so-called moment-magnitude of the earthquake (a measure of the total energy released) was 9.15, making it the third largest earthquake of the past 100 years and the largest yet recorded in the few decades of modern instrumentation.

"This earthquake didn't just break all the records, it also broke some of the rules," said Kerry Sieh, the Sharp Professor of Geology at Caltech and one of the authors of the Nature paper.

According to previous understanding, subduction megathrusts can only produce massive earthquakes if the oceanic plate is young and buoyant, so that it locks tightly against the overriding continental plate and resists rupture until an enormous amount of strain has accumulated. To the south of the Sumatra-Andaman earthquake where the plate is old, "there is now greater concern about a great earthquake on the section of the Sunda megathrust adjacent to the densely populated island of Java," said Bock. "Before the Sumatra-Andaman event, this tectonic environment was not thought to produce great earthquakes. The findings of our paper should provide concern to Indonesian disaster planners."

Yehuda Bock

Scientists have also thought that that the rate of relative motion between the colliding plates must be high for a giant earthquake to occur. Both of these conditions are true off the southern coast of Chile, where the largest earthquake of the past century occurred, in 1960.

Yet another factor that should have lessened the likelihood of a giant earthquake in the Indian Ocean is the fact that the oceanic crust is being stretched by formation of a so-called back-arc basin off the continental margin.

"For all these reasons, received wisdom said that the giant 2004 earthquake should not have occurred," said Jean-Philippe Avouac, a Caltech professor of geology, who is also a contributor to the paper. "But it did, so received wisdom must be wrong. It may be, for example, that a slow rate of motion between the plates simply causes the giant earthquakes to occur less often, so we didn't happen to have seen any in recent times—until 2004."

Many subduction zones that were not considered to be at risk of causing massive earthquakes may need to be reassessed as a result of the 2004 disaster. "For example, the Ryukyu Islands between Taiwan and Japan are in an area where a large rupture would probably cause a tsunami that would kill a lot of people along the Chinese coast," said Sieh. "And in the Caribbean, it could well be an error to assume that the entire subduction zone from Trinidad to Barbados and Puerto Rico is aseismic. The message of the 2004 earthquake to the world is that you shouldn't assume that your subduction zone, even though it's quiet, is incapable of generating great earthquakes."

According to Sieh, it's not that all subduction zones should now be considered a high risk of large earthquakes, but that better monitoring systems—networks of continuously recording GPS stations, for example—should be put in place to assess their seismic potential.

"For most subduction zones, a $1 million GPS system would be adequate," said Sieh. "This is a small price to pay to assess the level of hazard and to monitor subduction zones with the potential to produce a calamity like the Sumatra-Andaman earthquake and tsunami. Caltech's Tectonics Observatory has, for example, begun to monitor the northern coast of Chile, where a giant earthquake last occurred in 1877."

The image of an old primary tirangulation pillar from the 1880s being surveyed by a GPS instrument in 1989. Monuments such as these, surveyed between 1989-2001, were resurveyed after the 2004 Sumatra-Andaman earthquake to determine coseismic displacements.

The Pacific Northwest of the United States, where a giant earthquake occurred in the 1700s, is also a region of concern. According to Bock, "we at Scripps have started working with scientists at the Pacific Geocsciences Center in Vancouver, British Columbia, Canada, to use real-time GPS monitoring techniques developed at our institution as the basis for a tsunami warning system for the Canadian section of the Cascadia subduction zone. By measuring site displacements almost instantaneously and comparing them to scenario earthquakes, we should be able to provide early warning information. Such a system should be extended to the U.S. portion of this active zone."

In addition to Subarya, Sieh, Avouac and Bock, the other authors of the Nature paper are Mohamed Chlieh and Aron Meltzner, both of Caltech's Tectonics Observatory; Linette Prawirodirdjo of Scripps Institution of Oceanography; Danny Natawidjaja of the Indonesian Institute of Sciences; and Robert McCaffrey of Rensselaer Polytechnic Institute. The research was supported by the Gordon and Betty Moore Foundation, the U.S. National Science Foundation, the Southern California Earthquake Center and BAKOSURTANAL.

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