SEISMOLOGY

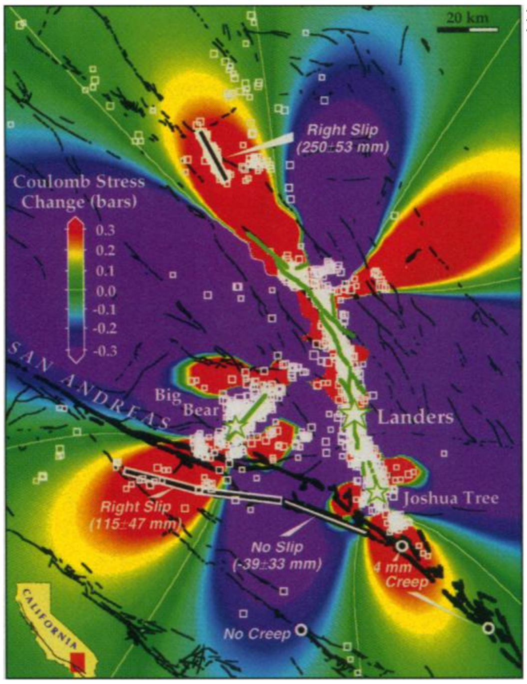
Seismologists Learn the Language of Quakes

Earthquake researchers have long been eavesdroppers, but until recently they listened mainly to the rumblings and groanings of individual faults. Now they are realizing that to understand what faults are saying, they need to monitor dialogues between a fault and its neighbors. This new way of thinking holds that each individual quake is part of a larger conversation in which a major rupture on one fault can transfer stress to a neighboring one and spark a response from it, or temporarily render it speechless by relieving its stress and imposing decades of quiescence on the region. "Faults are talking to each other," says seismologist David Jackson of the University of California, Los Angeles. "We don't know the language yet, but at least we can hear some of their utterances and see the reactions to them."

Already, seismologists have applied this notion to understand past strings of earthquakes on adjacent faults, in which each earthquake raised the probability of the next one. The focus on how faults talk to each other is also likely to improve broad-brush earthquake forecasting, which currently leaves out such triggering effects. Whether seismologists can ever grasp fault linguistics well enough to help predict specific large earthquakes remains to be seen. But at December's meeting of the American Geophysical Union (AGU), researchers traded examples of communication among faults and used new stress models to foretell a quake-filled future for California.

Researchers also learned that a crucial implication of the theory had been confirmed. Seismologists had suspected for many years that an earthquake on one fault affects nearby faults, but they had tested the idea only in hindsight; they hadn't made a quantitative prediction until a magnitude 7.4 earthquake struck near Landers in southern California in June 1992. Immediately after that event, three groups independently calculated how the 75-kilometer-long rupture—which generated the largest quake in the state since 1952—would change the stress on nearby faults. They used mathematical models that treat the upper 10 or 15 kilometers of the crust—where faults break—as an elastic layer able to stretch, compress, and deform like thick rubber. A fault slip of a few meters in such a crust will alter the stress in surrounding rock, in general increasing stress beyond the tips of the rupture and decreasing it on either side of the fault.

In separate papers published in 1992, all three groups [headed by Ross Stein and Ruth Harris of the U.S. Geological Survey (USGS) in Menlo Park, California, and Steven Jaumé of the University of Nevada in Reno] predicted that the Landers quake, which relieved about 85 bars of stress on the fault, also added



STEIN *ET AL.*/USGS

High stress. The Landers quake extended a lobe of high stress *(red)* to the San Andreas fault.

about 5 bars of "sympathetic" stress to a segment of the San Andreas near San Bernardino. That would be enough to drive 10 to 20 centimeters of slip or advance the time of the next large quake there by 1 or 2 decades, predicted Stein.

Now, several years later, Stein announced the results: Sure enough, three different kinds of measurements showed that this portion of the San Andreas had quietly slipped about 12 centimeters in the few months after the Landers event—far faster movement than usual. "It's remarkable that one fault 40 kilometers away from [a ruptured fault] could take off" and move as much in a few months as would normally take a decade, says Stein. "We hadn't seen that before."

The San Andreas's response to Landers is the latest evidence that seismologists' mathematical models of stress changes bear some resemblance to reality. "You really can calculate what these small changes of stress are," says James Mori of the USGS in Pasadena. And those stress changes "seem to correlate fairly well with small earthquakes. The place I have reservations is: How much does that affect the occurrence of larger earthquakes?" he says. Big quakes are rare, so reliable conclusions are hard to come by.

Still, at AGU Stein reported evidence that stress triggering can play a role in big earthquakes too. He and Aykut Barka of the Istanbul Technical University studied 10 earthquakes with magnitudes between 6.7 and 8 that since 1939 have ruptured parts of the North Anatolian fault, a San Andreas–style fault in Turkey. They calculated that nearby quakes added several bars of stress to nine out of the 10 faults—and so could have contributed to their subsequent failure. In fact, Stein and Barka found that a large quake on one segment added enough stress to a nearby fault to increase its probability of rupture by a factor of 4.

With results like that, it's tempting to apply stress change calculations to forecasts of future quakes (*Science*, 13 January 1995, p. 176). Still, the study of how faults speak to each other is in its infancy, and researchers are well aware of the limitations. "We're still learning," says Robert Simpson of the USGS in Menlo Park. "It's going to be a while before we can use the calculations in a predictive sense." Stein agrees that at this point, "it doesn't look like this alone is going to tell us which faults will fail next."

Despite the hesitancy, some researchers are using stress transfer calculations to understand broad historical patterns of California seismicity and, if not predict specific earthquakes, at least weigh the odds of future quakes. For the southern part of the state, Harris and Simpson, as well as Jishu Deng and Lynn Sykes of Columbia University's Lamont-Doherty Earth Observatory, have constructed models of recent stress changes, as each group reported at the AGU meeting. Deng and Sykes's model extends back to 1812 to encompass changes induced in nearby faults by both of the great San Andreas quakes of the past 200 years; they also include the slow buildup of stress due to tectonic plate motions. In their model, "almost all magnitude 6 and greater earthquakes—probably 95%—occur in the areas that have been moved closer to failure" by great quakes and tectonic stress, says Sykes.

Conversely, "the places where you've had a relaxation of stress are very conspicuous for the absence of moderate to large earthquakes," he says. Such "stress shadows" were presumed to dominate broad areas to either side of lengthy San Andreas–type ruptures, but researchers had not previously calculated just how they form or evolve. For example, the great quake of 1857 broke the San Andreas fault northeast of Los Angeles, and both the USGS and Lamont models show that this quake "turned off" seismicity over a large part of southern California. But that protection was only temporary. Inevitably, the grinding of tectonic plates slowly increased crustal stress and nibbled at the edges of the 1857 stress shadow. As more and more of the region came out of the shadow, seismic activity returned just after the turn of the century.

The 1857 stress shadow is continuing to shrink. Sykes sees the large 1933 Long Beach and 1992 Landers quakes as examples of faults rupturing within a few decades of emerging from the model's calculated shadow. Ominously, the San Bernardino segment of the San Andreas is due to come out of the 1857 shadow in the next few decades, according to the Lamont model. That, plus the rash of moderate to large quakes around the southern San Andreas since the mid-1980s (*Science*, 10 July 1992, p. 155), and the general belief that this part of the fault could be overdue for rupture (*Science*, 22 July 1988, p. 413), increases the odds that the millions of people living near San Bernardino will be rocked by a near-great quake in the next few decades.

At the same time, northern California is coming out of its own stress shadow. Modeling by Simpson, which he discussed at the AGU meeting, and by Jaumé and Sykes, shows that the great 1906 San Francisco quake cast a stress shadow over most Bay Area faults, imposing a seismic quiescence that only began to lift in the mid-1950s. In 1979, about the time the shadow shrank northward along the Calaveras fault southeast of San Francisco, a sequence of moderate quakes began striking that branch of the San Andreas system.

Farther north lies the worrisome Hayward fault, which cuts through the populous East Bay region and hasn't ruptured since the mid-19th century. According to Simpson's model, the southern end of the Hayward is probably out of the shadow and the northern end is close to being out. But Simpson cautions that many uncertainties remain, such as how much stress a given fault had accumulated before a stress shadow appeared, and how the deep crust responds to stress transfers. For now, conversations among faults will often remain private affairs—but seismologists have at least started to eavesdrop.

–Richard A. Kerr

PARTICLE PHYSICS

Quark Studies Put Theorists in a Spin

AMSTERDAM, THE NETHERLANDS—Eight years ago, a group of European particle physicists studying the internal structure of protons and neutrons—the building blocks of atomic nuclei collectively known as nucleons—made a startling discovery: The three valence quarks within each nucleon, which define its physical properties, do not define its spin. The group, known as the European Muon Collaboration (EMC) and working at the CERN particle physics center near Geneva, calculated the quarks' contribution to be a paltry 20%, a figure that includes contributions from short-lived "sea quarks" created by the gluons that hold the nucleon together. This small fraction presented a major problem for nucleon structure models: If the valence and sea quarks don't provide the spin, what does? The situation was soon dubbed "the spin crisis."

Spin, a fundamental quantum mechanical property of particles, can only assume certain fixed values. Protons and neutrons have a spin of +1/2, while quarks can have spins of +1/2 and –1/2. Until the 1988 EMC results, models of the nucleon simply assumed that its spin was the sum of the spins of the three valence quarks. Within a few years, other groups confirmed the quarks' small contribution, but they came up with widely differing estimates of its size. An experiment known as E142 at the Stanford Linear Accelerator Center (SLAC) in California put it at 57%, and CERN's Spin Muon Collaboration (SMC), successor to EMC, found only 6%. These discrepancies led many researchers to conclude that the experiments were flawed. "We believed there was something wrong with the data," says Stephane Platchkov of France's Atomic Energy Commission at Saclay, south of Paris. More recent results suggest, however, that that comforting assumption is no longer valid: They indicate that the spin crisis seems to be real.

Earlier this month, the three main collaborations that are now investigating quark spin met in Amsterdam to compare notes. Over the past few years, the differences between the teams' results have been decreasing, and at the meeting, results from SMC and another SLAC experiment, E143, both confirmed that quarks contribute around 25% of a nucleon's spin. The third team, the HERMES collaboration from DESY, Germany's particle physics laboratory near Hamburg, which joined the search last year (*Science*, 24 March 1995, p. 1767), is expected to announce a similar figure later this month.

"When we compare the asymmetries in the data of SMC and E143, we now see no differences."
—Stephane Platchkov

The three current groups, as did the EMC team, all use a similar method to assess quark spin. They fire a high-energy beam of electrons or muons, which is spin-polarized—meaning that all their spins are aligned in one direction—into a target of nucleons that are also spin-polarized. Some particles are scattered, deflected from their path, and the probability of scattering by a nucleon is different if their spins are parallel or antiparallel. These differences in scattering probabilities are called asymmetries, and they can be studied by varying the polarization direction of the beam or the target nucleons. Once the asymmetries are known, researchers use quantum theory to calculate the spin contributions made by the quarks.

The three teams found a way around their earlier divergent results by looking more closely at the inner structure of the nucleon. The three valence quarks are bound together in the nucleus by gluons, and researchers soon realized that because quarks exchange, or "radiate," gluons, quantum theory provides "radiative corrections," and these came to the rescue. "When these corrections were calculated and applied to the data, then the different experiments came closer and closer," says SLAC's Linda Stuart, a member of the E143 team. When the latest results are adjusted to compensate for the different beam energies used, they are now in agreement. "When we compare the asymmetries in the data of SMC and E143, we now see no differences," says Platchkov.

But while this has made the experimenters happy, it still leaves theorists with a big problem: Where does the rest of the nucleon spin come from? "We have a part of the spin that is not carried by the quarks, neither the valence quarks nor the quark-antiquark pairs of the sea quarks," says Piet Mulders of NIKHEF, the Dutch National Institute for Nuclear and High-Energy Physics. Most researchers now believe the answer lies with the gluons, but "the question we have now is 'how will we measure this?' " says Mulders.

Also, among the sea quarks, gluons sometimes produce "strange" quark-antiquark pairs, a type of quark that was not expected to occur in normal matter. Both the SMC and E143 have now confirmed reports that these strange quarks make an important negative contribution of about 12% to the nucleon's spin—so reducing the quarks' apparent contribution. So, far from resolving the spin crisis, the closer experimenters look into the nucleon's interior, the stranger it seems.

–Alexander Hellemans

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