dence of Roche's intent to limit their freedom to choose reagents. At the press conference, Linton had the passionate support of Stanford biochemist Arthur Kornberg, who won a Nobel Prize for his work on DNA polymerases, the class of enzymes to which Taq belongs. Kornberg argues that patents on PCR and Taq are invalid because the process and the enzyme were described in the scientific literature before their publication by Cetus scientists. Cetus's patents "were flagrant abuses of knowledge that has been in the public domain," Kornberg claims.

Ordoñez says Roche has no plans to prosecute the listed researchers. She accuses Promega of grandstanding—using the list in a publicity stunt to try to win the allegiance of the research community. "Promega asked for the list, took the list, and is waving it in the public eye," she says, "to create visibility and to cause anxiety among these institutions and scientists. If so, the strategy may be working.

Listed researcher Melvin Simon of the California Institute of Technology says it would be "outrageous" if Roche were to threaten individual investigators with legal action. He says his lab has not used Promega Taq for PCR in recent years because of Roche's "virulent stand" on the issue. The list, he predicts, will alienate researchers like himself who have "tried to go along with the system." Douglas Hanahan of the University of California, San Francisco, says he is not pleased with either Roche or Promega, noting that the legal sparring has become "pretty nasty" on both sides.

Stephen O'Gorman of the Salk Institute was one of several researchers who say their listed papers mention no source for Taq polymerase, and that they have never used the Promega enzyme. But O'Gorman says that in his case that wasn't due to concerns about license violations. "That's something we don't think about," he says. Basic scientists who use Promega Taq "aren't violating the patent for profit," O'Gorman says, "so I can't imagine that they would have any liability."

But Promega attorney Peter Carroll warns that "even if they [Roche] don't go after the researchers, no one should breathe a sigh of relief." If the courts accept that basic researchers can be considered infringers on the Roche patents, he says, that will overturn the general precedent that basic researchers are exempt from patent restrictions, leaving the door open for Roche to sue the researchers later. Says Ordoñez: "We have no intention to involve these or any other scientists in the litigation with Promega." But, she adds, "I wouldn't want to predict what action Roche would take relative to any patent ... in the future." Those carefully chosen words are unlikely to give comfort to researchers on the list.

–Marcia Barinaga

EARTH SCIENCE

At the Heart of Earthquakes, Seismologists Look for Pulse

Seismologists have it tough. While many researchers can delve right into their object of study—biologists manipulate DNA, physicists shuffle atoms about one by one, and meteorologists even fly through hurricanes—seismologists are separated from the source of earthquakes by kilometers of solid rock. What's more, the seismic waves that emanate from the depths of a fault during an earthquake only grudgingly reveal details about the processes that generate them. As a result, the deep parts of faults have largely remained terra incognita, leaving researchers unsure about why quakes strike where and when they do. Lately, however, seismologists have managed to glimpse the working heart of faults—and found persistent differences between the fault sections that generate earthquakes and those that don't.

Seismologists had long suspected that some fault property—the roughness of its faces, say, or the composition of its rock—varies along a fault and determines whether its sides slip harmlessly by each other or become stuck and eventually break loose in an earthquake. But until recently, researchers weren't sure if these "stuck spots," or asperities, really exist, or whether they persist for quake after quake, influencing their size, location, and timing. The stakes here are high. If the asperities do exist, they would help seismologists forecast when and where the next quake will strike, and how big it will be. If they don't, long-term earthquake prediction might be a vain hope. "It's a question of how orderly nature is," notes Stuart Nishenko of the U.S. Geological Survey (USGS) in Golden, Colorado.

"At the large scale or the small scale, there are physical features that control where rupture occurs and the dimensions of that rupture."

—David Schwartz

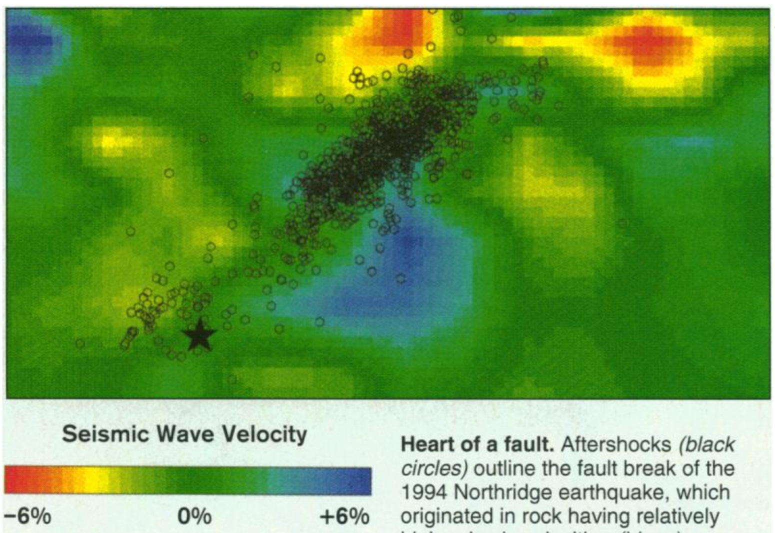
Two kinds of studies are now suggesting that nature is reasonably orderly—at least on some faults. New analyses of earthquake records by William Ellsworth of the USGS in Menlo Park, California, and by others have shown that smaller quakes often strike the same spot on a fault at more or less regular intervals, implying that the fault has a persistent stuck patch. Larger, more damaging earthquakes are generally too rare to reveal such clear regularities, but seismic tomography—a computer-aided technique for extracting images from seismic waves—is filling in by showing that quakes as large as magnitude 7.3 originate on patches of especially strong rock along the fault. "The bottom line," says geologist David Schwartz of the USGS in Menlo Park, "is that when you look at the large scale or the small scale, there are physical features that control where rupture occurs and the dimensions of that rupture."

Ellsworth suspected that was the case more than 20 years ago, when he and Robert Wesson of the USGS in Reston, Virginia, studied a 5-kilometer patch of the central San Andreas fault in Bear Valley, California, that had ruptured in a magnitude 5 earthquake in 1972. Based on details of the quake and its aftershocks, he and Wesson suggested that the site was an asperity that repeatedly locks up the fault until enough strain accumulates to break it in another nearly identical quake. That interpretation gained support when Ellsworth and Lynn Dietz, also at Menlo Park, compared the 1972 quake's seismogram with the reading from a 1951 quake. The seismograms matched like a pair of fingerprints, demonstrating that the two quakes had broken the same patch of fault.

Last month, Ellsworth and Wesson's interpretation looked even better when the same patch of fault ruptured again in an earthquake of about the same size. And the same pattern of repeating, nearly identical quakes is turning up elsewhere on the San Andreas, where some small and medium-size earthquakes recur at the same spots, sometimes with almost clocklike regularity.

Ellsworth and Dietz, for instance, have identified 10 series of repeating earthquakes of magnitude 4 to 5 along the central San Andreas. Each string of quakes includes as many as six events, which broke the same fault patch at intervals of from 10 to 20 years. Similarly, John Vidale of the USGS in Menlo Park, Ellsworth, and their colleagues recently showed that much smaller "microearthquakes" of magnitude 1.3 have broken the same 20-meter patch of the San Andreas just north of Parkfield nine times, with a mean time between repeats of 1.1 years ± 0.2 year. That sort of regularity, says Ellsworth, must mean that the fault has an asperity that persists through earthquake after earthquake.

Fault-gazing. Historical records generally aren't long enough to allow that kind of clear pattern to emerge for the larger, more damaging quakes—which are just the ones forecasters would like to predict. So some seismologists wondering whether larger quakes are constrained to recur on the same patch of fault have resorted to another strategy: trying to see asperities directly. When seismic waves from nearby earthquakes crisscross a fault, the waves slow down or speed up depending on properties of the rock along their paths. Processed in powerful computers, the travel times of thousands of waves yield a three-dimensional image of the fault, much as a CAT scan creates three-dimensional images of the human body from x-ray data. This seismic tomography has enabled several groups of researchers to peer into a total of 10 faults ruptured by recent quakes.



Heart of a fault. Aftershocks *(black circles)* outline the fault break of the 1994 Northridge earthquake, which originated in rock having relatively high seismic velocities *(blues)*.

In those images seismologists have found a consistent pattern of rock properties that seems to correlate with quakes' location and size. In the 1 April issue of *Geophysical Research Letters*, for example, Dapeng Zhao, now at Washington University in St. Louis, and Hiroo Kanamori of the California Institute of Technology show three-dimensional images of the rock that ruptured in the disastrous 1994 Northridge earthquake. The Northridge images show that the quake's main rupture took place in rock with relatively high seismic velocities, while surrounding rock has velocities that are relatively low. And the same pattern emerges in images of other earthquake sites, from the magnitude 6.0 Parkfield shock of 1966 to the magnitude 7.3 Landers quake of 1992.

Many seismologists outside the small community of tomographic imagers have been suspicious of these claims, says Jonathan Lees of Yale University, who pioneered fault imaging, "because we haven't been able to supply a physical explanation." He and his colleagues don't know why earthquakes regularly take place in strong rock, although they guess that only strong rock can accumulate enough stress to break in a large earthquake. And they don't know what weakens the surrounding rock, although Lees offers a couple of possible explanations. His favorite is high-pressure fluids, which may ease the squeeze on the fault, letting it slip without quakes. Or the rock may simply have a composition that is weaker at relatively low temperatures (*Science*, 11 October 1991, p. 197). "But the pattern keeps turning up," says Lees. "I think it's real."

Even if earthquakes large and small do take place at persistent asperities, however, there's no guarantee they will recur at the predictable intervals needed for long-term forecasting. In spite of the near clockwork regularity that Vidale and his colleagues saw in a few small, repeating earthquakes, others are markedly irregular. A magnitude 1.5 quake, for example, has repeated 19 times at the same spot on the Calaveras fault, a branch of the northern San Andreas, the researchers found—but at intervals ranging from 3 days to 3 years. Even the Bear Valley quakes, which offered the first example of an asperity, haven't been perfectly regular; the sequence of lone quakes roughly every 15 years includes a pair of smaller quakes that broke the Bear Valley patch in two steps in 1982 and 1985.

Whether or not a quake repeats at regular intervals probably depends on how much it is affected by neighboring quakes, says Ellsworth. He believes that along the San Andreas, the asperities that break at fairly regular intervals probably lie far enough from neighboring asperities to feel only the steady accumulation of strain generated by the forces of plate tectonics. The Calaveras asperity, on the other hand, feels the influence of nearby earthquakes, which dump additional stress on it at irregular intervals. When the magnitude 6.2 Morgan Hill earthquake struck just to the north in 1984, for example, the recurrence interval of the Calaveras quake jumped from months or years to as little as days.

The outlook for forecasts. To some researchers, such intricate fault behavior spells trouble for forecasting. "One way to look at it is that it's so complex, there's no way we can tell what's going on," admits Ellsworth. That's the stance seismologist David Jackson of the University of California, Los Angeles, has taken (*Science*, 18 June 1993, p. 1724). He argues that plate boundaries like those around the Pacific rim are so complex, with so many interconnecting faults and segments of faults, that interactions among them make long-range prediction unreliable.

Ellsworth disagrees. At least for moderate-size repeaters along the San Andreas, he says, "my sense of it is that [forecasters] have a fighting chance." Combining the recurrence intervals of the 10 repeating quakes from the central San Andreas, for example, reveals an encouraging amount of regularity. The standard deviation of their recurrence intervals is 40% of their mean interval, says Ellsworth. Reasonably well-behaved microearthquakes—with uncertainties of 3% to 30%—can also be found in tiny clusters of seismic activity around Parkfield, according to work by Robert Nadeau, William Foxall, and Thomas McEvilly of the University of California, Berkeley. Such variability is about twice the amount forecasters have assumed for faults in southern California (*Science*, 13 January, p. 176), but good enough to allow forecasting, says Ellsworth.

Still, seismologists would feel a lot more confident in their understanding of fault patches and their behavior if they could see them up close. "It would really be nice to be able to go down and look at what makes up a patch," says Schwartz. "Drilling would be the only way to see if there really is something different" about it.

Drilling is just what some researchers hope to do in the next few years. The first target would probably be one of the tiny repeating quakes near Parkfield; at a depth of 3 kilometers or so, the fault patch would be within economical reach. Then perhaps seismologists will be able to join their more fortunate colleagues in doing some hands-on science.

–Richard A. Kerr

Additional Reading

W. L. Ellsworth, "Characteristic earthquakes and long-term earthquake forecasts: Implications of central California seismicity," F. Y. Cheng and M. S. Sheu, Eds., *Urban Disaster Mitigation: The Role of Science and Technology* (Elsevier Science Ltd., Oxford, in press).

R. M. Nadeau, W. Foxall, T. V. McEvilly, "Clustering and periodic recurrence of microearthquakes on the San Andreas fault at Parkfield, California," *Science* **267**, 503 (1995).