Double Fault: The Landers Earthquake

The Landers quake . . . which fortunately struck in the sparsely populated desert 100 miles east of Los Angeles, occurred in a tectonic setting luckier for scientists too.

This fence near Landers was offset in two places, neatly shifted a few feet by separate traces of the first segment of the fault.

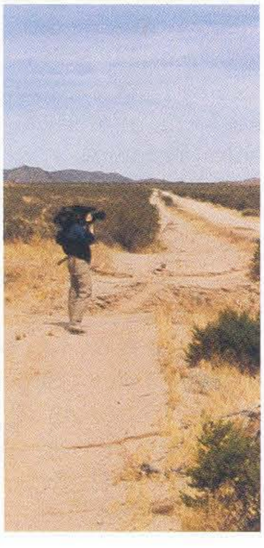
The magnitude 7.5 Landers earthquake that shook up southern California on June 28 overturned a "prediction" *E&S* made in the Winter 1990 issue: "Loma Prieta may . . . become California's best-studied earthquake, at least until the Big One hits." Landers was not the Big One, yet it suddenly presented Caltech seismologists and geologists with a spectacular experiment right in their own back yard. And no time was lost in going to work on it.

Unlike the Loma Prieta temblor, which had a significant amount of vertical displacement, the Landers quake occurred on a strike-slip fault, in which the two sides of the fault slide past each other horizontally—right-lateral slip in which opposite sides of the fault seem to move to the right—with only very slight vertical movement. But while the 7.1 Loma Prieta earthquake in October 1989 killed 62 people and caused extensive damage in the Bay Area, it didn't rupture the surface. Geologists could not pinpoint the absolute location of the fault. The Landers quake, on the other hand, which fortunately struck in the sparsely populated desert 100 miles east of Los Angeles, occurred in a tectonic setting luckier for scientists too. "The rupture came right up to the surface," said Ken Hudnut, at the time of the quake an associate scientist at Caltech's Seismological Laboratory and now with the U.S. Geological Survey . "It's not quite bedrock faulting, but we're looking at bedrock on one side of the fault and sediment on the other. The bedrock is closer to the surface and not buried by a thick sedimentary layer. So we have a relatively unobscured view of the slip distribution from the surface faulting of this earthquake."

The "unobscured view" was particularly remarkable from above, and the scientists took to the air right away. "You could follow the crack in the ground," said Hudnut, one of the first out in the field. "This is the first time we've gotten out there with a couple of helicopters and were able to do a really rapid evaluation of faulting along the whole fault. Within two days we had enough information on where the surface faulting was, so that by the third morning I was able to go up in an aircraft and navigate for the pilot when we took the aerial photographs. The aerial photographs were done very quickly after the earthquake and were done quite well."

When they weren't observing the fault from the air, about a dozen scientists tracked and measured the Landers earthquake's traces on the ground. (The magnitude 6.6 Big Bear quake, which followed the Landers quake by about three hours, did not rupture the surface.) The team, which included Hudnut, Professors of Geology Kerry Sieh and Brian Wernicke, Associate Professor of Geology and Geophysics Joann Stock, and a number of grad students and postdocs, found offsets they could measure—to determine how far one side of the fault had moved past the other—in interrupted stream channels, in fences, and in roads. Disjointed tire tracks also provided very specific information on how far the ground had moved—particularly motorcycle tracks. "Motorcycle tracks are unambiguous in a lot of cases," according to Hudnut. "The tires are nicely aligned, and they make a deep furrow in the sand or silt"—a furrow

Right: Seen from a helicopter, the rupture from the Landers quake snakes across the desert, its relief highlighted by late-afternoon shadows. Below: A TV cameraman surveys a disjointed road near the site of the largest offset—6.7 meters.



that can be neatly offset by a fault running across it. "This is the first time I found myself wishing I could find *more* motorcycle tracks in the desert," said Sieh.

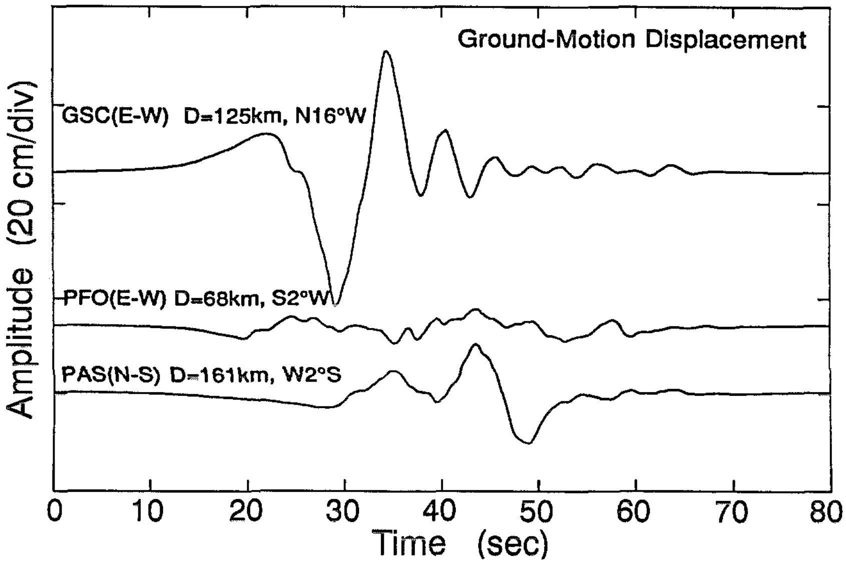
"That's the kind of thing we were looking for," said Hudnut, "and we would measure slip along the orientation of the fault. We were actually measuring the slip vector at all of these sites, instead of measuring just the lateral offset or the vertical offset. When you can see that there was some vertical movement as well as lateral, you really want to measure the slip vector to be very precise about what it is you're measuring. So we were spending about a half hour at each site measuring slip vectors in three dimensions instead of just making a single-length measurement."

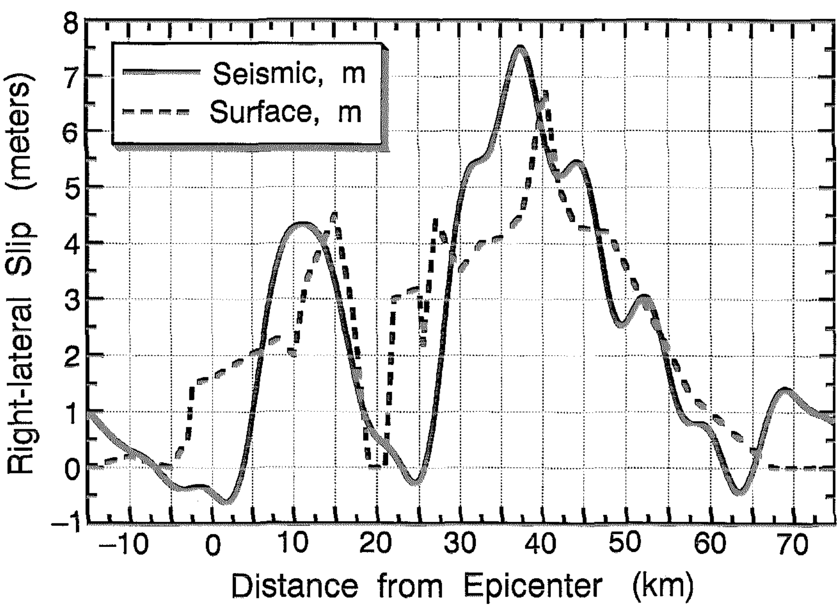
In mapping the surface faulting to determine the slip distribution, the scientists found one segment of the fault running almost due north from Yucca Valley about 20 kilometers. They measured slip up to about three meters in this section, but the slip fell to zero where the direction of motion appeared to bend and sidestep about two kilometers across Johnson Valley, where it picked up again in a northwest-trending direction for about 50 kilometers. Offsets along this segment were larger; the Caltech crew found a road offset by 6.7 meters, described by Sieh as "the largest offset in North America in the 20th century."

But what was most interesting about the slip distribution was not the size of the slip but the way it jumped between faults. The system that broke on June 28 actually involved four previously mapped faults—the Johnson Valley, the Homestead Valley, the Emerson, and the Camp Rock faults—and some geologists have split it even more finely into six segments. "It should be fun to model," said Sieh. The slip gap occurred over a two-km. transfer of the rupture from the Homestead Valley fault to the Emerson. There are a number of other significant faults parallel to the Emerson, all part of the complicated zone where the Pacific plate, on its journey northwestward, rubs up against the North American plate. This area, the Mojave shear zone, had been mapped and the faults identified, but the magnitude 7.5 earthquake in June was a surprise. "This is probably larger than anyone might have expected," said Hudnut. "The largest size anyone might have expected for an earthquake out there would have been based on the maximum length of any continuous fault segment that looked straight. And now we see that, there at least, the larger earthquakes can certainly rupture multiple fault segments. In this case there are just the two main fault segments, although the surface faulting does involve several subsidiary faults."

It took the geologists a week of laborious measurements in the field to come up with the plot of the slip distribution of the Landers quake (the broken line in the bottom figure on the opposite page). The graph shows the first segment rupturing northward from the epicenter with slip up to about three meters; then the motion stops—the graph drops to zero as the break sidesteps over to the neighboring fault. This is then followed by the greater slip—up to

The top figure below shows the wave produced by the Landers quake as recorded at three TERRAscope stations: the top seismogram from the north (the direction of the rupture), the middle one directly south, and the bottom one a side view from the west. Analysis of the TERRAscope data produced the curve of slip distribution along the fault represented by the solid line in the bottom figure. It matches almost perfectly with geologists' surface mapping (broken line).



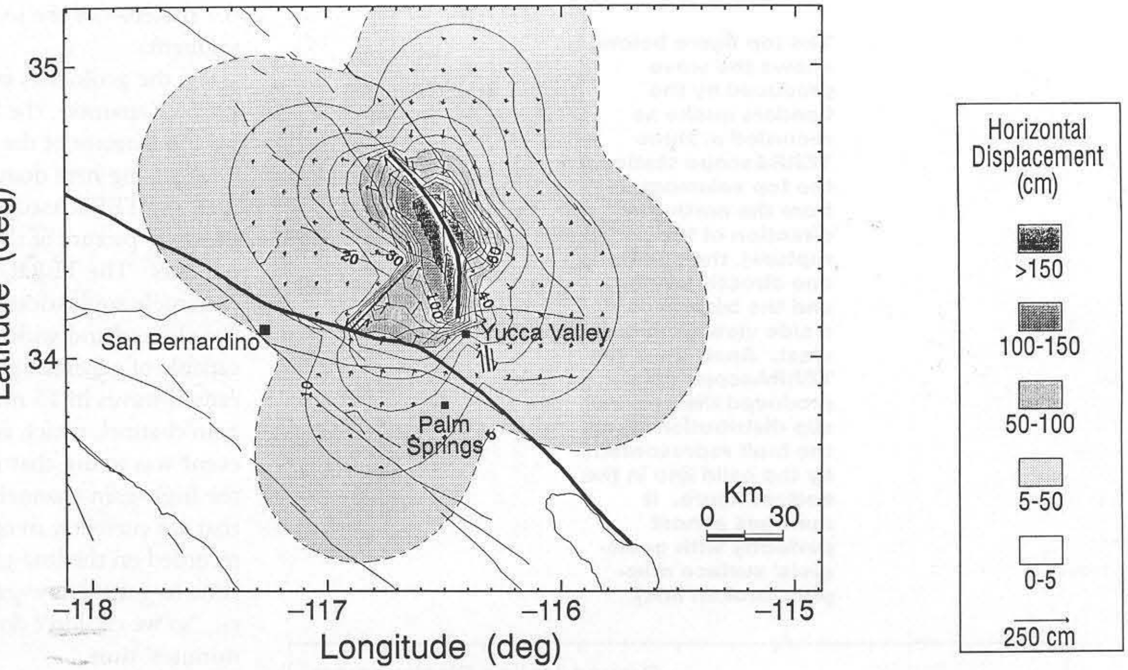


6.7 meters—of the longer northwest-trending segment.

As the geologists tramped around the desert, Hiroo Kanamori, the Smits Professor of Geophysics and director of the seismological laboratory, "just sitting here doing nothing" in Pasadena, used the TERRAscope to put together an almost identical picture of the double-pulse in a couple of hours. The TERRAscope, a network of extremely sophisticated seismometers with broad-band and wide dynamic range, is usually capable of generating a picture of the quake-caused waves in 15 minutes through its high-gain channel, which is easier to use. The Landers event was so big that it "clipped" (went off-scale) the high-gain channel of all six TERRAscopes that are currently in operation, but it was recorded on the low-gain channel. "It takes some time to get the low-gain channel," said Kanamori, "so we couldn't do it in the ordinary 15 minutes' time."

Three of the TERRAscope stations happened to be propitiously placed to determine the fault-rupture pattern of the Landers earthquake. One station had been set up at Goldstone (GSC), 125 km almost due north of the source; one at Pinyon Flat (PFO), 68 km away, near Palm Springs, to the south; and another in Pasadena (PAS), due west and almost perpendicular to the fault. The original three TERRAscope records are shown at left. From the source (the epicenter near Landers) a wave of energy propagated northward, its energy narrowly focused in the large amplitude picked up at Goldstone. The amplitude recorded at Pinyon Flat was smaller, the energy more spread out, even though it was closer to the source. "So just from that, without doing anything, you can immediately tell that the source propagated to the north," said Kanamori. The view of the fault rupture from Pasadena was "like looking at a train going past you from the side rather than coming straight at you," he added. From the side, the original trace combines the effects of both rupture propagation and amount of slip (whereas with a train you only have to consider its speed), but the two pulses of the quake are still clearly visible.

To get his final plot of the slip distribution (the solid line in the figure at left), Kanamori had to do some analysis and make some assumptions. Because the wave is propagating through a complex medium, it is constantly being modified. Correcting for this is easy, according to Kanamori, because the TERRAscope has recorded many small quakes in the area, a record that allowed him to unscramble the signal. Seismologists term this "deconvolution," a process that



Geodetic data from the Global Positioning System are confirming this model of ground displacement in the Landers earthquake. The boomerang-shaped dark line running north-south and then veering to the northwest represents the two segments of the fault which ruptured northward from Yucca Valley. Running almost perpendicular to the main fault from the west is the Big Bear fault, whose westernmost end just grazes the San Andreas fault, the dark line crossing the center of the frame diagonally from northwest to southeast. The shading indicates the amount of horizontal displacement, and the small arrows its direction as well as size.

Kanamori calls "a bit complicated" but a standard method of analysis. The assumptions involved rupture speed and fault depth. To determine the slip distribution along the fault from the seismogram, Kanamori had to assume that the fault rupture propagated at a constant speed. He also assumed that the depth extent of the faulting was 15 km.—a reasonable assumption based on the maximum depth of earthquakes in California which is about 15 km. Aftershocks of the Landers quake have borne out this assumption.

Usually seismologists can calculate only the average slip along a fault in an earthquake, but the position of the TERRAscope network and the clarity of the ground offsets were able to document the *change* in slip along the fault. And Kanamori's assumptions seem justified by the close agreement with Hudnut's graph of displacement from surface mapping; the two plots match almost exactly. "I never thought I'd see it happen that seismologists and geologists are agreeing to a factor of one," said Kerry Sieh. Kanamori claims to be not *too* amazed. "Seismology works very well for this kind of problem," he says. "So to me it wasn't too surprising, but it's still good to see that there's good agreement." For most earthquakes, which don't rupture the surface, there's no opportunity to compare data anyway. The 6.1 magnitude Joshua Tree quake on April 22, for example, which scientists consider part of the Landers sequence, left no traces on the surface of the earth. "So from a geologist's point of view, the earthquake didn't happen," says Kanamori.

Still other instruments are contributing to the total picture of what happened on June 28. A network of geodetic markers for high-accuracy surveying was already in place, recording tiny changes in movements of the earth's surface but also lying in wait for something more exciting. Ken Hudnut had survey networks all along the nearby San Andreas fault and through the San Bernardino Mountains that caught the south and west sides of the rupture. And the U.S. Geological Survey had the north end covered that Hudnut missed. Altogether, in the immediate area of the Landers quake, a total of about a hundred stations were in place. These can monitor any movement in relation to one another using the Global Positioning System (GPS) satellites—17 military satellites continuously transmitting a complicated set of radio signals to be used for navigation. The differences in the time it takes for a signal to be received by two stations can be used to determine a station's exact position. Geologists use the signals to detect very small shifts in the ground—on a baseline of several hundred kilometers to an accuracy of a couple of parts in 10^7 —and, on occasion, very large ones like those produced by the Landers quake. "We use the parts of the signal that are accessible to civilians," says Hudnut, "and we do some little tricks to essentially perform interferometry with the radio signals. We take signals from a number of stationary receivers on the ground, including some stations that are at known reference sites, called fiducial stations, whose coordinates we know to within a very small tolerance."

The GPS data on the Landers quake are

Right: This asphalt road near Landers exhibited one of the first offsets observed by the helicopter-borne geologists. Below: Another fence offers a clear illustration of right-lateral slip, in which objects on the far side of the fault appear to have been shifted to the right. The fault runs horizontally through the middle of the picture.

accurate to a few millimeters on slip displacements up to several meters. But it takes longer than two hours with the TERRAscope or a week of measuring motorcycle tracks to get the geodetic picture. After the task of just collecting the data from 100 stations, "we go through a long tedious procedure of cleaning the data—getting out all the errors in each receiver's data," says Hudnut, "and getting it all into the proper formats. And once that's all done, we just lump all the data into a large matrix and solve it for the coordinates of each station." When this is done, the modeled "butterfly" pattern of displacement (with "nodes" similar to those of an electromagnetic field) is expected to emerge.

In the computed displacement pattern on the opposite page, the small arrows indicate the size and direction of the displacement. The two fault segments that broke in the Landers quake form the boomerang-shaped dark line through the center; the San Andreas fault runs diagonally northwest/southeast through the center of the frame from just above 35.5 degrees latitude. Just three hours after the Landers quake, the magnitude 6.6 Big Bear shock, on the fault running almost perpendicular to Landers from the west and just grazing the San Andreas, did produce "a notable change in the usual butterfly pattern of displacement from the earthquake," according to Hudnut. The Big Bear earthquake was important in defining the overall pattern of deformation and also caused local stress changes on the nearby San Andreas fault.

Some scientists consider Big Bear an aftershock to the Landers earthquake. The numerous aftershocks since the end of June, although unsettling to the millions of people in southern California, follow a declining pattern that conforms to a normal rate of decay, and in that sense seismologists consider Landers a normal, "generic," earthquake. Its proximity to the San Andreas and the consequent change in stress along that fault, however, is causing some scientists to reassess the probability of a large earthquake on the southern section of the San Andreas in the not-too-distant future.

And in a couple of other ways, too, the Landers quake seems to be, if not unique, at least a demonstration of phenomena that scientists had not observed before. One was the rupture of separate faults, jumping across from one to the other. Sieh believes that this multi-fault path of the Landers earthquake could have implications for faults closer to the Los Angeles area, such as the Raymond and the Sierra Madre faults, which are *really* in Caltech's back yard. The second, probably unique, phenomenon was the increased seismic activity that the quake seems to have triggered all over the state, particularly in the volcanic areas in northern California. Speculation has it that this could be just a sort of plumbing problem—shaking up the gas bubbles in the volcanic pipes—but it's not at all well understood. Despite what isn't understood, however, what has already been learned from the data on Landers, consistent from so many sources, fills in one more piece of the puzzle. Ultimately this will help scientists to chart California's substructure and perhaps learn what it holds in store for the future. □ —*JD*