

The Loma Prieta earthquake caused damage from San Francisco to Salinas, as shown here. The "Damaged two-story viaduct" is I-880.



Fault rupture of Loma Prieta earthquake—Arrows show relative horizontal movement; small arrow and numeral show direction and amount of dip; U, upthrown side; D, downthrown side

--- Fault—Dashed where approximately located

★ Mainshock epicenter

Area of aftershocks and abundant landslides

////// Area of ground cracks possibly related to faulting

..... Approximate limit of structural damage

- . - . - . Approximate limit of landslides

(L) Prominent area of liquefaction

(B) Damaged bridge

(D) Damaged dam

(V) Damaged two-story viaduct

0 10 MILES

CONTOUR INTERVAL
500 FEET

Shift Happens

The ground moved about two meters laterally, which was expected, and about one meter vertically, which wasn't.

All hell broke loose for 15 seconds in the San Francisco Bay area on October 17 at 5:04 pm PDT. The Loma Prieta earthquake, magnitude 7.1, killed 62 people, caused parts of the Bay Bridge and Interstate 880 to collapse, and put the World Series on hold. Loma Prieta may also become California's best-studied earthquake, at least until the Big One hits. (San Franciscans have dubbed Loma Prieta the Pretty Big One.) Scientists dissected it, in detail, with unprecedented speed—in some cases, while the ground was still quivering—thanks to a new generation of high-tech equipment. They found some surprises.

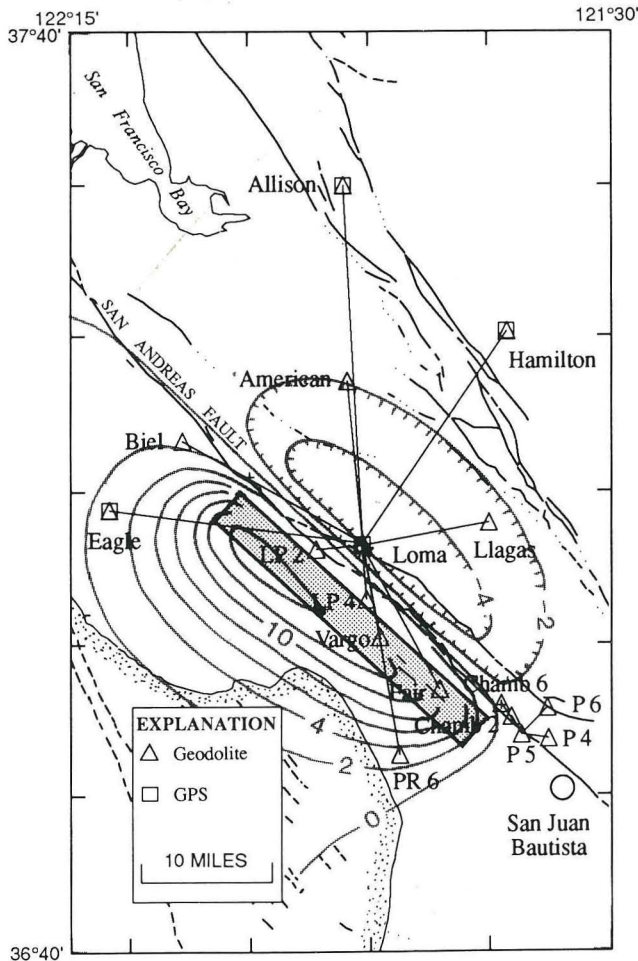
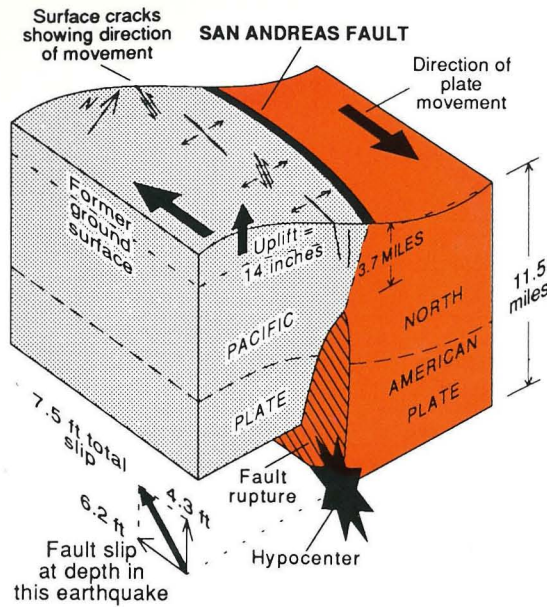
Initial seismographic analyses revealed that the ground moved about two meters laterally, which was expected, and about one meter vertically, which wasn't. The San Andreas fault, which bisects the state from the Gulf of California to Point Arena, about 110 miles north of San Francisco, and is presumed to have caused all the commotion, is a "strike-slip" fault, meaning that the two sides of the fault slip by each other horizontally along the line, or "strike," of the fault. The motion along the fault is "right-lateral"—an observer looking across the fault would see objects on the far side moving to the right. The fault marks the boundary between two of the dozen or so large pieces, or "plates," that make up the earth's crust. The Pacific Plate grinds along the edge of the North American Plate in a northwesterly direction at the rate of about two inches per year, about as fast as your fingernails grow. (The San Andreas absorbs roughly half that motion, with the rest being dis-

tributed along a complex tracery of less notorious faults.) The vertical component of Loma Prieta's motion, however, resembles that of a "reverse fault," in which the sides of the fault are thrust against each other, forcing crust on one side of the fault—the Pacific Plate, in this case—to ride up over the other.

Teams from Caltech, the United States Geological Survey (USGS), and other institutions surveyed the area to measure actual ground motion and confirmed that 1.8 meters (6½ feet) of strike slip and 1.2 meters (4¼ feet) of reverse slip had occurred. Postdoc Ken Hudnut and graduate students Shawn Larsen and Frank Webb spent about a week in the field with the USGS party. The party established 6 additional geodetic markers, or "monuments," in the mountains between Santa Cruz and Mount Hamilton, east of San Jose. Geodesy is the science of measuring the earth, and the monuments' exact positions on the planet's surface were recorded as they were deployed, so later surveys can track any subtle earth movements. A total of 10 stations are now sprinkled across the 20-kilometer-wide fault zone. The pre-existing stations (Loma Prieta, Eagle, Allison, and Mt. Hamilton) had had their positions updated monthly before the quake, allowing the displacements that caused the shaker to be measured very accurately.

The monuments' locations relative to each other and to other ones far from the fault zone were determined to within 0.5 centimeters (cm) horizontally and 2 cm vertically by using the Global Satellite Positioning (GPS) system. The GPS system will eventually include 21 satellites

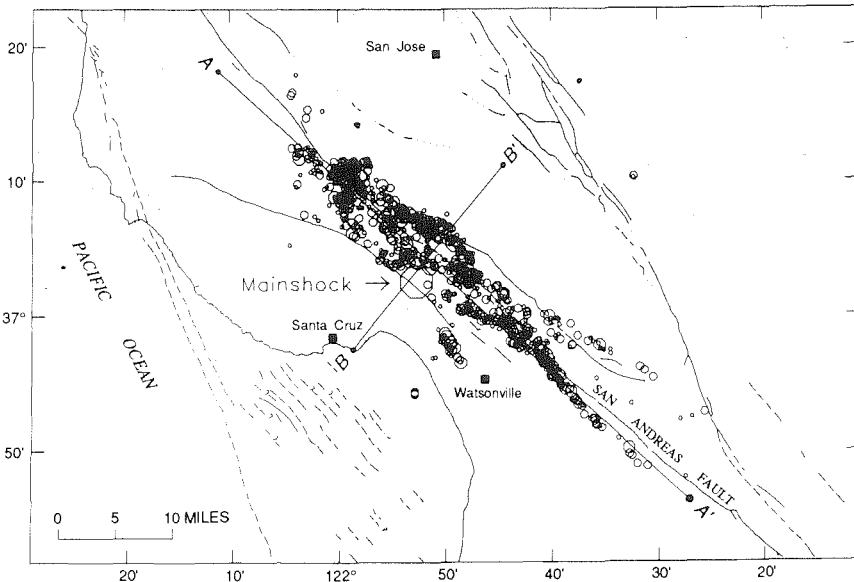
Right: How the fault moved.
Below: The geodetic network established to look for gradual ground movement since the earthquake. The contour lines to the west of the San Andreas show uplifted areas in 2-inch increments; the barbed contours to the right of the fault show subsidence. Geodolites are rangefinders: a laser beam at one station is bounced off a target at another to find the distance between them.



spaced so that at least 4 of them will usually be visible from any point on the earth's surface. (There are 10 GPS satellites functioning now, providing good coverage over North America for several hours each day.) The system was developed as an aid to navigation, and is widely used by ships and aircraft to determine their positions.

The geodetic data proved all-important, because when the Caltech team—which, in addition to the above three, included Professor of Geology Kerry Sieh, graduate students Lisa Grant, Paul Haase, and D. J. Wood, and Scott Lindvall, of Lindvall, Richter and Associates (a grandson of the late Professor of Engineering, Emeritus, Frederick C. Lindvall, and a colleague of Sieh's)—took a night trip up to look for corresponding surface ruptures, they couldn't find any. They crossed the fault on every road on the map between San Juan Bautista and Santa Cruz and came up empty. "We didn't do a whole lot of walking," says Sieh, "although some of the roads were closed, and we had to walk where there were trees across the roads, or rockslides."

"When we started up there on Tuesday evening, the day of the earthquake, I was quite confident that we were going to see 1½ to 2 meters (5 to 6½ feet) of offset, along maybe a 60-kilometer (km) (37-mile) length of the fault. That's because a year and a half ago, 12 of us from Caltech, the USGS, and other institutions had put together a report in which we forecast a magnitude 6½ to 7 earthquake along roughly this segment, based upon what was seen there in the San Francisco quake of 1906. The slip then was reported to have been about a meter and a



Left: The main shock and its aftershocks in relation to the San Andreas. The circles' sizes are proportional to the magnitudes. Lines are faults, dashed where inferred but not visible. The Sargent fault is the line parallel to, and immediately east of, the San Andreas. The line from B to B' is the cross-sectional plane into which the aftershocks are projected below.

Below: The vertical cross section shows how the aftershocks propagated up to the surface at a 70° angle. The "blob of seismicity" lies just under the surface, at the top of the belt of aftershocks.

half (5 feet) along the fault, and we suspected that the next earthquake would be accompanied by a similar offset at the surface. But, in fact, there was no surface displacement this time.

"This earthquake was unusually deep. It's about the deepest major earthquake in California during the period of instrumental record. The rupture zone appears to extend upward from about 18 km to about 6 km (11 to 4 miles) below the surface; commonly we see ruptures from 10 km (6 miles) right up to the surface. So the fault begins deeper than we had anticipated. I don't believe we've ever seen major slippage of the San Andreas fault at this depth before."

But this quake may not have been caused by the San Andreas fault, in the strictest sense. The aftershocks line up on a plane that rises from the hypocenter—the quake's point of origin, 18 km (11 miles) below the earth's surface—and rises toward the northeast at a 65 to 70 degree angle. Says Sieh, "The aftershocks aim up toward a point on the surface that is nearer the Sargent fault. The Sargent is a couple of kilometers east of the San Andreas at the surface, and is known to dip back toward the San Andreas. The San Andreas was presumed to be vertical here, but this earthquake and its aftershocks indicate it may not be. It may be that the San Andreas and the Sargent both dip to the southwest and merge together at a few kilometers' depth. That detailed structure is yet to be worked out." According to Hudnut, the latest cross-sections produced by the USGS show that many aftershocks lie in a "blob of seismicity" some 3 to 5 km (2

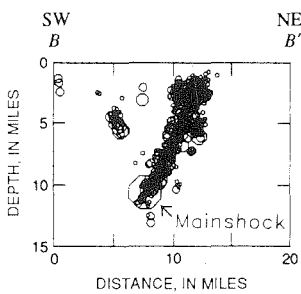
to 3 miles) underground between the Sargent fault and the San Andreas fault.

"We had forecast an earthquake of about this size in this location with a very high probability over the next 30 years," says Sieh. "And an earthquake of this size and location has happened, but it looks as if it's happened *underneath* the section of the fault that we thought was going to produce it.

"That raises an interesting set of questions. First of all, could the upper 6 or so kilometers (4 miles) now break with a magnitude 6½ or 7 earthquake? In some parts of the state, the Imperial Valley for example, creep occurs along the upper few kilometers of the fault in the years and decades following a big earthquake. On October 15, 1979, when there was a magnitude 6.4 earthquake down there—the Imperial Valley quake—the movement was about 2 meters (6½ feet) at a depth of, say, 8 to 10 km (5 to 6 miles), but only a fraction of a meter at the surface. The surface has been catching up ever since, by creep. It's still creeping at a centimeter or so a year. So a large percentage of the offset that occurred at the surface has been afterslip. But I understand that the geodetic resurveys after the Loma Prieta earthquake are not showing much additional slip. This fault may behave differently than faults in the Imperial Valley.

"Second, the length of fault that broke was not quite as long as we had thought. There are 30 km (19 miles) of the fault to the northwest, and 20 or so km (12½ miles) to the southeast that we are still nervous about."

In making their predictions, the seismologists





The crack seen round the world. This house on Summit Road, a few miles from Loma Prieta, became a media image when its front yard was found to host the biggest and most photogenic fissure.

divided the San Andreas into segments, each of which they suspect acts independently, accumulating and releasing strain on its own characteristic timetable, or "recurrence interval." Using the estimated recurrence interval and the date of each segment's most recent earthquake yields a probability for a similar quake in the next 30 years. Moderate to large earthquakes occur when a single segment lets go, but if one segment triggers a neighbor, like dominoes toppling, then a great quake such as the 1906 one occurs.

Seismologists were betting that the other shoe was about to drop when they predicted an earthquake on the Southern Santa Cruz Mountains Segment. In 1906, the 300-odd km (about 190 miles) of fault northwest of Palo Alto moved 4 or 5 meters (13 to 16½ feet), but the 75-km (45-mile) segment running to the southeast through the Santa Cruz Mountains moved only about one-third as much. If the amount of slip seen in the Santa Cruz Mountains back then is characteristic of that segment when it moves, then it should move three times more often in order to keep up.

"We thought a segment of the fault from Palo Alto to San Juan Bautista had a higher probability of rupturing than the segment farther northwest," says Sieh. "But in that 75-km segment there was one particular 30- to 40-km (19- to 25-mile) segment on the very southeast end that we thought had an even higher probability. What actually happened was that this earthquake sort of straddled those two segments. It was right in the middle of the 75-km segment on which we thought a magnitude 7 was

likely—a 20 percent probability in 30 years—and it overlapped about 50 percent with this southernmost 30 km. It isn't exactly the beast that we thought we were trying to catch. But it's pretty close."

Hiroo Kanamori, the John E. and Hazel S. Smits Professor of Geophysics, is not so sure. "The obvious question we need to ask is, first of all, is the type of event that people had expected, in terms of mechanism—the size and direction of the fault movement that caused the earthquake. The mechanism has caused a lot of trouble, because we still don't know whether this is really the characteristic San Andreas-type earthquake or not.

"This one apparently had almost one meter of uplift. And if this is the San Francisco-type earthquake, which happens, say, once every 100 years, that's equivalent to getting 1 cm of uplift per year—a meter uplift in an event with a 100-year recurrence time. If that were happening, you'd find a huge mountain, because 1 cm per year uplift is *very* fast, geologically—much faster than erosion."

Says Sieh, "It's not clear how rapidly the Santa Cruz Mountains are rising. Until better geologic studies are done in the area, we really won't know if this earthquake is characteristic."

"So this means two things," says Kanamori. "Maybe this is not the event people have been talking about. Maybe this is a much rarer event, a once-every-thousand-year event. And the other important question is whether this fills the entire gap or not. You can determine the rupture length of an earthquake from seismic body waves

because if the rupture is very large, it tends to produce a very wide pulse—a pulse with a long wavelength. But we could see that the pulse wasn't wide enough. We think that the rupture is more like 30 km or so, less than half of the gap. There is still a very substantial gap where the strain hasn't been released that can easily produce a magnitude 6 or so, which can have a profound effect on already-damaged structures. We are still worried about that. But I think the real problem is that we still don't quite understand how this fits into the recurrence pattern of the 1906 San Francisco-type earthquake, because the mechanism is different from what we expected. One possibility is that this wasn't on the San Andreas, and this particular fault might break once every thousand years instead of every hundred years. I wouldn't rule out that possibility, even if most geologists think that it's on the San Andreas. It isn't quite clear."

Although the media carried lots of pictures of spectacular cracks in the ground, none of these represent long ruptures along the San Andreas, according to Sieh. "Two types of fractures are common to earthquake regions: fractures that produce the earthquake, and fractures that result from the earthquake. Most of what geologists have seen can be explained best as fractures produced by the shaking—landslides and the like. A small percentage of the fractures are probably along minor faults within the broad zone of the San Andreas. The geodetic measurements seem to confirm that. Imagine strain accumulating over the years until the fault snaps. A geodetic station sitting near the fault is going to show an amount of motion similar to the amount of offset on the fault. But if instead you have strain accumulation and then breakage quite deep below ground, and the fault stays locked together near the surface, then you'll see much less stretching across the fault. The Loma Prieta monument, very close to the epicenter, only moved about 10 or 20 cm (4 to 7¾ inches) relative to stations quite far away. That alone suggests that not much happened on the surface. And that's quite consistent with the lack of surficial faulting that the geologists saw along the San Andreas."

Says postdoc Ken Hudnut, "This is the first significant earthquake where Global Positioning Satellite measurements before and just after the event provided displacement estimates within a day or two of the quake. GPS measurements have been made for other earthquakes, but they usually took a few months to process." A new GPS receiver, christened the "Rogue receiver" by its developers at Caltech's Jet Propulsion Labora-

tory (JPL), can get a highly accurate GPS fix in minutes instead of the six hours or so it usually takes. Therefore the receiver can be moved to various sites around the fault during the course of a day, rather than dwelling on one spot. This enhanced performance required both improved hardware and new techniques for data acquisition and analysis.

The GPS satellites broadcast time signals, which two ground-based receivers compare to their own internal clocks. The difference between the two times of reception is proportional to the distance between the ground stations, projected along the line-of-sight to the satellite. At least four satellites must be observed to pin the distance down in three dimensions. This information combined with phase measurements of the microwave carrier signal produces baseline estimates precise to about 1 cm.

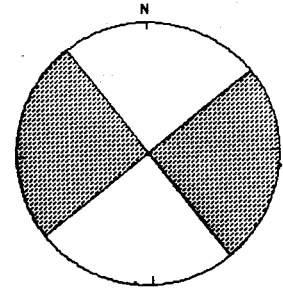
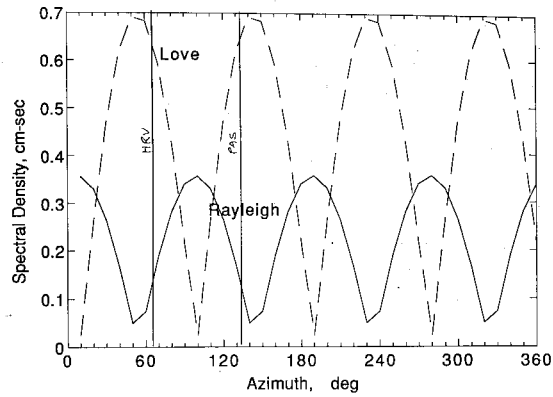
JPLers Geoffrey Blewitt, Tim Munson, and Steve Fisher took the Rogue receiver to their own set of 10 geodetic stations daily for 6 days in search of postquake creep, while Larry Young, Steve Dinardo, and Mark Caissy manned two fixed sites located on either side of the fault at San Jose and Soquel (near Santa Cruz), achieving with two fixed stations and the roving Rogue what it would have taken a dozen dedicated instruments to do before. Their preliminary results show postseismic motions of less than about 2 cm in the first week following the quake. The group plans to continue monitoring the area over the next year or so, with the next visit scheduled for January.

Meanwhile, back in the seismo lab, Kanamori observed the earthquake through the eye of the TERRAscope, which at the moment consists of a single high-fidelity, broad-band, high-dynamic-range digital seismometer, the first of a network of 12 that Caltech hopes to install in southern California.

The TERRAscope-type instruments have several significant advantages over the old-fashioned pen-and-drum variety. The data are recorded directly in a computer-readable digital format, making the information accessible instantaneously. Any seismology lab with a modern-equipped computer can call up the instrument and retrieve digital, ready-to-process data. The new instruments have a dynamic range about 10,000 times that of an ordinary seismometer, meaning that ground motions of all sizes—from a magnitude 1.5 tremor 30 km away that even the most nervous Nellie couldn't feel, all the way up to the Big One itself—are digitally recorded in faithful detail on a single scale. Ordinary seismometers have limited dynamic range, so

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Left: Surface waves such as Rayleigh waves (in which the ground vibrates forward and backward along the direction of propagation) and Love waves (in which the ground moves from side to side perpendicular to the direction of propagation) vary in intensity in different directions in a manner characteristic of the mechanism that produced them. The mechanism can be deduced from observed intensities in a few directions. In this case, the Rayleigh wave at Pasadena was very small for an event of this size, indicating that Pasadena lay near a node—a ray of zero amplitude. Plugging the data from Harvard into the standard strike-slip model with the proviso that Pasadena lay on a Rayleigh node gave this pattern. Zero azimuth is due north from the hypocenter. Pasadena, to the southeast, is the line at 133°, while Harvard, to the east-northeast, is at 66°.



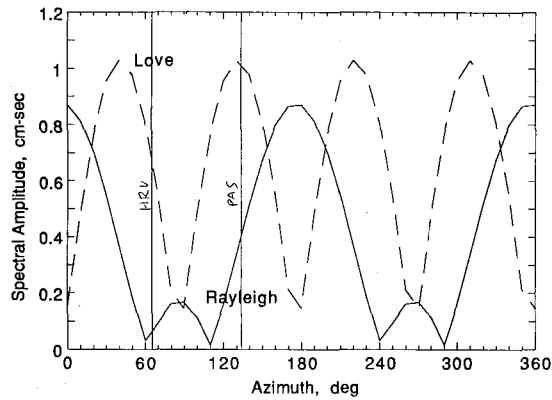
Right: The mechanism. Think of the circle as a top view of a tennis ball, sliced horizontally and its bottom half buried at the hypocenter. When the earth moved, the shaded quadrants were squeezed while the white quadrants were stretched. Thus, from the hypocenter's point of view, the Pacific plate shoves material ahead of it to the northwest, and drags material from the southwest along behind it. (The San Andreas runs northwest-southeast, but this same diagram would also apply to a southwest-northeast fault, where the northern plate is moving west and the southern one is going east.)

that if the instruments are set to record small earthquakes, as they usually are, their recorders are blown off the scale by anything larger—not unlike listening to a recording of the 1812 *Over-ture* and turning the volume way up so you can hear the quiet passages in the first movement. Standard seismometers also have a narrow frequency response, being sensitive only to motions with frequencies between 10 cycles per second (cps), and 0.01 cps. TERRAscope seismometers can detect movements at extremely low frequencies—all the way down to 0 cps or direct current, i.e., a very slow horizontal motion with no rebound, such as plate tectonic movement. Seismologists compare the birth of ultra-low-frequency seismometry to the advent of the radio telescope in astronomy, which revealed a whole new spectrum of phenomena visible only at wavelengths that were previously undetectable. Previous studies suggest that at least some earthquakes are preceded by “silent quakes”—long-period motions—in the minutes or hours beforehand. Says Kanamori, “Even the single station is useful. It’s very important to continuously record earthquakes from the smallest to the biggest, because there are so many puzzle pieces that we can look at.

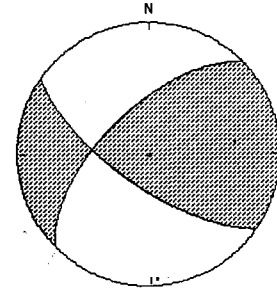
“Another aspect worth mentioning is the dial-up system. People can phone the station and retrieve data immediately after the earthquake. And this is very important, both scientifically and for disaster response. We can do a very quick analysis to determine the mechanism and how big the rupture zone is, and that shows where the damage is likely to be heaviest. And

people know this, so they call up.” The first caller, who logged on 11 minutes after the quake, was Brad Woods, a graduate student at Caltech. Kanamori, who had been on the phone during the quake, logged in 8 minutes later. Within 24 hours, more than 10 institutions had called, including the USGS and groups in Tokyo and Rome as well as half a dozen universities in the U.S. “When I look at the list of people who logged on, I see familiar names, like Susan Beck, who works at the Lawrence Livermore National Laboratory in the Bay Area. I was worried about our colleagues up there, of course, after the disaster, so it was nice to see her name. We knew that they were alive.”

Kanamori and everyone else initially assumed that this quake had a textbook San Andreas-type of right-lateral movement. This assumption, when superimposed on the TERRAscope data and data from a similar dial-up station installed at Harvard in early 1987, allowed him to fill in the details of a plausible mechanism. “Both Harvard and we did the same thing, and the initial solution we came up with, very quickly, was the San Andreas-type mechanism. And that fit the very-long-period waves recorded at Pasadena and Harvard. However, when we looked at some of the shorter-period seismic body waves, it became very obvious that that mechanism couldn’t explain these waves. Actually, [Professor of Geophysics] Don Helmberger saw this record for the first time right after the big quake and said, ‘Wow. This can’t be the San Andreas-type mechanism.’ He knows these things by experience, just by looking at them.”



Above: Additional data forced a revision of the mechanism. Pasadena still lies near a Rayleigh node, but the rest of the intensity pattern is quite different.



Far right: The new mechanism corresponding to this pattern. The quadrants are tilted because the fault plane is no longer perpendicular to the page—the Pacific Plate, to the southwest, is riding up over the North American Plate to the northeast. (Remember, this is the bottom half of the tennis ball!)

Right: Although scientists chose this diagramming system for a good reason—the waves recorded at all seismographs except for those in a quake's immediate vicinity emanate downward from the hypocenter and are reflected back up to the instrument—even they find it hard to visualize. Most, like Kanamori, keep a visual aid on hand to help them align fault motions with the map.

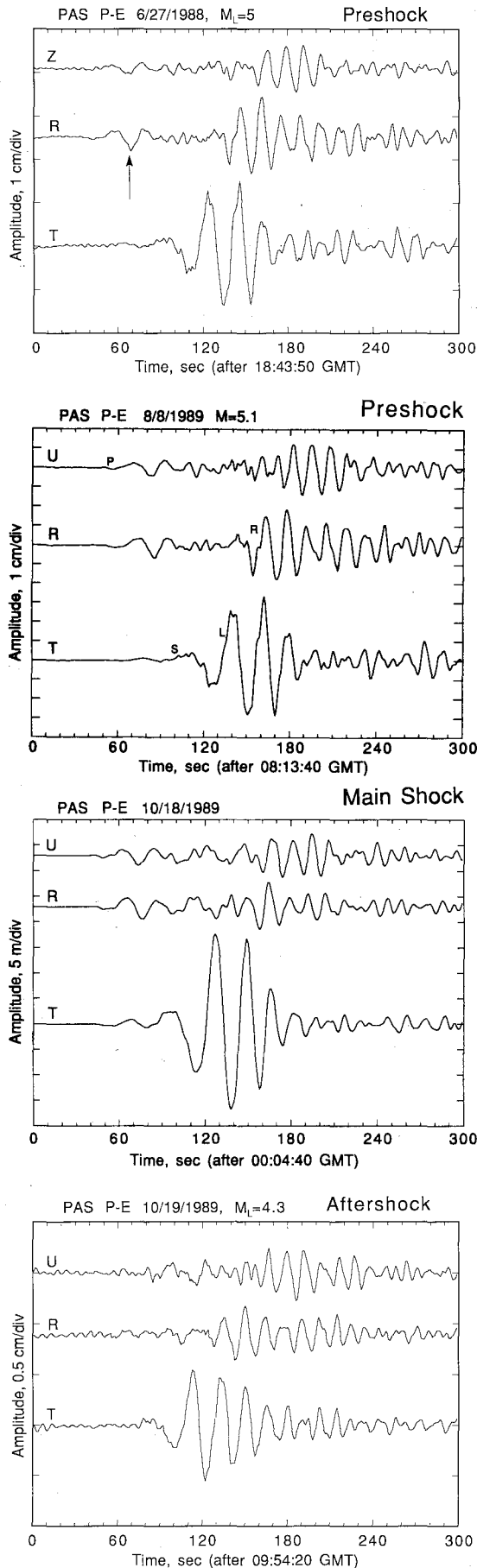


Like the light waves from an electric bulb, seismic waves can be thought of as rays emitted by a point source—the hypocenter. Just as a person looking at a light bulb in a glass box will see multiple images of the bulb because reflected and refracted rays take many different paths to the viewer's eye, so does the waveform recorded at a seismographic station show seismic rays reflected back from many directions to the instrument. But seismic rays have different amplitudes (and polarities) in different directions, depending on the exact motion, or mechanism, that generated them. A better analogy is a light bulb that has been painted black in places, so that no light shines through those areas. Now if the bulb were rotated 90 degrees, say, the viewer would see a new set of multiple images. So, too, an earthquake at the same hypocenter but with a different mechanism—the product of different forces—would produce a different set of seismic rays adding up to a different observed waveform.

The long-period surface waves have periods of about 200 seconds, and propagate around the earth's surface with wavelengths on the order of 1000 km. These waves also appear on the regular, old-fashioned pen-and-drum seismograms, but they cannot be seen until the record has been laboriously converted into digital form by hand, and certain high-frequency surface waves—which have much bigger amplitudes and thus mask the long-period waves—have been removed by mathematical analysis.

The short-period body waves that forced a modification of the mechanism have periods of about 10 to 20 seconds and travel through the

Seismograms reconstructed from the Pasadena station TERRAscope data. The wave missing from the aftershocks is marked by an arrow. Each seismogram has three components. Z or U is vertical displacement. R is radial displacement—compression or expansion in the plane of the earth's surface, on lines radiating outward from the source. T is transverse displacement—also in the plane of the earth's surface, but perpendicular to R. Real seismographs, including the TERRAscope, record vertical ground motion to give Z directly, but record horizontal ground motion only along north-south and east-west axes. T and R must be derived from that data and the direction to the hypocenter from the instrument, a calculation that used to take hours or days. In the second seismogram, R is the Rayleigh wave, L is the Love wave, P is the "primary" body wave whose arrival at the seismograph is the harbinger of a quake, and S is the "secondary" body wave—a slower-moving shear wave. The arrival-time difference between the P and S waves is proportional to the distance to the quake, and the P wave's direction of first motion shows which way the earth moved.



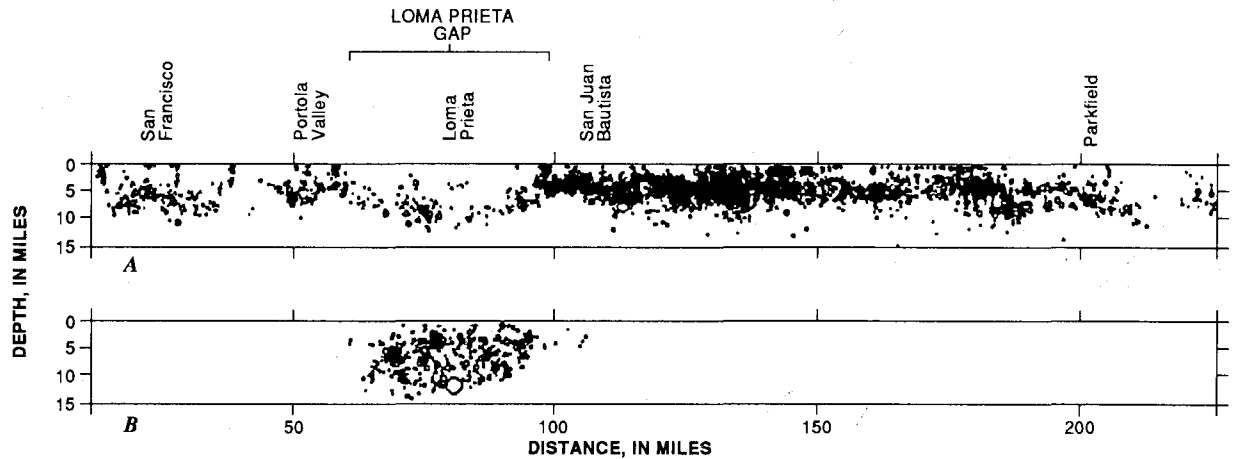
"Seismology is getting more exciting, because we have high-quality data immediately, instead of in a few months."

earth's interior, where they are reflected and refracted back to the surface. (These body waves travel faster than the surface waves, and arrive early enough so that they don't mask the long-period waves.)

"So by combining those waveforms," says Kanamori, "we came up with a solution where the fault is dipping southwest from the earth's surface, and in addition to pure right-lateral slip, there is a vertical component. Many people called up the data and obtained this solution the day after the quake.

"In the past, it took us months to do this, collecting all the records one by one, digitizing them by hand, and doing very primitive analysis. Now we can do it in a day, using telephone lines. It should be possible, eventually, to do it within minutes through satellite telemetry. This is really the difference modern seismic networks like the TERRAscope make.

"Another interesting thing is the TERRAscope record of the two preshocks, on June 27, 1988, and August 8, 1989, both of about magnitude 5, shown above left. The vertical scale of 1 cm per division is the amplitude we would have seen if this had been recorded on a standard paper recorder—about 3 cm amplitude. For the main shock below it, the vertical scale is 5 meters per division, so its amplitude would have been about 35 meters! (The actual ground motion in Pasadena was about half an inch.) Ordinary seismic instruments can't accommodate such a large range, but the TERRAscope does this very easily, so you can immediately compare events of different sizes. The interesting thing is



A: Earthquake distribution along the San Andreas over the past 20 years. Sections of the fault that are sticking and accumulating strain have fewer earthquakes. These segments are called "gaps," and are likely to release their strain in one large quake. In the Loma Prieta gap, what few earthquakes had occurred defined a U-shaped region that had been very quiet indeed.

B: The Loma Prieta quake (largest circle) and its aftershocks almost completely filled the gap.

that aside from the difference in the amplitude, the waveforms look very similar. And for them to be very similar, we need to have a very similar mechanism. So that makes the preshocks somewhat special.

"Now compare them to this other earthquake on the bottom, which is an aftershock of magnitude 4 or so. It also appears similar to the main shock, but if you look at it very carefully, one wave [labeled] is missing. This aftershock is presumably more the strike-slip-type, San Andreas-type mechanism, but the main one and the preshocks aren't, which again might indicate that another fault is involved."

Says Sieh, "Those two earthquakes were recognized as being unusual at the time. That particular part of the fault hadn't had earthquakes of that size since 1906. The geologists and seismologists who are aware of these patterns looked at those quakes and said, 'Hey, there's something very strange going on here.' And they were very worried. The community talked a lot about the implications of those earthquakes, and, in fact, the USGS issued a 'short-term advisory' each time." A short-term advisory states that for three days from the date of issue there is a slight increase in the probability of a damaging earthquake of magnitude 6.2 or greater in the area named. Such predictions are based on an analysis of foreshock behavior published in 1985 by the USGS's Lucy Jones, who is also a visiting associate in geophysics at Caltech. A foreshock is an earthquake that precedes a larger earthquake in the same spot by less than 72 hours. Since roughly a year separated these events, the term

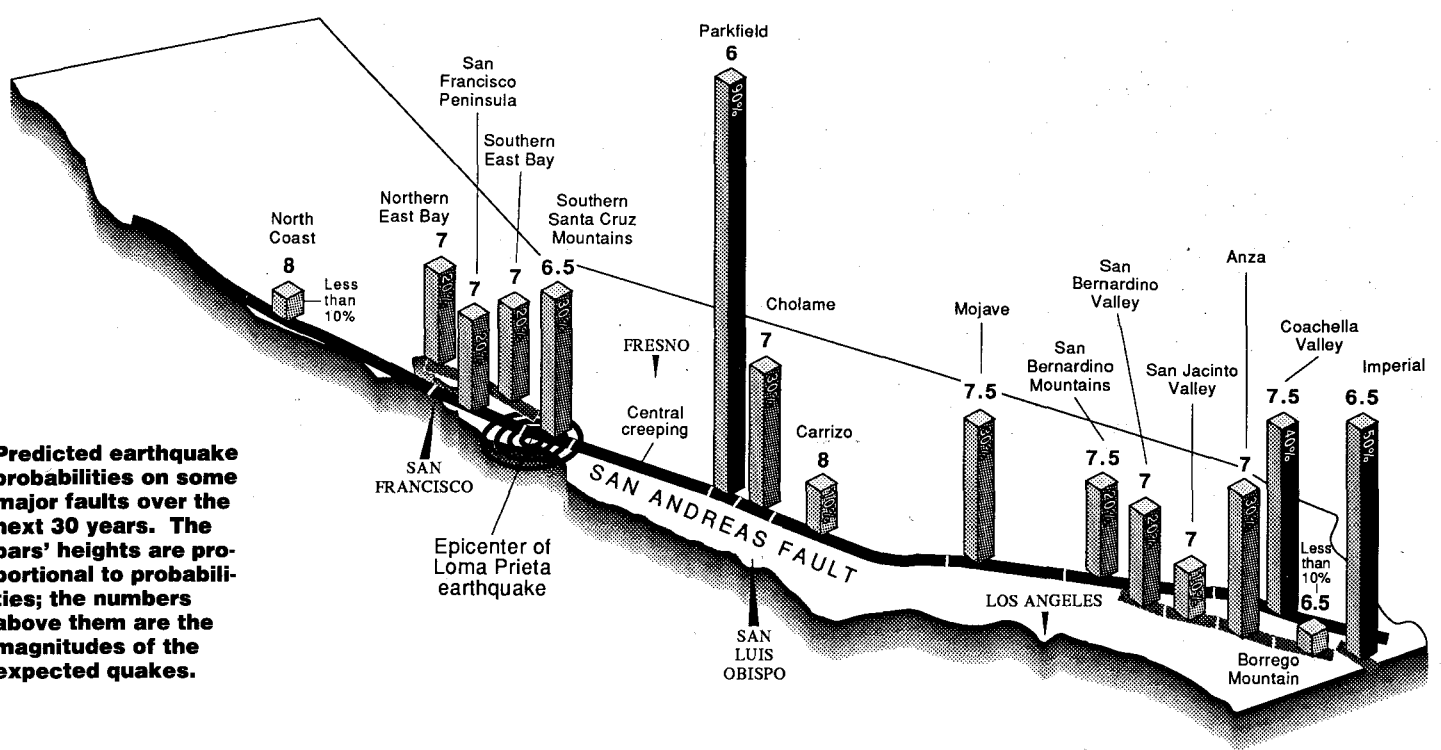
"preshock" was coined instead. All such designations are necessarily retroactive.

"In the next few years we'll have several TERRAscope-type real-time stations," says Kanamori, "which is important because in order to do such detailed mechanism studies we really have to be very close in—within, say, 10 km or so of the epicenter. We can still get valuable data from farther away, but most of the important information is lost by attenuation.

"Sometime in January we hope to have a second station at Piñon Flats, on the San Jacinto fault near Hemet, to be collocated with a station operated by UC San Diego. And by late summer 1990, we'll have three more, supported by the Whittier Foundation. The candidate sites are near Goldstone, in the Mojave desert; near Santa Barbara; and probably near Lake Isabella. The Pasadena station will remain where it is, in the Kresge Laboratory—in the San Rafael Hills near the Rose Bowl. There will also be a TERRAscope-like station near San Bernardino, to be operated by the Pasadena office of the USGS. So by mid-1990, we'll have a reasonably configured network in southern California. And UC Berkeley is planning a similar network up in northern California.

"But even with just one station, we are getting a tremendous amount of information. Seismology is getting more exciting, because we have high-quality data immediately, instead of in a few months. And I think it's very important that we can involve the whole world in the study of this earthquake. Everyone has the same advantage that we do, in a sense. It's a good,

Predicted earthquake probabilities on some major faults over the next 30 years. The bars' heights are proportional to probabilities; the numbers above them are the magnitudes of the expected quakes.



healthy competition, and that promotes science. Five years ago, this wasn't easy data to share. It was this technology that made it possible.

"And this system isn't the final configuration. It's slow, and it can clog up the phone lines. The next step is the Gopher system, run by the University of Washington as part of the IRIS (Incorporated Research Institutions for Seismology) program to deploy state-of-the-art instruments all over the world. IRIS is a consortium of about 50 universities, including Caltech. Several of the TERRAscope stations, including the Pasadena one, will also be part of the IRIS network. Gopher itself is a software package that dials up all these stations at Pasadena and Harvard and Albuquerque and so on after a major earthquake, automatically retrieves the data from them, and sends it to a data-management center in Austin for distribution. That's more convenient for most people, because the center is on several nationwide computer networks. Eventually, of course, we need satellite telemetry, which is much faster and more expensive. So this is really semi-real-time seismology, but we're moving toward real-time seismology. We need to get the data very quickly, determine the mechanism, and provide that information to local government officials so that they can take appropriate postseismic measures."

Says Sieh, "Yes, there were some surprises, but the most important thing, in my opinion, is that we had forecast an earthquake of about this size at about this location. We took 1,100 km (700 miles) of the San Andreas fault, and there are five segments of that fault likely to have a

big earthquake in the next 30 years. This was one. The other four segments are in southern California. This earthquake gives me and my colleagues greater confidence in those forecasts. The lesson, I think, is that we basically got this one, and now people ought to be paying a lot of attention to these other ones." □—DS

The other four predictions, published in the USGS Open-File Report 88-398, are: for the Imperial fault (which runs through the predominantly agricultural Imperial Valley from south of the Salton Sea on into Mexico), a 50 percent chance of a magnitude 6.5; for the Coachella Valley segment of the San Andreas (its southernmost 100 km, starting at the San Geronio Pass and running by Palm Springs and Indio to the east bank of the Salton Sea), a 40 percent chance of a magnitude 7.5; the Anza segment of the San Jacinto fault (a 50 km segment in the Santa Rosa Mountains, west of the Salton Sea), a 30 percent chance of a magnitude 7; and the Cholame segment of the San Andreas (a 55-km stretch extending from the tiny, central-California town of Cholame on south), a 30 percent chance of a magnitude 7. The fifth prediction, published in the same report, is for the Parkfield segment of the San Andreas (a 30-km stretch through rural country north of San Luis Obispo), better than a 90 percent chance of a magnitude 6; this segment, which has had a similar earthquake approximately every 21 years since 1881, last broke in 1966 and is currently the focus of an intensively instrumented USGS study to detect earthquake precursors.

"There are five segments of the fault likely to have a big earthquake in the next 30 years. This was one."