Delving into Faults and Earthquake Behavior

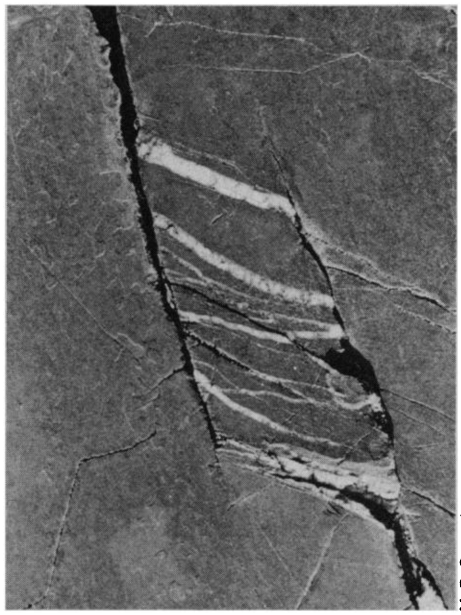
Seismologists attending last month's meeting of the American Geophysical Union in San Francisco heard much about how the irregularities on faults control their behavior and thus the generation of earthquakes. The identification of small crucial areas of a fault, such as the strong spot where a rupture can begin or the fault jog where it can end, is proving a challenge, but it also offers one of the best hopes of understanding and predicting fault behavior.

How to Stop a Quake by Jogging

Seismologists not only want to know where and how earthquakes start, but also where they will end, if only because the longer the section of fault that breaks, the larger the earthquake. Researchers have in recent years pointed to likely obstacles on faults, such as bends and offsets, that might stop a rupture from propagating any farther, but they are often not sure which features really will act as barriers and which will not. There has been no agreement at all on how recognized barriers actually work. Now geologists can peer into a particular type of barrier and can see how it works.

Richard Sibson of the University of California at Santa Barbara had suggested that a certain kind of offset on a fault can stop ruptures, not through its inherent strength but through its resistance to the sudden extension induced across the offset by a rupture. He noted several examples, including the 1-kilometer jog at the southern end of the 35-kilometer Parkfield section of the San Andreas fault that last broke in 1966. The fault ruptured from north to south, one side slipping to the right as seen from the other side, and the rupture stopped where the fault jogged to the right. Sibson argued that such a right-stepping jog could stop right-lateral motion on a fault because that motion would tend to suddenly open up or dilate the jog. In water-saturated rock, the resulting suction would be strong enough to stop the rupture, at least until diffusion slowly relieved the water pressure differences and allowed the fault slippage to propagate slowly without an earthquake.

Sibson reported at the meeting that in lieu of funds for excavating the Parkfield jog to show what makes it work, he has found a long-dead fault jog of the same type that miners had conveniently dug out for him. The discovery came after Sibson spoke to a group in New Zealand and a mining geologist in the audience realized that he knew just the spot Sibson wanted to see. It was the abandoned Martha Hill mine just 100 kilometers from Auckland, where Sibson grew up. Miners had penetrated 600 meters beneath the surface to remove about 1100 tons of gold and silver.



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A small jog. *This centimeter-scale, mineral-filled jog in a fault in sandstone operated in the same way as the 1-kilometer jog that has stopped Parkfield earthquakes.*

Most of the mine is now flooded, but the miners' detailed maps of the mineral veins and the still accessible rock revealed the inner workings of a jog. Dilation induced on the jog by slippage on the rest of the fault created a suction that imploded the rock on the wall of the fault jog and led to boiling of the water saturating the rock. The boiling in turn led to rapid deposition of minerals, including the gold and silver, in the resulting veins. The next event would shatter the mineralized veins as well as rock, boiling would recur, and another increment of minerals would form. The resulting honeycomb mesh of fissure veins and faults represents almost 100 meters of slippage on the flanking fault, which remained barren of mineralization in the absence of any dilation. Sibson estimates that such dilational barriers may last tens or hundreds of thousands of years before the fault somehow bypasses them.

The connection between earthquake dynamics at dilational jogs and the formation of mineral deposits is a common one, but it is not widely recognized, Sibson says. The same principle applies to other types of faults as well, he says.

Earthquakes Are Giving Little Warning

Earthquake prediction will depend on some warning given by faults that they are about to rupture, but two groups reported at the meeting that faults generating moderate earthquakes do not measurably deform the surrounding rock before they break. That behavior is contrary to expectations based on theory and laboratory experimentation, but some researchers expect that great earthquakes will still give some precursory signal. Others are more pessimistic.

James Savage, William Prescott, and Michael Lisowski of the U.S. Geological Survey (USGS) in Menlo Park reported that they could find no evidence of crustal deformation preceding three recent magnitude 6 earthquakes in California—the 1984 Morgan Hill, 1986 North Palm Springs, and 1986 Chalfant events. They monitored deformation by determining with laser distance-measuring instruments the lengths of 10- to 40-kilometer-long lines. Their error was about 1 centimeter. They measured three-line networks near each of the three earthquakes 4 to 12 times a year, 1 week and 1 day before the main shock in the case of Morgan Hill. They saw nothing unusual.

That is particularly remarkable in the case of the North Palm Springs and Chalfant shocks because they were two of a trio of earthquakes striking central and southern California in successive weeks last July. This temporal clustering of widely separated events had a probability of occurring by chance of between one in a thousand and one in ten thousand, according to Savage. Even seismologists, a normally conservative lot, had tended to assume that a wave of crustal deformation swept the region and triggered these quakes, but Savage and his group see no sign of it.

Malcolm Johnston and Roger Borcherdt of the USGS in Menlo Park, Michael Gladwin of the University of Queensland, and Alan Linde of the Carnegie Institution of Washington monitored crustal deformation preceding the same three earthquakes plus four others ranging up to magnitude 7 using continuously recording instruments. Their error was about one part in a billion. Records that are as continuous as possible are crucial because seismologists are uncertain just when the early stages of fault failure should begin. The increasing deformation across the fault should accelerate in the last day or certainly the final hours and seconds as it weakens the fault and the fault begins to slip. "If more than a few millimeters of slip occurs before an earthquake," says Johnston, "we should see it. It cannot hide." They saw no precursory slip, even with second-by-second records that showed the slip of the earthquake itself.

Rather than slip occurring over the entire fault, it appears that the rupture begins on a small area of the fault, a strong point where the two sides of the fault have snagged. Such asperities have been proposed, but they are difficult to locate without observing the earthquake itself. "This makes prediction a much more difficult job than we thought 5 to 10 years ago," said Johnston. The trick will be to locate and instrument the right asperity before the next earthquake.

Coastal Ups and Downs Point to a Big Quake

All great earthquakes along the western coasts of North and South America are sudden slippages on the upper surfaces of ocean plates that are jerkily descending into the mantle. But, do all descending plates cause great earthquakes? That has been a controversial question among seismologists studying the Juan de Fuca plate that descends beneath northern Oregon and Washington. No great earthquake has struck that coast during the 200 years of historical records, but some researchers see no difference between this subducting plate and others that do generate great earthquakes. Now there is physical evidence, extracted from the gray mud of Washington coastal estuaries, that the Juan de Fuca plate has indeed generated great earthquakes.

The quiescence of the Washington coast prompted some researchers to suggest that the Juan de Fuca plate is anomalous, that it can somehow slip smoothly beneath the edge of the North American plate without snagging and causing earthquakes. Perhaps this ocean plate is not subducting at all, other researchers speculated.

Thomas Heaton and Stephen Hartzell of the U.S. Geological Survey (USGS) in Pasadena and Hiroo Kanamori of the California Institute of Technology have argued that the Juan de Fuca subduction zone may be all too active. They found that the plate is probably subducting at a rate of 3 to 4 centimeters per year.

Heaton and his colleagues concluded that this unavoidable subduction in all likelihood is producing great earthquakes. The plate is only 10 million to 15 million years old and every subducting plate younger than 40 million years is still warm enough and thus light enough to couple tightly to the overlying plate and produce great earthquakes. By analogy with the behavior of other plates, the Juan de Fuca plate could generate earthquakes as large as magnitude 8.3 ± 0.5. In light of this and other evidence, these researchers have argued that the quiescence of the Juan de Fuca subduction zone denotes, as seen elsewhere, the locking together of the two plates while stress accumulates that eventually will drive the next great earthquake.

Even assuming the reasonableness of this consistency argument, few researchers are likely to be convinced without some physical, hands-on evidence of past great earthquakes along the Washington-Oregon coast. Brian Atwater of the USGS in Seattle reported at the meeting that he may have found such evidence in his studies of Washington estuaries. Because no sign of earthquake-induced uplift had been reported, Atwater looked for the other kind of crustal deformation induced by subduction earthquakes, crustal subsidence. If such subsidence occurred in coastal Washington estuaries, as it apparently had in South America, vegetated lowlands just high enough to avoid inundation by the sea most of the time would sink far enough to be submerged regularly and become barren tidal mud flats. Between great earthquakes enough mud could fill the tidal flats to raise them once again to the level that supports extensive vegetation. Thus repeated earthquakes should produce alternating layers of lowland soil and tidal flat mud.

Atwater studied low-tide outcrops and drill-core samples from five Washington estuaries along 220 kilometers of the coast. In each of the five he found one to six or more layers of peaty mud, which he took to be the soil of long-dead, vegetated lowlands, overlain by sharply defined layers of gray mud, the tidal flat deposits. Atwater can see no way that flooding rivers, local settling, or gradual sea level rise could have created this layering. In fact at one site three different peaty layers, and only peaty layers, are overlain by thin sandy layers that resemble South American estuarine deposits from a tsunami generated by the great 1960 Chile earthquake.

Atwater believes that the alternating layers of peaty soil and mud probably do represent repeated subsidence induced by great Washington earthquakes, at least six during the past 7000 years, but he notes that a major test remains. He can trace a given peaty layer in outcrops and from borehole to borehole over hundreds of meters, but a magnitude 8 earthquake would leave subsided estuaries along at least 100 kilometers of coast. To show that one layer created by the same great earthquake extends that far, the layers must be carefully dated. That work is still under way.

Cutting the Gordian Knot of the San Andreas

The San Andreas fault turns into a mess as it heads north from the Salton Sea toward San Bernardino. It splits, its offshoots split again, the branches become distorted, and then they rejoin to form a single fault trace. The job of figuring out which traces are active at any moment and what size earthquakes they produce is a geologist's nightmare. But last July's North Palm Springs earthquake suggests that the behavior of the San Andreas system there may be simpler than it appears.

Lucile Jones and Douglas Given of the U.S. Geological Survey in Pasadena and Katherine Hutton and Clarence Allen of the California Institute of Technology reported at the meeting that the fault rupture of the North Palm Springs earthquake did not follow the path a geologist might have predicted. Despite its breaking a segment of the Banning fault—the major branch of the San Andreas—just south of its turn toward the west, the rupture ignored the turn of the visible fault trace and continued straight toward the northwest.

The rupture extended 10 to 15 kilometers beyond the turn in the fault trace, which carried the break one-third of the way to the southern end of the San Bernardino strand. There is no visible fault trace indicating that the fault should take such a direct route to rejoin the San Andreas proper, but then this event failed to break the surface at all.

Jones noted that this straight trend of the rupture beneath a maze of surface traces supports the idea that there is a single, throughgoing fault in the region on which motion occurs. The alternative, that all or most of the short fault traces are active, would lead to numerous but moderate earthquakes. The simpler picture allows for larger events. This section of the San Andreas has been viewed by some as part of a 150-kilometer knot that ties up or locks itself and perhaps the entire 350 kilometers of the southern San Andreas until a great earthquake breaks the knot. In consequence, both geologists and seismologists will be taking a much closer look at this area. ■

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