



The Northridge Earthquake and the “Earthquake Deficit”

by Egill Hauksson

This four-story apartment building on Hollywood Boulevard west of Normandie Avenue is actually a seismic success story. The building had been retrofitted with steel tie rods to hold its brick facade to its interior members. As a result, although the building suffered severe damage, it did not collapse and no one was killed in it. The tie rods' ends are the disk- and diamond-shaped plates visible at floor and roof level across the front of the upper stories.

The Northridge earthquake, moment magnitude 6.7, occurred on Monday, January 17, at 4:30 a.m., getting those of us who live in the Los Angeles region out of bed a little earlier than usual. We were lucky in that respect—if the earthquake had occurred in the daytime, many more than 60 people would certainly have died. (Incidentally, several hospitals had to be temporarily closed or evacuated, mostly because of water loss or water damage from broken plumbing.) Seven large parking structures belonging to malls, hospitals, and a university collapsed—some partially and some almost completely—and many public buildings, from schools to shopping malls, suffered heavy damage, as did several freeways. But that's another story, one for the structural engineers to tell. I'm going to describe the earthquake itself, how we measured it, and what we learned from it.

Shortly after the earthquake, the press pointed out that all the recent earthquakes—San Fernando in '71, Whittier Narrows in '87, Sierra Madre in '91, and Landers in '92—had been in the early morning hours. Why was that? So we went back to our earthquake catalog and looked at the last 50 years, and the press had indeed identified a pattern. A plot of Southern California earthquake magnitudes from 1945 to 1994 as a function of time of day shows five earthquakes of magnitude 6.7 or greater between 4:00 and 6:00 a.m. But below magnitude 6.6, the earthquakes are scattered randomly throughout the day and night. This tells us that the sample of large earthquakes is statistically insignificant. Simply put, we haven't had enough big earthquakes to complete

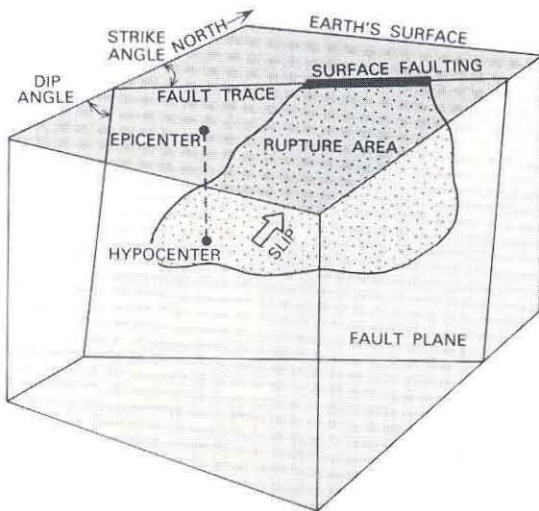
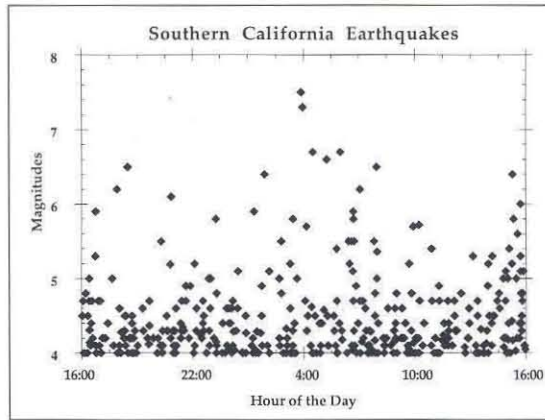
the plot. Big earthquakes can happen at any time, so everybody has to be earthquake-prepared day and night.

At Caltech, we're always prepared. We record earthquakes whenever they happen—24 hours a day, 365 days a year—through a network of instruments we run in cooperation with the U.S. Geological Survey (USGS). These instruments are scattered from the Mexican border up into Owens Valley, and from Needles to Coalinga. There are 240 seismographic stations that contain 340 different seismometers, which are the instruments that actually record earthquakes. Most of these stations contain a single instrument that measures vertical motion, but some of the stations contain multiple instruments to measure motion in all three dimensions. All of these instruments are connected to Caltech's earthquake data center by dedicated phone lines, microwave links, or radio links, so that we get the data immediately.

Most of our network consists of standard-issue instruments, but 17 of our sites are TERRAScope stations—state-of-the-art digital seismometers. Unlike conventional seismographs, which are designed to measure only ground motions within a fairly narrow frequency range and which “saturate,” or go off-scale, if the earthquake is very large or very close by, digital seismometers can record movements of any size at any frequency. A TERRAScope station has a set of three sensors that measure small-amplitude up-down, north-south, and east-west motions; a second set of sensors for measuring large-amplitude motion (the shaking that actually causes damage) along

We've had a lot of earthquakes over the last five years, and we're likely to have some more over the next five years.

Right: Earthquakes of all sizes happen at all hours. We just haven't had enough large ones to fill in the graph.
Below: An earthquake's moving parts.



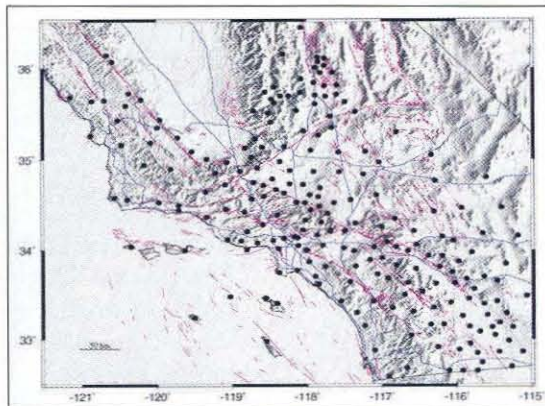
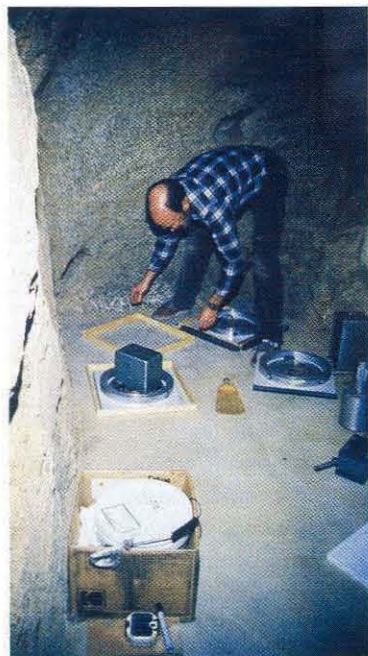
Below: The Southern California Seismographic Network, run jointly by Caltech and the USGS, consists of 240 seismographic stations (black dots). The purple lines are faults; blue lines are freeways.
Left: David Johnson, the seismo lab's field technician, installing new TERRAscope instruments in an old gold-mine tunnel near Lake Isabella.

those same three axes; and a GPS (Global Positioning Satellite) receiver that we use to determine the waves' arrival times very precisely. (Most applications of the GPS system use these receivers to determine locations, but the system also generates time signals that are accurate to one-millionth of a second.) A computer at the station records all this data and transmits it back to Caltech via satellite or over a dedicated phone line. Seismologists at other institutions can then retrieve the data from our data center, using high-speed modems, or over the Internet.

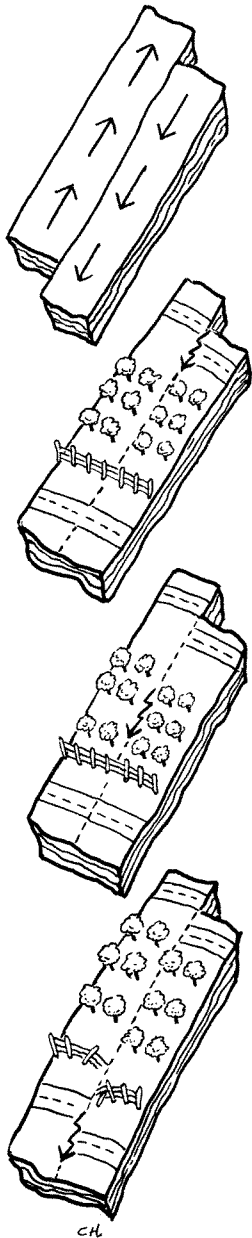
When an earthquake happens, we don't know where it was or how big it was, but computers in the Seismo Lab automatically record its waves and their arrival times at our seismometers. An earthquake record consists of a P, or primary, wave—so called because it travels fastest and arrives first—followed by a slower S, or secondary, wave, plus other waves. The P and the S waves travel at well-known speeds, so the delay between the P wave's arrival and the S wave's arrival tells us how far away the earthquake was from the recording instrument. It's exactly analogous to seeing a lightning flash and then counting the seconds until you hear the thunder in order to find out how far away the lightning bolt is. One distance measurement tells us only that the earthquake lies somewhere on a circle of that radius from the seismographic station, but taking the data from many stations gives us the exact location in three dimensions—the point where all the circles intersect. Once we know the location, we can derive the magnitude from the size of the waves we record, because the waves get smaller as they travel farther away from the source. All these measurements and calculations used to be done by hand, with a ruler and a pencil, but now we use high-speed workstations that do much of the work automatically and allow the data analysts to review the results very quickly.

Where the earthquake starts—its focal point at depth—we refer to as the hypocenter. The epicenter is the projection of that point up to the earth's surface. While you can think of a magnitude 2 or 3 earthquake as having a point source, that's not so in larger earthquakes. In the Northridge earthquake, for instance, a section of fault 17 kilometers long and 13 kilometers deep broke. We *do* calculate a latitude and a longitude for the epicenter, so there is an "exact point" of sorts where the earthquake began, but we seismologists don't take that location too seriously because we know that the earthquake's waves are, in fact, radiating off every point on the entire plane of the fault that breaks.

The graphic on the opposite page lists the



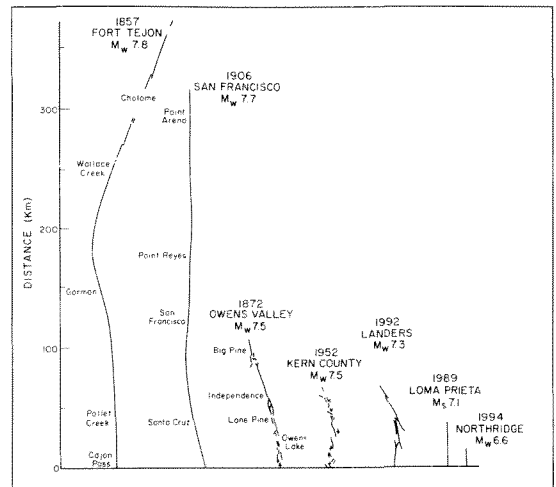
Right: A comparison of how much fault broke in several notorious California earthquakes. Left: Until recently, it was assumed that an entire piece of fault moved as a unit during an earthquake (top drawing). But seismologists now believe that the slip begins at a single point, and travels along the fault like a zipper (the jagged arrow in bottom three drawings).



fault length for several California earthquakes. As you can see, Northridge, Loma Prieta (40 kilometers), and Landers (80 kilometers) all broke fault sections of roughly similar length. But compare the Fort Tejon and San Francisco earthquakes, which respectively ruptured for about 370 and 400 kilometers—the latter including some 80 kilometers of seafloor from Bodega Bay north toward Cape Mendocino that's not shown on the graph. These two are what we refer to as major or great earthquakes, the sort that occur on the San Andreas fault, like the coming earthquake that the press refers to as the Big One. So Northridge was, in fact, only a moderate-sized earthquake. It just happened to be underfoot.

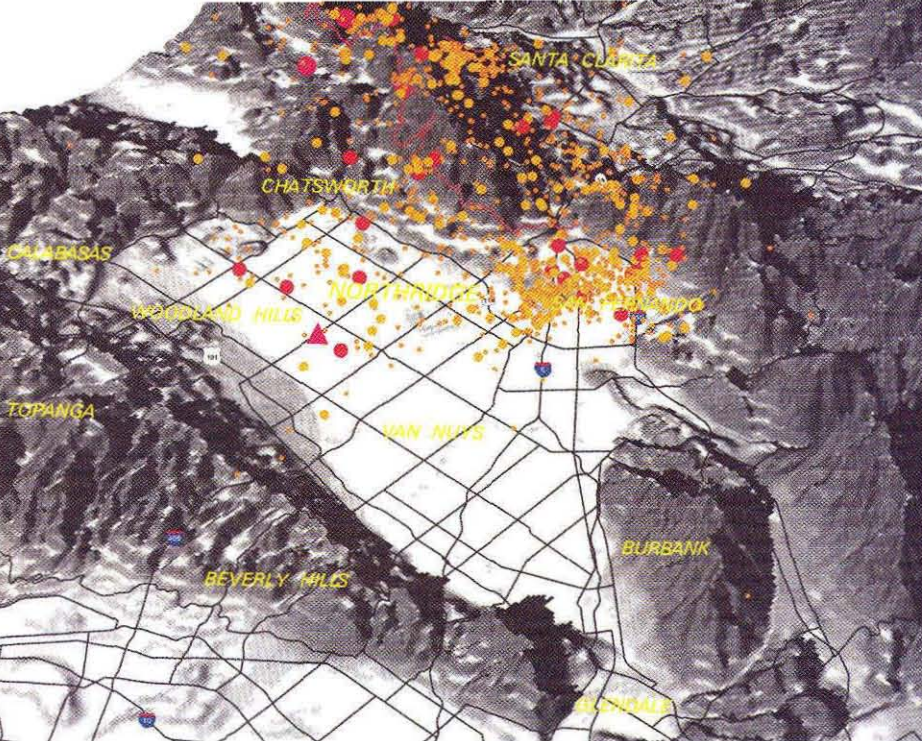
There are a few simple rules about earthquakes: the bigger the earthquake, the larger the piece of fault that breaks; the bigger the earthquake, the farther the fault is displaced; and, finally, the bigger the earthquake, the longer it's going to last. In the Northridge earthquake, the fault moved about two meters. In the Big One, the movement could be 10 meters. It took six or seven seconds for the rupture to complete its travel along the fault segment that the Northridge earthquake was on. The Big One may take two or three minutes to break, depending on where the rupture starts. So if by the time you realize you're in an earthquake it's all over, you know it was a small earthquake. But if the shaking continues or even intensifies, you know you're in a big earthquake.

Our ideas about how earthquakes work have changed over the last decade. We used to think



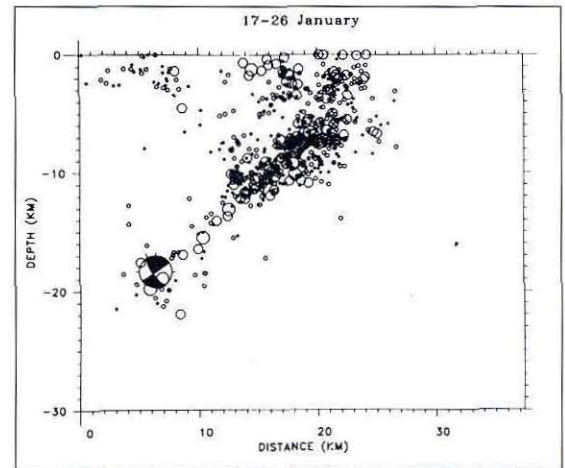
that one rigid block of rock would lurch past another rigid block, so that the whole fault moved at once. We now believe that the movement starts in one spot on the fault and propagates along it at about a mile and a half per second. (The speed at which the fault breaks is not the speed at which the P, S, and other waves travel.) A carpet layer putting a big rug on a ballroom floor is a good analogy. Suppose he suddenly realizes he's made a mistake—the rug is too close to the wall, and he has to move it out two feet. He tries pulling on the rug, but it's too heavy to move. But if he walks over to the wall and makes a fold in the rug, he can push the fold across the room with very little effort and move the rug two feet. The same thing happens underground—there's a fold, or pulse, that goes along the fault and allows the rock to move.

Other earthquakes rattled the Los Angeles area in the days before the Northridge earthquake. Starting on Sunday, January 9, there was a swarm of about two dozen small earthquakes under Santa Monica Bay. Many of them were felt, including a magnitude 3.7 just offshore of Venice Beach at three o'clock that afternoon. At Caltech, we refer to these as "media earthquakes"—they don't cause damage or injuries, but all the TV crews go out and ask people what it felt like. Also, 12 hours before the Northridge earthquake, we had a small cluster up near the Holser fault, by Castaic Lake. Both clusters were part of the same overall process that created the Northridge earthquake—the compression of this part of California—but neither was on the same fault as the Northridge earthquake, so we don't



Above: The San Fernando Valley, as seen from the east-south-east. Downtown Los Angeles is off the map to the lower right. The main shock's epicenter is the pink triangle in the lower left, and the first week's worth of aftershocks are plotted as circles. The circle's size is proportional to the aftershock's magnitude; those of 3.9 or less are in yellow, 4.0 or greater are in red. The jagged red line in the mountains is the Santa Susana fault. (3-D Map courtesy of ESRI, Redlands, CA; street map © Thomas Brothers Maps.)

Right: A cross section through the valley and north-northeast into the San Gabriel Mountains, into which the aftershocks have been projected. The main shock is shown as a beach ball; aftershocks are open circles. The beach ball's dark quadrants indicate compression and the light quadrants expansion, showing that the fault moved up toward the surface at an angle of about 40 degrees.



refer to them as foreshocks. We prefer the term “preshock” instead, because we don’t really understand how they are related mechanically to the Northridge earthquake.

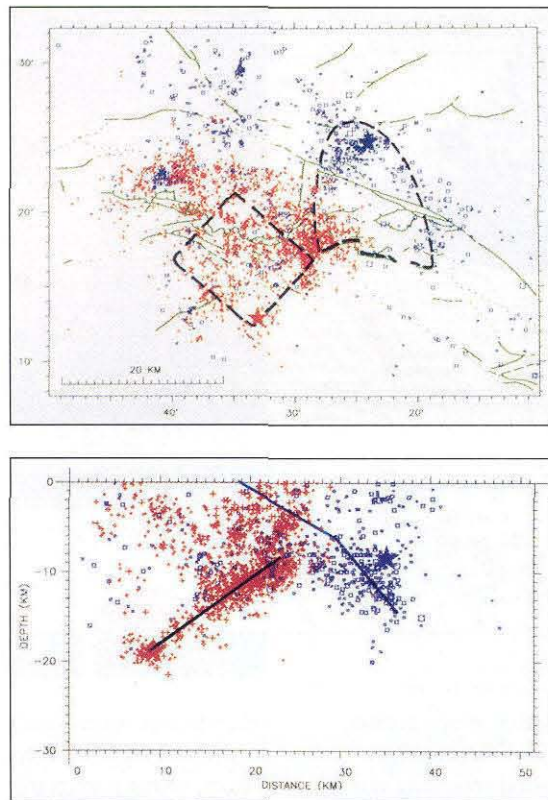
The Northridge main shock was beneath the floor of the San Fernando Valley, as shown in the map above. The majority of the aftershocks (circles) were also below the valley, and most of the rest were below the Santa Susana Mountains. (The Santa Susana fault, by the way, was not involved in this earthquake sequence.) The main trend in the aftershocks is northward and toward the surface, but there is a second block of very shallow aftershocks directly over the hypocenter, as shown in the cross section, above right. The main shock was about 19 kilometers deep, and the aftershocks that scattered up from there to a depth of eight kilometers or so defined the fault plane that broke during the earthquake. The aftershocks that continue straight up to the surface from there are probably related to the deformation of the near-surface material in response to the main shock—as the rock deep underground is thrust upward, the shallower layers on top of it had to move to accommodate it.

Because the Northridge earthquake’s fault lies directly beneath the densely populated San Fernando Valley, there was tremendous damage. Most of the valley lies within the Los Angeles city limits, and by mid-February the city’s Department of Building and Safety had inspected some 65,000 residential buildings in the valley and elsewhere and had red-tagged—declared unsafe to enter—1,608 of them, including many large apartment complexes. Another 7,374 bore

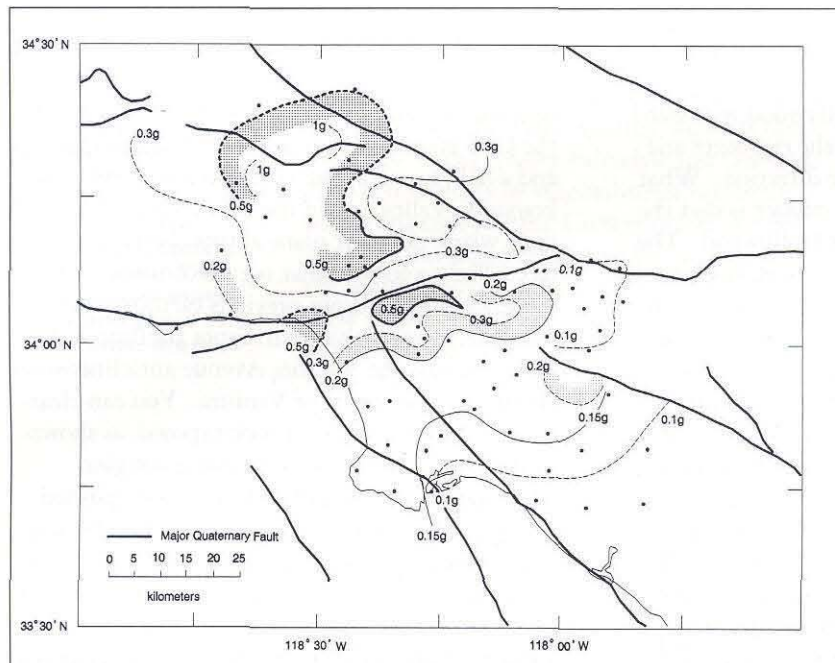
yellow tags, indicating they were safe for entry for short periods to retrieve personal possessions. (An estimated 20,000 people camped outdoors for the first few days after the earthquake, either because their homes were uninhabitable or for fear of aftershocks; some 9,000 remained in Red Cross shelters and tent cities 10 days later.) Transportation links were severed. Collapsed bridges shut down portions of Interstates 5 and 10 and State Routes 14 and 118, and a freight train derailed in Northridge, blocking the tracks. Several major high-voltage substations within a few miles of the epicenter were knocked out, and some two million customers in the Los Angeles area lost power for the better part of the day; 900,000 of them had their lights back by dusk, but service to some places was not restored for more than a week. In a demonstration of the interconnectedness of our technological society, shattered ceramic insulators in Sylmar led to a three-hour blackout for 150,000 customers in rural Idaho, as well as isolated outages in seven western states and British Columbia. By contrast, the 1971 San Fernando earthquake, which was of equal magnitude and occurred right next door, was beneath the San Gabriel Mountains. Most of the strong ground shaking then was in the sparsely populated mountains, so the damage was much less severe.

Despite their resemblance in size and place, the San Fernando and Northridge earthquakes were very dissimilar animals. Their rupture planes (dashed areas on the top map on the opposite page) abutted, but didn’t cut across each other. A cross section through their faults reveals

The San Fernando earthquake and its aftershocks (in blue) and the Northridge earthquake and its aftershocks (in red) ruptured adjacent fault planes (dashed outlines), as shown in the upper plot. The two main shocks are rendered as stars. The solid black lines are mapped faults. North is at the top. Projecting the epicenters into a cross section from southwest to northeast reveals the faults that broke (lower plot). The San Fernando earthquake ruptured a steeply dipping fault and then a more shallowly dipping fault all the way to the surface. The Northridge earthquake was on a buried fault that didn't reach the surface.



Below: A contour map of horizontal ground shaking as a percentage of gravity. The darker shaded areas experienced in excess of 50 percent of gravity (0.5 g). The dots are instrument locations.

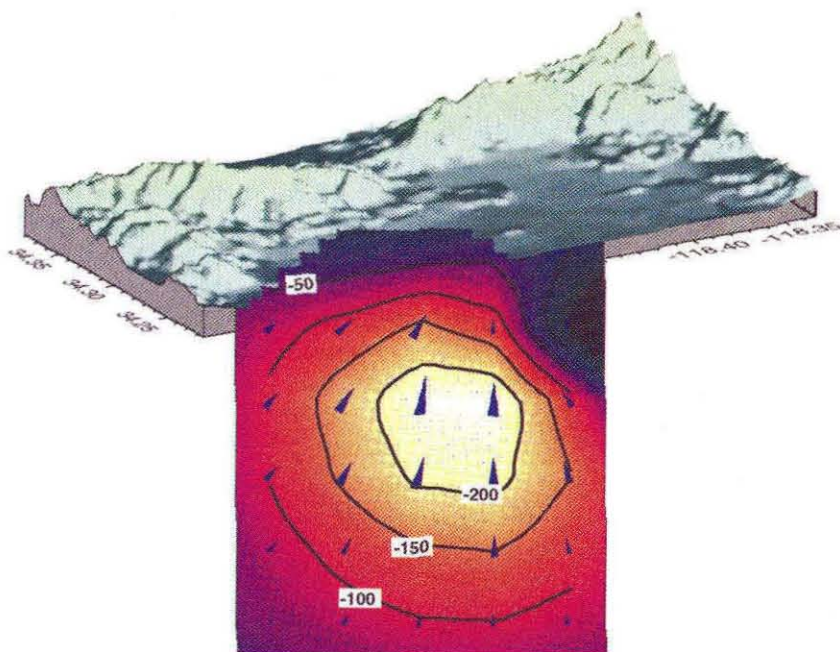


the key difference. The San Fernando earthquake started at a depth of 12–15 kilometers and ruptured all the way up to the surface. In contrast, the Northridge earthquake started at a depth of about 19 kilometers and ruptured up to a depth of 8 kilometers. These are two basically different types of faults: the San Fernando earthquake was caused by movement on a surficial, or surface-breaking, fault, and the Northridge earthquake was caused by movement on a blind, or buried, fault. (Both earthquakes were on reverse faults—a type of fault in which one side of the fault thrusts itself up and over the other. The San Andreas fault is a different type, called strike-slip, in which the two sides of the fault slip sideways with little or no vertical motion.)

And that's the first of three important lessons from the Northridge earthquake: that these blind faults, whose existence was first revealed by the Whittier Narrows earthquake in 1987, lie beneath much of the greater L.A. area. This earthquake confirmed that these faults are widespread and thus extremely dangerous.

The 1971 San Fernando earthquake left a surface rupture—a fault scarp. Nothing like this was found following the Northridge earthquake, simply because the rupture zone did not make it up to the surface. Nonetheless, the Northridge earthquake did cause ground deformation in the epicentral region, in Mission Hills, and in Potrero Canyon. This deformation was subtle in many cases—a slight bump in a sidewalk, an inch or two offset in a curb—but sufficient to crack foundations and break water and natural-gas mains.

About 95 percent of earthquake damage is caused by ground shaking, not deformation. If the ground is shaking with an acceleration that is 10 percent of the force of gravity, you'll feel it but there won't be much damage. Buildings that conform to California's Uniform Building Code are built to withstand horizontal shaking at 40 percent of gravity. (Buildings are routinely designed to carry much greater vertical loads—100 percent of gravity, which is simply the building's own weight, plus another 100 percent or so as a margin of safety to account for the occupants.) During the Northridge earthquake, the San Fernando Valley, Granada Hills, Mission Hills, and Woodland Hills all experienced horizontal ground shaking 50 percent or more of gravity, as did areas in Santa Monica and Hollywood. This is very severe shaking, and explains why there was so much damage. The strongest shaking generally gets focused in the direction along which the fault plane breaks. This fault plane aimed north and to the surface directly at



Above: In this view of the San Fernando Valley, we are looking down into the ground at an angle perpendicular to the Northridge earthquake's fault plane, or about 40 degrees from the vertical and 30 degrees east of north. The arrows show the direction of movement along the fault, while the contours show the thrust (vertical) component of that motion in centimeters. The numbers on the contour lines are negative to indicate that the north, or underside, of the fault moved downward with respect to the south side of the fault. The south side of the fault is a thin wedge that carries the San Fernando Valley and the Santa Susana Mountains on it.

the I-5/SR-14 interchange, which is one reason why it was so heavily damaged. The strong ground-shaking waves continued traveling north, ravaging the Simi and Santa Clarita Valleys and the city of Fillmore.

And that's the second lesson from the Northridge earthquake: the ground shaking was severe over a wide area around the epicenter. For the first time, this shaking was recorded on numerous instruments and was thus well documented. In previous earthquakes, such instruments were more thinly distributed, and only one or two of them would register strong shaking. These few records could always be explained away as anomalies of one sort or another—site effects or quirks of the building in which the instrument was located, for example.

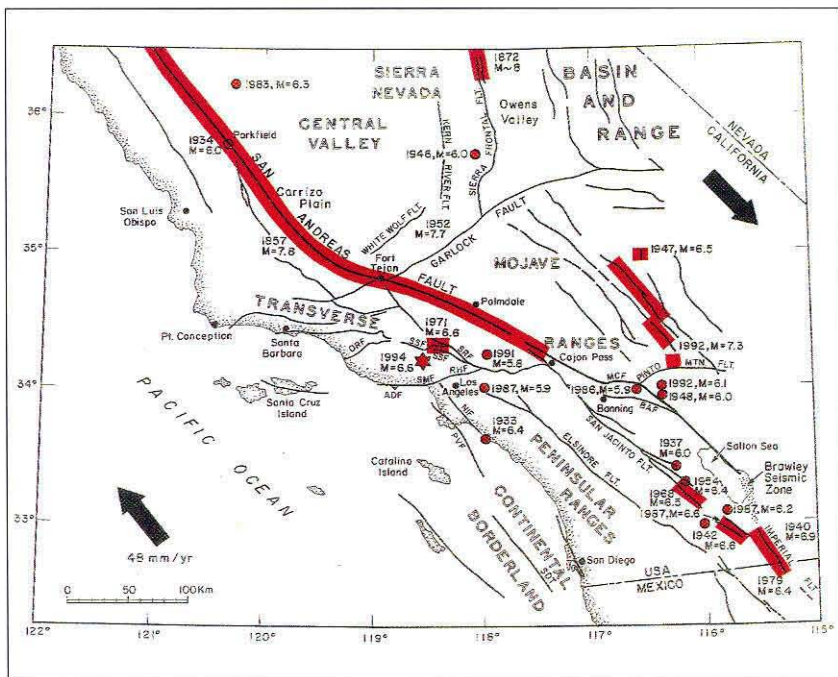
But Santa Monica and Hollywood were hard hit, too, and they're far from the epicenter and to the south—in the opposite direction. What happened there? Part of the answer is that the ground is very soft in parts of Hollywood. The I-10 freeway collapsed at La Cienega Boulevard; La Cienega, in Spanish, means The Swamp. In areas where the soil is water-saturated, ground shaking is amplified and structures are more likely to be damaged. (See the article on liquefaction in the Winter 1990 *E&S*.) Santa Monica, on the other hand, may have fallen victim to an edge effect. The city sits on a sediment-filled basin whose edge is the Hollywood Hills. The earthquake's waves traveled through the hard rock of the hills into the sediment, where they got trapped—reverberating off the basin's rock walls and floor like a shout in an empty room. The

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rebouncing waves canceled one another in some locations but reinforced one another in other places, causing extremely strong and long-lasting shaking in the latter spots. Ventura Boulevard, on the San Fernando Valley side of those same hills, suffered heavily for the same reason. (In passing, I'll note that the earthquake caused the usual severe damage to masonry buildings, but we're making progress—the ones that were reinforced may have been badly damaged, but at least they didn't collapse and kill anyone. And that's what reinforcement is all about, really—not making a building earthquake-proof, which is prohibitively expensive and perhaps impossible in most cases, but earthquake-resistant. This earthquake proved we can do that.)

In addition to ground deformation and shaking, the earthquake caused uplift, as measured by the GPS system. The maximum was about a foot and a half, found at the northern end of the San Fernando Valley and in the Santa Susana Mountains where the fault plane approached the surface. The geology of that region contains ample evidence of uplift from previous earthquakes. For example, as you drive up to Santa Barbara on U.S. 101, you pass the Ventura Avenue anticline about four miles west of Ventura. You can clearly see the folded layers of rock exposed, as shown in the photo above. An anticline is a region where once-flat layers of rock have been pushed up by compression from the sides. This one was created by a cycle of erosion and uplift, as shown in the three drawings below the photo. The process starts with the ocean cutting into a hillside. Erosion creates a cliff with a gently sloping beach



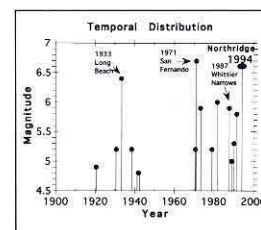
Above: As we all know, Southern California has its faults. This map shows some of the more prominent ones. ORF is the Oak Ridge fault, SSF is the Santa Susana fault, SRF is the San Gabriel fault, SMF is the Santa Monica fault, RHF is the Raymond Hill fault, ADF is the Anacapa-Dume fault, NIF is the Newport-Inglewood fault, PVF is the Palos Verdes fault, BAF is the Banning fault, and MCF is the Mission Creek fault. SDT is the San Diego Trough fault. The red regions show the portions of faults that have broken in historic earthquakes. The earthquakes' magnitudes and years of occurrence are also shown.

at its foot. When an earthquake happens, the cliff and its beach get uplifted. The ocean resumes cutting its cliff and beach into the new, freshly exposed hillside, until another earthquake uplifts the hillside yet again. And if the uplift continues over the eons, it carves the hillside into a series of terraces that once were beaches. We can date the earthquakes by dating the terraces, using carbon-14 dating on the seashells we find buried there.

Stepping back a little bit, why do we have all these earthquakes in Los Angeles? Because the Pacific plate and the North American plate meet there, and they're moving past each other in opposite directions. The interface between the two plates is the San Andreas fault, which comes north out of the Gulf of California, extends past the Salton Sea and Palm Springs, jogs left near Morongo Valley, passes Palmdale and Gorman, and then resumes its original more northerly course through Central California and the Bay Area. So the plates move parallel to each other on the southern and northern parts of the fault, but there's this kink in the middle. Material on the Pacific plate gets compressed as it goes into the bend near Morongo Valley, and that causes earthquakes. Then the plate gets shoved out to the west when it wants to go north, and that causes still more earthquakes. This whole process has created about 300 secondary faults, some of which are shown above.

We know from geological and geophysical studies that the net average movement between the Pacific and North American plates is about four and a half centimeters per year. This is

Below: Plotting earthquake magnitudes in the L.A. basin versus the year in which they occurred reveals two clusters of activity, one of which continues today.



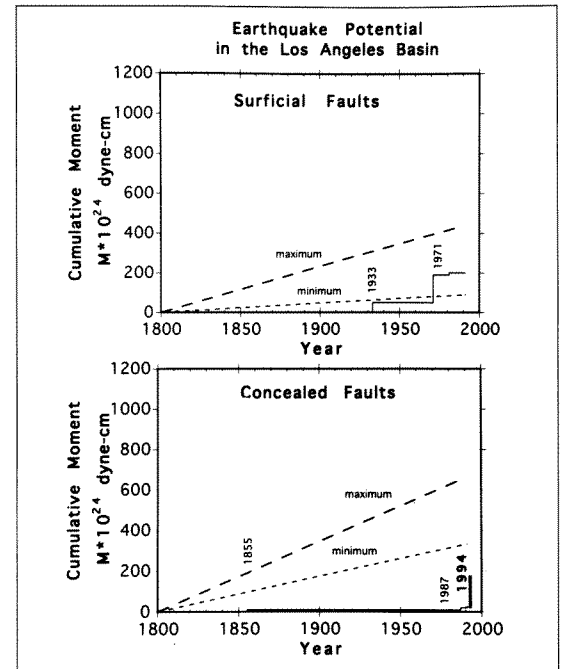
about as fast as your fingernails grow. But unlike your manicure going ragged, this movement doesn't happen gradually—it happens in discrete events, i.e., in great earthquakes. We also know that about 80 percent of this movement is accommodated along the San Andreas fault. The remaining 20 percent occurs on the secondary faults. Of that 20 percent, about 5 percent occurs out in the Mojave Desert, and has caused the Landers and other earthquakes. The remaining 15 percent occurs in faults in the L.A. area and in the Transverse Ranges to the northwest.

In the past 60 years, the L.A. area has had three sizable earthquakes and a number of moderate ones, but they haven't been evenly distributed over time or space. If we plot earthquake magnitudes since 1900 as a function of time, we find two clusters of activity. The first one, from 1920 to 1942, included the Long Beach earthquake. The second one runs from 1970 to the present. Most of the earthquakes in the first cluster were south of downtown Los Angeles. Nearly all of the second cluster have been along the northern edge of the Los Angeles Basin, along the front of the San Gabriel Mountains.

A simple forecasting method works quite well, at least for the weather in Los Angeles: the weather today is probably the weather we're going to have tomorrow. So we've had a lot of earthquakes over the last five years, and we're likely to have some more over the next five years. And this is the third lesson from the Northridge earthquake: it drove home the point that we're in a period of increased seismicity.

There's another reason for surmising that we're

The diagonal lines show the calculated minimum and maximum amounts of strain energy stored in L.A.'s faults over the years; the vertical lines show how much of that energy has been released in our various earthquakes.



The Modified Mercalli Scale

I – Not felt.

II – Felt by persons at rest or on upper floors.

III – Felt indoors. Hanging objects swing. Vibration feels like a passing light truck. Duration may be estimated. May not be recognized as an earthquake.

IV – Vibration as of passing heavy trucks, or a heavy object striking the wall. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. Wooden walls and frames creak, especially in the upper range of IV.

V – Felt outdoors. Direction may be estimated. Sleepers awakened. Small, unstable objects displaced or upset. Doors, shutters swing closed or open. Pictures knock against wall and tilt. Pendulum clocks stop, start, or change rate.

VI – Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Many dishes and glasses and a few windows break; knickknacks, books fall off shelves. Pictures fall off walls. Light furniture often overturns; heavy furniture and appliances move. Weak plaster and masonry cracks. Small church bells ring. Trees, bushes sway visibly and rustle audibly.

VII – Difficult to stand. Noticed by drivers of motor cars. Furniture broken. Unreinforced masonry cracks. Weak chimneys snap off at roof line. Waves in ponds, swimming pools. Plaster, loose bricks, tiles, cornices fall. Large bells ring.

VIII – Steering of motor cars affected. Partial collapse of well-built but unreinforced masonry; masonry properly reinforced against lateral forces endures. Stucco walls fall. Chimneys, monuments, towers, elevated tanks twist and fall. Frame houses move off foundations if not bolted down, panel walls thrown out. Branches broken from trees. Cracks appear in wet ground and on steep slopes.

IX – General panic. All masonry, except that especially designed and reinforced to withstand lateral forces, destroyed or seriously damaged. General damage to foundations. Bolted-down frame houses thrown out of plumb. Serious damage to reservoirs. Underground pipes may break. Conspicuous cracks in ground. Sand blows and craters in alluvial areas.

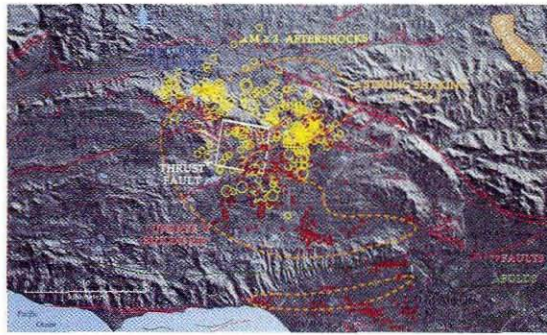
X – Most masonry and frame structures and their foundations destroyed. Large landslides. Serious damage to dams, dikes, embankments. Sand and mud shifted horizontally on beaches and flat land. Railroad rails bent slightly.

XI – Rails bent greatly. All buried pipes broken. Widespread ground disturbances of all sorts, including fissures, slumps, and slides.

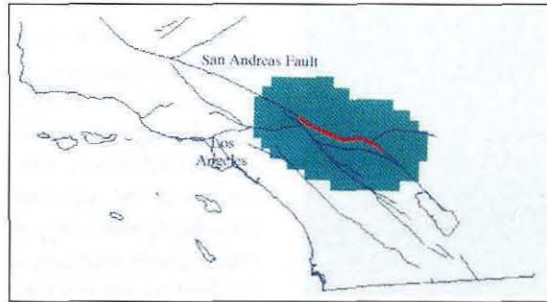
XII – Damage nearly total. Large rock masses displaced. Rivers change course. Lines of sight and level distorted.

in for more earthquakes. The red patches in the map on the previous page show which parts of the local faults have broken in recent earthquakes. There are large expanses that aren't red, so we have quite a bit of fault area that still has to move. We can divide these faults into two basic types: surficial faults like the Newport–Inglewood fault, which caused the Long Beach earthquake, and buried faults like the Whittier Narrows thrust ramp (not shown on the map), and the Santa Monica thrust ramp. We can sum up the energy stored on these two groups of faults since 1800, although our knowledge of the accumulation rates isn't perfect. But still, we can get a maximum and minimum value for each fault class. We've had two surficial-fault earthquakes, Long Beach and San Fernando, and it turns out that we're about in balance—the energy released in those two events is about half way between our calculated minimum and maximum. Measuring slip rates on the buried faults is much trickier, obviously, because we can't see them directly, but consulting geologists Tom Davis and Jay Namson have examined geological data from the L.A. basin and found deeply buried sediments known to have been deposited at sea level. Dating these sediments and noting their current elevations gives us a rough idea of how fast they're being moved. (These estimates are really a lower limit, since there are buried faults lurking out there that haven't made themselves known yet.) The buried faults are accumulating energy at about twice the rate of the surficial faults, but we've only had one sizable "blind" earthquake—Northridge. In other words, energy

Above right: The areas of strong shaking (in excess of 50 percent of gravity horizontally) felt in the Northridge earthquake are outlined with dashed orange lines. They include most of the San Fernando Valley, and a strip running from Santa Monica to Hollywood.



Below right: For a hypothetical magnitude 7.0 earthquake that breaks the San Andreas fault from Banning to Tejon Pass (red line), the area of horizontal shaking at 10 percent of gravity or greater is shown in green. Here the regions at risk are the San Bernardino, Riverside, and Palm Springs areas.

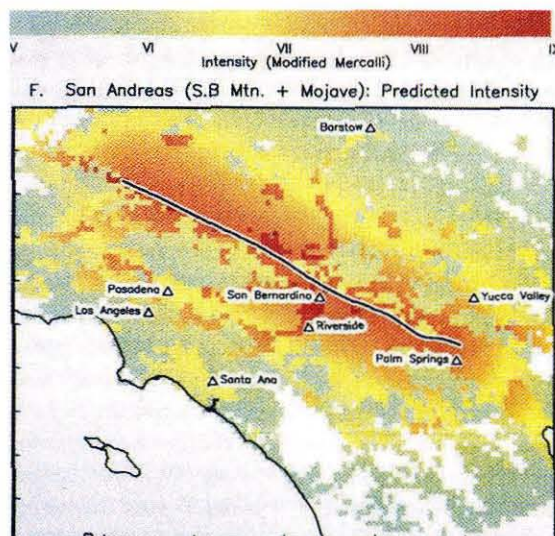
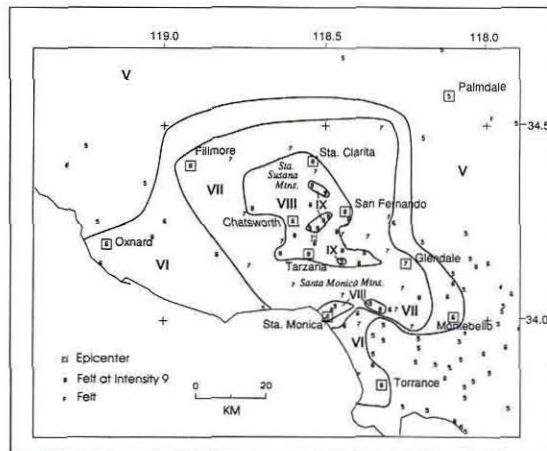


is accumulating on these buried faults faster than it's being released. That's why we seismologists talk about an "earthquake deficit"—we're missing five or six Northridge-sized earthquakes, or one magnitude 7.2 or 7.3 earthquake.

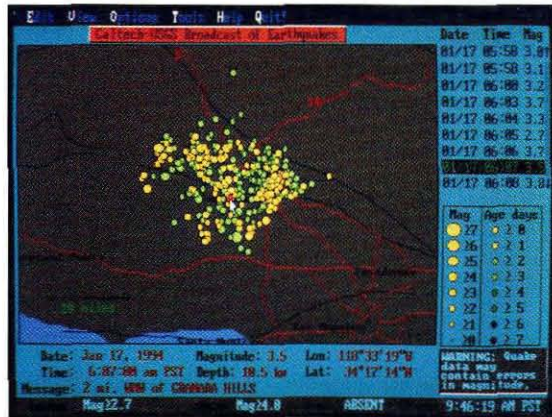
We've designed computer models that estimate the shaking from various plausible earthquakes, so let's compare the Northridge earthquake with what we might expect in a great earthquake on the San Andreas fault. The Northridge earthquake's area of shaking at about 10 percent of gravity or greater is 30 to 40 kilometers across, as shown in the top map at left. If we do a calculation for the San Andreas fault using a magnitude 7 earthquake that starts near Banning and runs up toward Tejon Pass (next map down), we get an area of shaking at 10 percent of gravity or greater that extends for 170 kilometers or so. But the earthquake doesn't cause very strong shaking in the Los Angeles metropolitan area itself. The communities at risk from this earthquake are San Bernardino, Riverside, and their environs.

Another way to look at earthquake damage is with the modified Mercalli intensity scale, which was invented in 1902, back before we had a lot of seismological instruments. It was modified in 1931 by Harry Wood, the first director of what became Caltech's seismo lab, and Frank Neumann, then chief of the seismological division of the U.S. Coast and Geodetic Survey (the forerunner to the USGS), to take into account such innovations as skyscrapers, motor cars, and underground pipelines. This scale describes the strength of the shaking observed at any given location, and goes from I up to XII. (We give Mercalli ratings in Roman numerals to avoid confusion with the Richter and other magnitude scales.) In Northridge, the maximum Mercalli rating was IX, as shown in the third map down. At IX, apartment buildings lose stories, unreinforced masonry buildings are severely damaged, and trains are knocked off their tracks. Where the Mercalli intensity was VIII, everything was thrown off shelves, chimneys toppled, and there was significant damage. At VII, there was strong shaking, but not all that much damage. If we again do a calculation for that 7.0 on the San Andreas (bottom map), we see a much larger area of intensity VIII or greater. Very significant damage would occur in San Bernardino and Riverside Counties, but there would be pockets of damage in the San Gabriel Valley, and somewhat more widespread damage in the San Fernando Valley and communities to the north like Santa Clarita. In an earthquake of this type, you would feel the shaking for a long time—for

Above right: A contour map of the modified Mercalli intensities felt in the Northridge earthquake. The small numerals are data points. The squares represent the named cities. Below right: Calculated intensities for that same hypothetical 7.0 on the San Andreas. The intensities are coded according to the color bar across the top of the map.



Right: After gallivanting across the country from East L.A. to Chicago, Atlanta, and back again, the CUBE data winds up on a computer display. This one shows the first few days' worth of Northridge aftershocks (colored circles). The information in red pertains to the red-highlighted earthquake under the cursor arrow. Black lines are faults; red ones are freeways. Below: The Northridge earthquake bounced some of the 64 cars in this freight train clean off the track. Even though one tanker spilled 8,000 gallons of sulfuric acid, the line was back in service within 48 hours.



several minutes—but most of that would be light shaking. The strong shaking would only last for several tens of seconds.

At Caltech, we don't merely study earthquakes. We're also working on various ways to mitigate their effects. I've just described one method, which is to calculate the effects in advance so that structural engineers will know what forces a building in a given area must be designed to withstand. And while we still don't know how to predict earthquakes, we can do the next best thing, which is to provide information about the earthquake very quickly after it happens. This allows dispatchers to send emergency crews (such as fire brigades and ambulances) to the hardest-hit areas, enables gas and water companies to shut off mains that might be broken, permits electric utilities to reroute power around damaged lines, and so forth. We've put together a system called CUBE, which stands for Caltech-U.S. Geological Survey Broadcast of Earthquakes. It's still in the development phase, but we already have 15 utilities and transportation companies as subscribers. Local governments also subscribe to it, and we have two media subscribers—KTTV and KNX radio. CUBE uses the earthquake data—location, magnitude, and time—that's automatically generated by the computers here at Caltech, and sends that information on a radio link to our local cellular-phone company, which pages the 200 or so individual users. In some cases, people carry beepers that read out the information; in others, the pagers are hooked up to PCs that plot earthquakes as dots on a map. It takes about a minute to a minute and a half to

determine the earthquake's location and magnitude, and then about 20 seconds to route the data through the paging system. The message has to go from Caltech to the phone company's office in East L.A., which sends it by satellite to Chicago, then Atlanta, and then back to Los Angeles. This is what happens when you really get caught up in high-tech.

But CUBE isn't as high-tech yet as it needs to be, and the system did not respond to the Northridge main shock as a result. (The system has done a good job of reporting the aftershock sequence, however.) CUBE missed the main shock because most of the seismometers in the network are the old-fashioned analog kind that record their data in the form of frequency-modulated waves, a method of data-encoding similar to the way that an FM radio station broadcasts audio signals. The seismic data are transmitted over microwave links that suffer from random bursts of noise caused by various atmospheric phenomena. Our computers think that the noise bursts are actually big earthquakes, and the system gets saturated trying to process them. To prevent this, we've designed "traps" in our software that recognize the noise bursts and discard them. So when the Northridge earthquake hit, the computers assumed that the huge waves in the incoming data were another noise burst, and ignored them. We need to replace our analog instruments, which were state-of-the-art in the early 1970s, with modern digital ones that record and transmit the data as packets of digital information. Then the computers would know that all the data reaching them is real. We're working with our local phone companies to see if we can get dedicated phone lines that wouldn't be subject to the atmosphere's whims, but what we really need to do is to replace those analog instruments with digital ones that have capabilities similar to the TERRAScope. And that's expensive, so we're installing the digital ones as we can afford to. □

Egill Hauksson, senior research associate in geophysics, earned his M.S. in geophysics from the University of Trondheim in Norway in 1974, and his M.A., M. Phil. and Ph.D. from Columbia University in 1978, 1980, and 1981, respectively. He joined the Caltech faculty as a research fellow in 1989, becoming a senior research associate in 1992. Hauksson keeps seismology in the family—his wife, Lucile Jones, is a seismologist at the USGS's Pasadena office, conveniently located across Wilson Avenue from the Seismo Lab. (Jones is also a visiting associate in geophysics at Caltech.)