A Fall Harvest of Earth Science in San Francisco

Whenever geophysicists gather, a recurrent theme is catastrophes. At the fall 1991 meeting of the American Geophysical Union (AGU), held in San Francisco December 9 through 13, the catastophes under discussion ranged from earthquakes—tremors of Earth's brittle outer rind—to turbulent flows in its fluid core.

Loma Prieta's Long Reach Was a Matter of Mirrors

By rights, the San Francisco area should not have been so badly shaken by the Loma Prieta earthquake. The quake's epicenter was a full 100 kilometers away and, like the ripples from a pebble tossed in a pond, the seismic waves should have weakened considerably as they spread away from their source. But the waves from Loma Prieta seemed to keep up much of their strength kilometer after kilometer until they reached the ill-fated Marina District and the double-decker highways of San Francisco and Oakland.

The secret of Loma Prieta's long reach lies deep in the crust, researchers reported at the AGU meeting. By probing the crust with artificial seismic waves, seismologists Rufus Catchings and Gary Fuis of the U.S. Geological Survey in Menlo Park have added support to an early suggestion that Loma Prieta's waves were focused on San Francisco by deep crustal layers acting like mirrors. "The focusing seems to be there and looks very strong," says Catchings. That implies yet another variable that must be factored into predictions of seismic hazards from future earthquakes in San Francisco and elsewhere.

The researchers tested the focussing hypothesis in the course of a field experiment to probe the deep crust for 200 kilometers around the Loma Prieta epicenter. In such imaging, seismic waves—generated in this case by the detonation of a ton or more of explosives in shallow bore holes—dive into the crust and are partially reflected or refracted back to recorders at the surface by regions where seismic velocity increases. By measuring round-trip travel times and relating seismic velocities to rock type, seismologists can get a picture of crustal structure.

Catchings and Fuis are still at a preliminary stage of their analysis, but already it appears that the deep crust near Loma Prieta could have efficiently reflected seismic waves from the event back toward the surface. Key to the reflection process, Catchings says, would have been the layers of denser rock he and Fuis detected in the lower crust between depths of 10 to 21 kilometers.

As it happens, those reflecting layers are well positioned to relay seismic energy from Loma Prieta to San Francisco, says Paul Somerville of Woodward-Clyde Consultants in Pasadena, who with colleague Joanne Yoshimura originally proposed the reflection idea. The reflectors would have been most efficient when seismic waves struck them at an angle of about 50 degrees or more from the vertical, so that the waves would glint off the lower crust like sunlight off a pane of glass. Most of those critically reflected waves would have reached the surface 50 to 80 kilometers from the epicenter. That falls a little short of San Francisco, but the shaking that the city experienced from reflected waves still would have been almost three times stronger than from waves traveling directly from the quake, says Somerville.

The realization that the deep crust plays an important role in exacerbating earthquake damage gives engineers, planners, and homeowners yet another worry. Not only must they consider soil conditions and the proximity and orientation of faults (quakes tend to focus their energy along the direction that the fault ruptures), but they also should factor in the nature of the deep crust. They might ask: How far down can danger lurk? ■ RICHARD A. KERR

Are Earthquakes a Ticking Clock for Los Angeles?

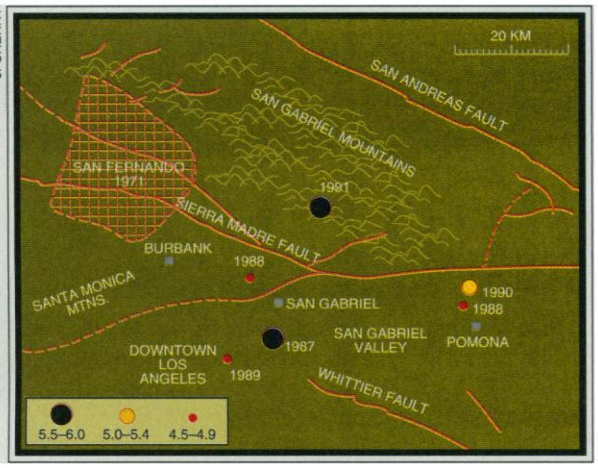
It may be the last thing Southern Californians need: Seismologists are seeing yet another sign that the earth beneath their feet could shudder mightily at any moment. This time the suspect fault is not the famous San Andreas, but one far closer to downtown Los Angeles: a companion of the San Andreas called the Sierra Madre, which skirts the San Gabriel Mountains within 20 kilometers of the city.

The fault, where the crust of the Los Angeles basin is being wedged under the San Gabriels, pushing them upward, is part of a fault system that has been a killer in the past. In 1971 a section of it gave way in the magnitude 6.6 San Fernando earthquake, which took 60 lives. And now a 4-year-long progression of six moderate but unsettling quakes across the San Gabriel Valley east of Pasadena has seismologists wondering whether something even bigger—a magnitude 7 or even 7.5 earthquake—might be ready to strike the heavily populated Los Angeles area.

The series of quakes, a group of seismologists argued at the AGU meeting, seems to trace a wave of enhanced strain that is moving northward across the Los Angeles basin toward the Sierra Madre fault. The quakes also make for "a lot of parallels with the San Francisco Bay region," which experienced unusual tremors in the years before the Loma Prieta earthquake, says Lucile Jones of the U.S. Geological Survey in Pasadena, one of the seismologists studying the San Gabriel quakes. But she is at pains to say that she and her colleagues have no idea whether this unusual sequence of quakes will end in something disastrous or simply peter out.

Still, the nature and distribution of the recent San Gabriel quakes paint a disquieting picture of goings-on deep underground, according to Jones and her husband, Egill Hauksson of the California Institute of Technology, who are working with Hiroo Kanamori of Caltech. Before 1987, when the string of six magnitude 4.5 to 5.9 earthquakes began, the area had experienced none of that size in the past 50 years—and nothing of magnitude 5 or larger during the past 150 years, says Jones. Now the four largest moderate quakes have marched northeastward from near downtown L.A. all the way to the Sierra Madre fault itself, a small patch of which ruptured last June. And the nature of the events—deep and intense with few aftershocks—is just what you would expect from a strain wave, according to the group's calculations. The train of events also seems to have inhibited smaller, shallower shocks, in keeping with predictions.

To explain the earthquake pattern, the researchers surmise that the slab of crust beneath the San Gabriel Valley has two layers that tend to act independently. Deep-seated plate motions are dragging both layers to the northeast, shoving them under the San Gabriel Mountains at the Sierra Madre fault. But beginning in 1987, according to their model, the lower crust back near Los Angeles—which is too malleable to break and produce an earthquake—surged ahead. That region of slippage between the upper and lower crust has been propagating toward the Sierra Madre fault since then at about 6 kilometers per year. As the upper 15 kilometers or so of crust feel the tug of the lower crust slipping beneath it, faults that are already strained near the breaking point



J. CHERRY

What next for L.A.? *A progression of moderate quakes could trigger a large one on the Sierra Madre fault.*

and are oriented so as to be most sensitive to the added strain have been rupturing.

That picture might account for the earthquakes that have been registered so far, but what does it mean for Los Angeles' future? "We don't know," Jones quickly points out. The slippage in the lower crust seems to have reached at least part of the Sierra Madre fault, and the fault may well be primed to uncork a big one. It is longer than the San Fernando fault that broke in 1971, and as far back as records go, it has released only a small part of the total strain generated by plate motions.

Added to all that is the unsettling parallel between the San Gabriel Valley quakes and seismic activity in the Bay Area just before the Loma Prieta earthquake. Like the San Gabriel region, the Bay Area experienced a series of moderate quakes—eight of them larger than magnitude 5 between 1979 and 1989—that ended a period of relative quiet. The last two events, which struck a long-quiet section of the San Andreas, were unusually deep and had few aftershocks, reminiscent of the San Gabriel events. There was no clear progression of quakes toward the San Andreas, but seismologists publicly fretted about the possibilities (*Science*, 18 August 1989, p. 704). And two months after the last moderate shocks near the San Andreas, it ruptured in the Loma Prieta earthquake.

On the other hand, notes Jones, similar clusters of unusual seismic activity have come and gone around California with no great harm. One 15-year cluster of six events began in 1935 near San Gorgornio Pass and Palm Springs, a possible trigger point for a magnitude 8 rupture of the San Andreas, but nothing bigger than a magnitude 6 came of that cluster.

So far, Jones herself is far from panicking. She still leaves her youngest child at a daycare center that is built right on the Sierra Madre fault. ■ **R.A.K.**

A Conundrum at Steens Mountain

A navigator plying the seas 15 million years ago would have had a hard time following his compass. Earth was in the midst of a magnetic reversal—an episode in which the North and South Poles trade places over the space of a few thousand years. That might sound like a leisurely pace. But according to a record of the magnetic field's shifting orientation frozen in the lava of an extinct volcano, the reversal may have been punctuated by magnetic jumps in which the field shifted by as much as 50 degrees in the space of a week. With magnetic north swinging around at that rate, a mariner would never have reached port.

Present-day researchers are also at sea with the findings, described at the AGU meeting by paleomagnetician Robert Coe of the University of California, Santa Cruz. Unless Coe and his colleagues Michel Prévot and Pierre Camps of the University of Science and Technology in Montpellier, France, have somehow been misled, the work implies that Earth's magnetic field can change 1000 times faster than has ever been observed. "I find that thoroughly implausible," says Jeremy Bloxham, a theorist at Harvard University. But he acknowledges that he and his colleagues are having a hard time explaining away the findings. "People are taking them seriously," he says.

The results that are causing all this head scratching come from Steens Mountain, Oregon, a 1500-meter pile of lava flows spurted out by a volcano that was erupting just in time to capture a highly detailed record of the magnetic reversal. As each of the 130 flows that erupted at intervals over about 10,000 years cooled below about 500°C, it captured a snapshot of the magnetic field's orientation—normal, reversed, or in one of several intermediate positions it adopted during the reversal process. But in several of the flows Coe and Prévot studied in the mid-1980s, the snapshot was blurred, as if a single flow had captured many different directions.

To test that possibility, Coe and his colleagues drilled closely spaced samples from two of the flows, then analyzed each sample for its magnetic direction. The results: "The samples at the bottom and top of each [anomalous flow] show the same direction as the underlying flow. But as you ascend toward the middle the direction swings out in the direction of the overlying flow." The only way Coe and his colleagues could make sense of the pattern, he says, was to assume that the field shifted just as each flow was cooling. You would expect the top and bottom of a fresh lava flow to cool fastest, Coe explains, thus capturing the field in its earlier position. The center of the flow, like the middle of a baked potato, would stay hotter for longer, providing a later record of the field.

In that picture, it was a simple matter to work out how fast the field had changed. "We could calculate quite well how long a flow should take to cool," says Coe—and thus how fast the magnetic shift must have been. The calculation for the first of their flows, which Coe and Prévot published in 1989, suggested that the 50 degrees of change it recorded must have taken just 15 days. In the second flow, whose magnetic biography Coe reported at the meeting, a magnetic shift of the same size had apparently been squeezed into as few as 6 days.

Taken at face value, the results suggest that during a reversal, the magnetic field can pivot by several degrees per day. And that could imply that the electrically conductive liquid metal of Earth's outer core, whose churning generates the magnetic field in a process that is still largely mysterious, can sometimes surge in currents that reach speeds of several kilometers per hour. That's up to 1000 times faster than existing theories suggest, and it's too much for many geophysicists to swallow. "I can't really understand the mechanism," says Kenneth Hoffman, a paleomagnetician at California Polytechnic State University. "I don't see how a body as large as the core could change so fast."

In the face of that conundrum, some geophysicists are trying—so far unsuccessfully—to pin the rapid shifts on something other than the core itself. Bloxham offers one possibility: "My hunch is that it's an artifact of the recording process"—the process by which the cooling lava captured the field's orientation. But Coe points out that the two flows his group looked at have quite different magnetic properties and yet show similar signals, making it harder to blame some glitch in the record. Hoffman agrees. "We haven't found anything really questionable about the rock magnetics."

And that leads Coe back to the notion that many of his colleagues reject out of hand: that his group has found a true signature of Earth's internal field, and the deep currents of metal that sustain it. "Maybe a few kilometers an hour is not impossibly fast when you consider that the outer-core fluid may be only a little more viscous than water," he says. After all it would be only one more mystery added to the enigma of the magnetic field itself. ■ **Tim Appenzeller**