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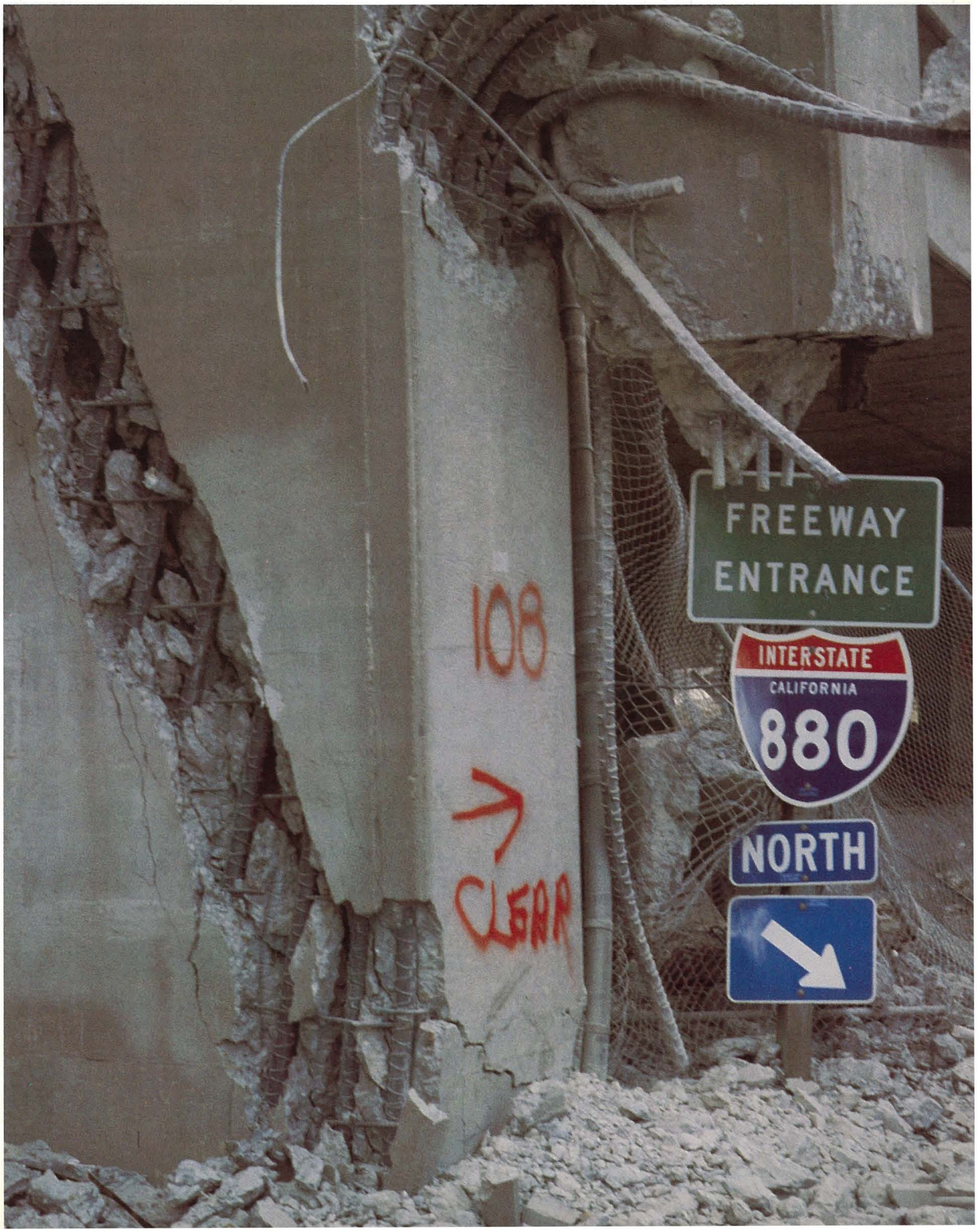

In this issue

Loma Prieta earthquake: causes and consequences

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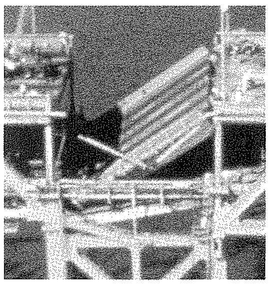

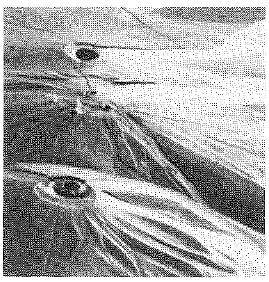

Departments

On the cover: Collapse of the double-deck Cypress Street section of Interstate 880 accounted for two-thirds of the fatalities from the Loma Prieta earthquake. Recent experiments have revealed that an insufficient number of steel wrapping bars caused brittle shear failure at the base of the upper column, seen dangling here above the freeway sign.

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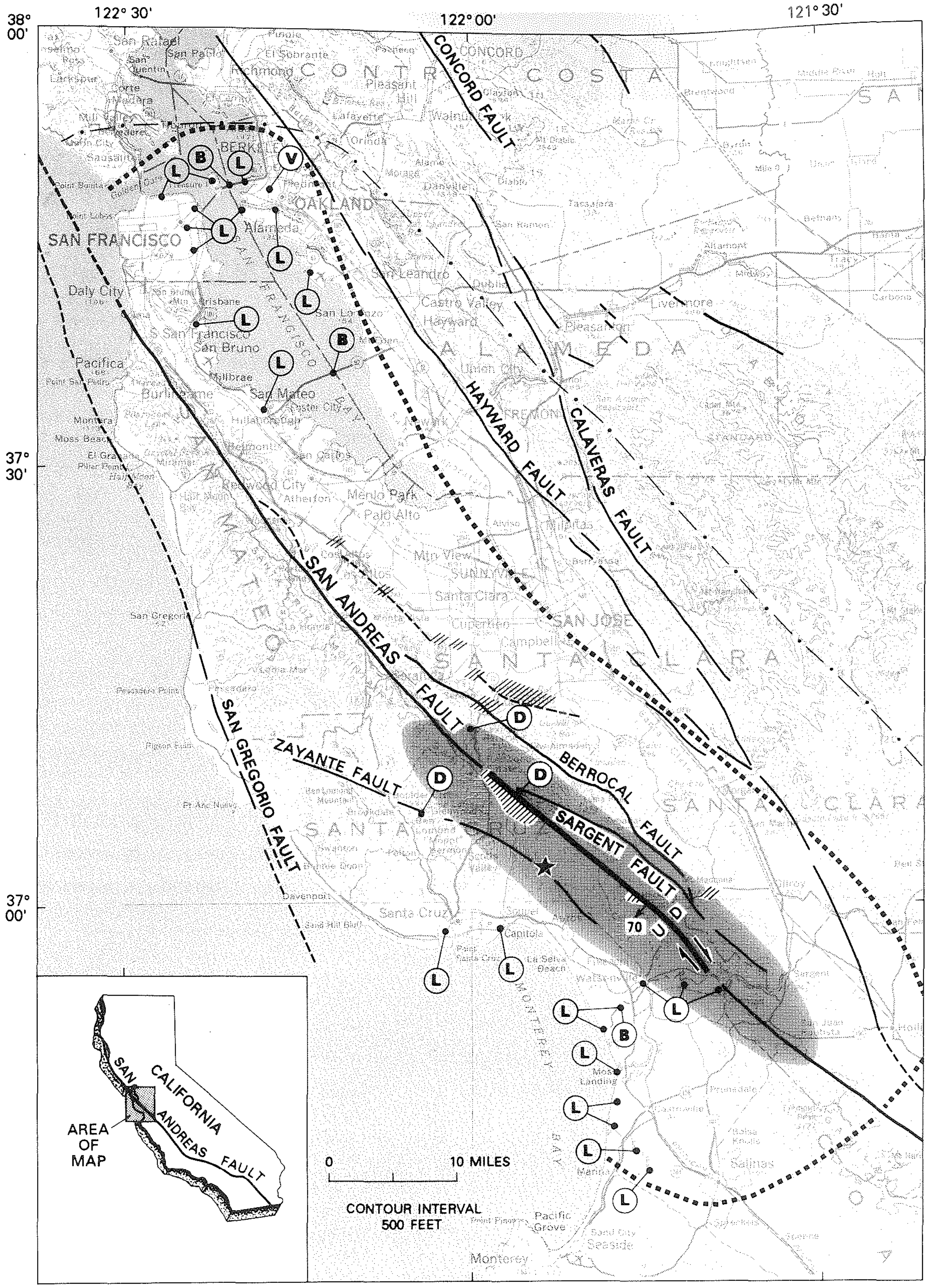
The Loma Prieta earthquake caused damage from San Francisco to Salinas, as shown here. The "Damaged two-story viaduct" is I-880.



D / U / 70 — 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

Shift Happens

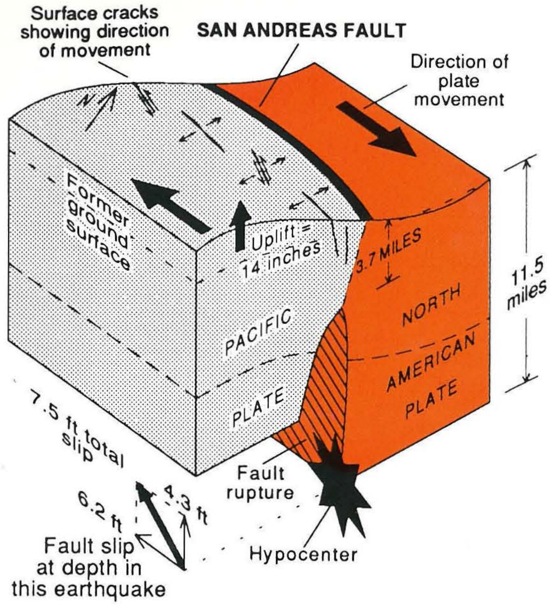
The ground moved about two meters laterally, which was expected, and about one meter vertically, which wasn't.

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.

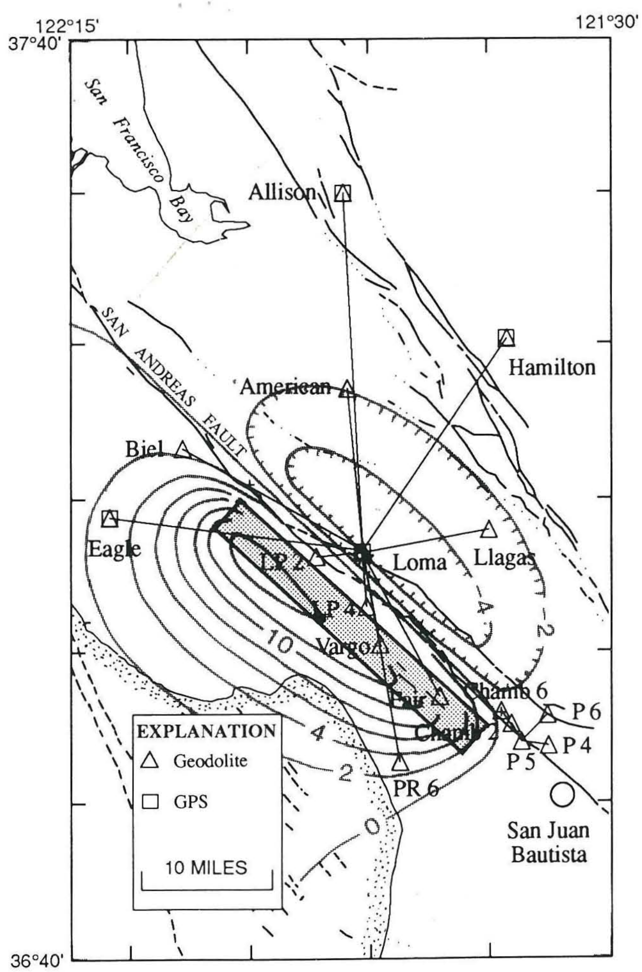
Initial seismographic analyses revealed that the ground moved about two meters laterally, which was expected, and about one meter vertically, which wasn't. The San Andreas fault, which bisects the state from the Gulf of California to Point Arena, about 110 miles north of San Francisco, and is presumed 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 distributed 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



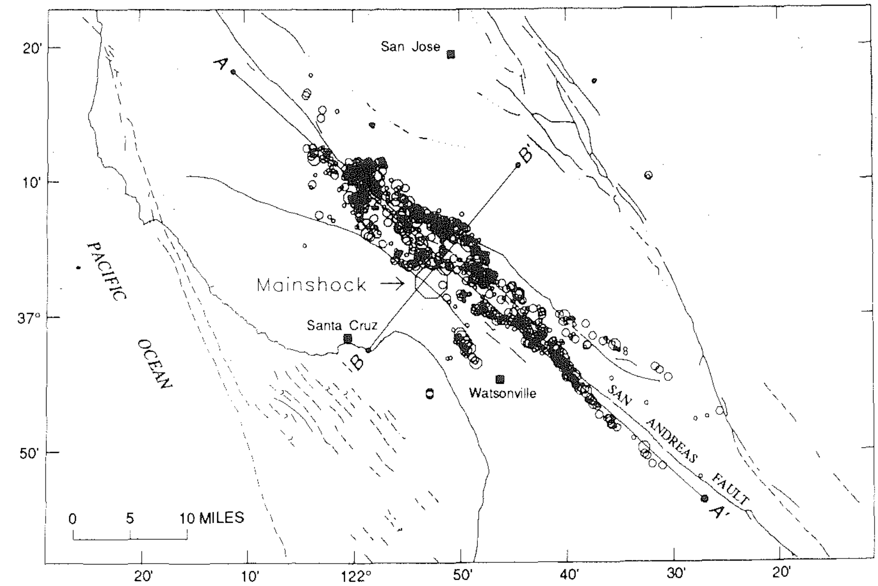
Right: How the fault moved.
Below: The geodetic network established to look for gradual ground movement since the earthquake. The contour lines to the west of the San Andreas show uplifted areas in 2-inch increments; the barbed contours to the right of the fault show subsidence. Geodolites are rangefinders: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



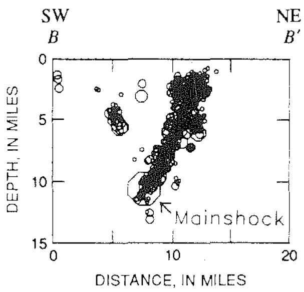
spaced so that at least 4 of them will usually be visible from any point on the earth's surface. (There are 10 GPS satellites functioning now, providing good coverage over North America for several hours each day.) The system was developed as an aid to navigation, and is widely used by ships and aircraft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

"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."

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."

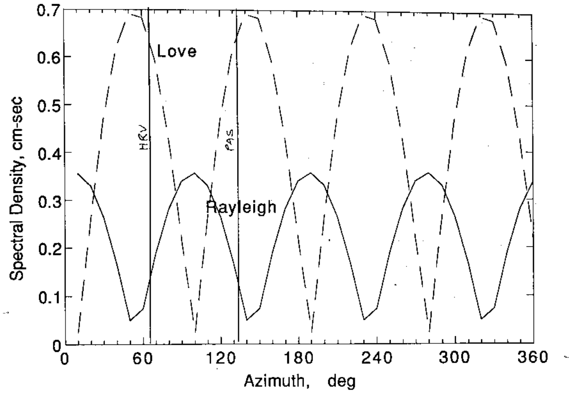
Says postdoc Ken Hudnut, "This is the first significant earthquake where Global Positioning Satellite measurements before and just after the event provided displacement estimates within a day or two of the quake. GPS measurements have been made for other earthquakes, but they usually took a few months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

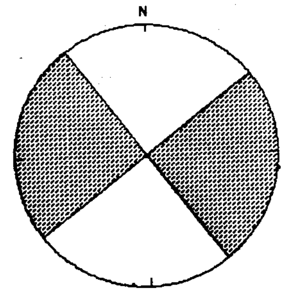
The GPS satellites broadcast time signals, which two ground-based receivers compare to their own internal clocks. The difference between the two times of reception is proportional to the distance between the ground stations, projected along the line-of-sight to the satellite. At least four satellites 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 modem-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





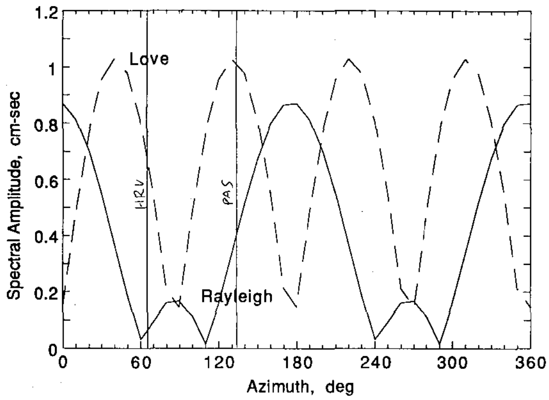
Left: Surface waves such as Rayleigh waves (in which the ground vibrates forward and backward along the direction of propagation) and Love waves (in which the ground moves from side to side perpendicular to the direction of propagation) vary in intensity in different directions in a manner characteristic 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.)

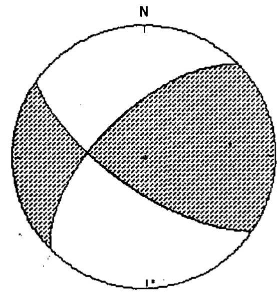
that if the instruments are set to record small earthquakes, as they usually are, their recorders are blown off the scale by anything larger—not unlike listening to a recording of the *1812 Overture* and turning the volume way up so you can hear the quiet passages in the first movement. Standard seismometers 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."

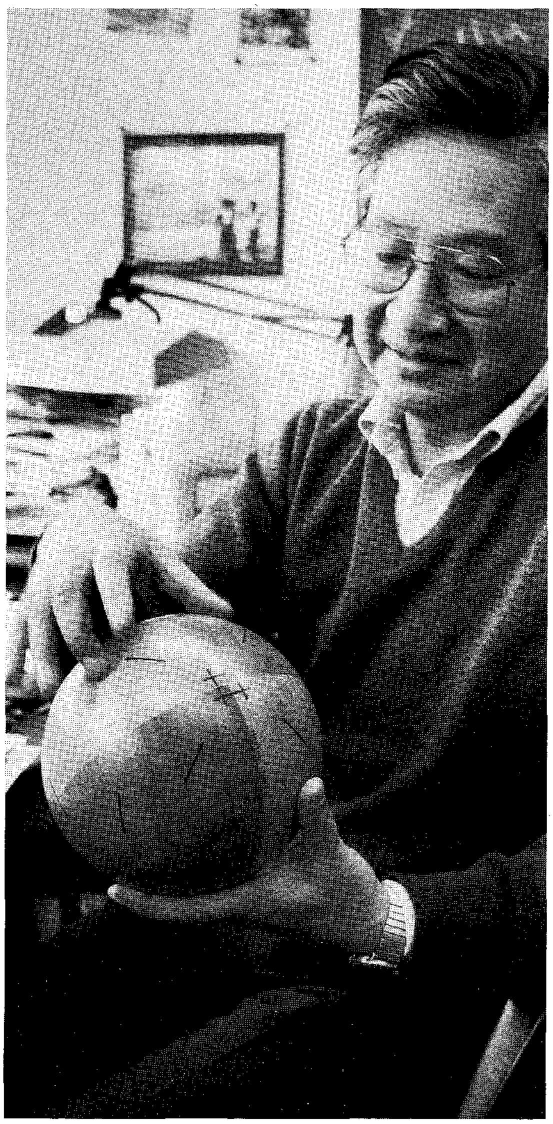
Kanamori and everyone else initially assumed that this quake had a textbook San Andreas-type of right-lateral movement. This assumption, when superimposed on the TERRAscope data and data from a similar dial-up station installed at Harvard in early 1987, allowed him to fill in the details of a plausible 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!)



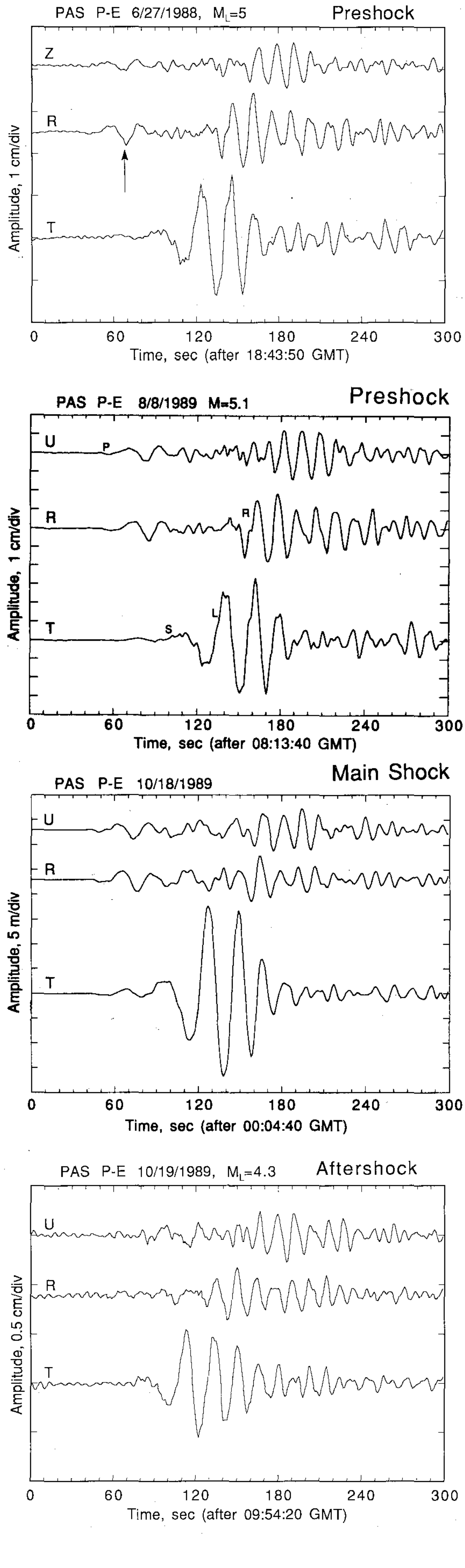
Right: Although scientists chose this diagramming system for a good reason—the waves recorded at all seismographs except for those in a quake's immediate vicinity emanate downward from the hypocenter and are reflected back up to the instrument—even they find it hard to visualize. Most, like Kanamori, 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—a fast-moving compression 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.



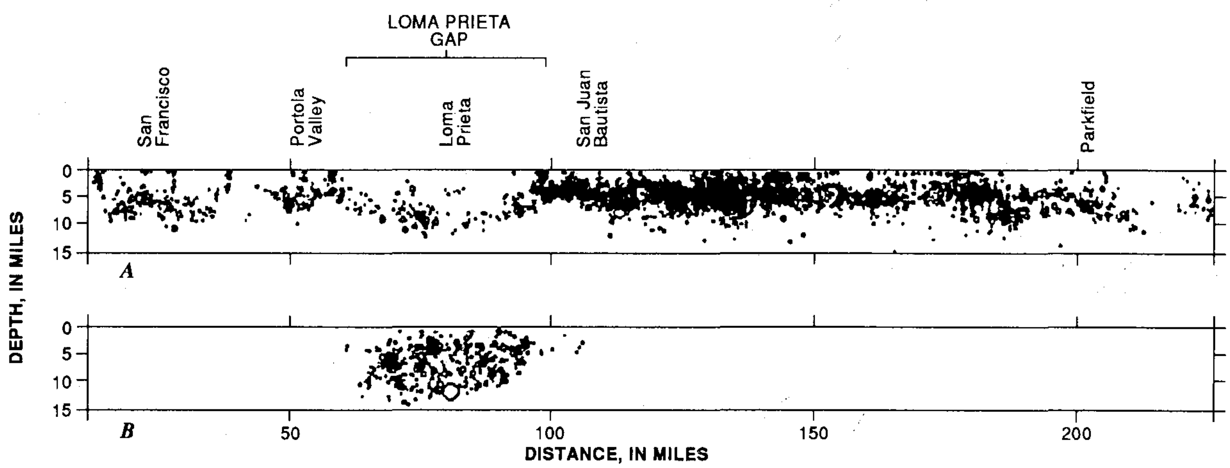
"Seismology is getting more exciting, because we have high-quality data immediately, instead of in a few months."

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.

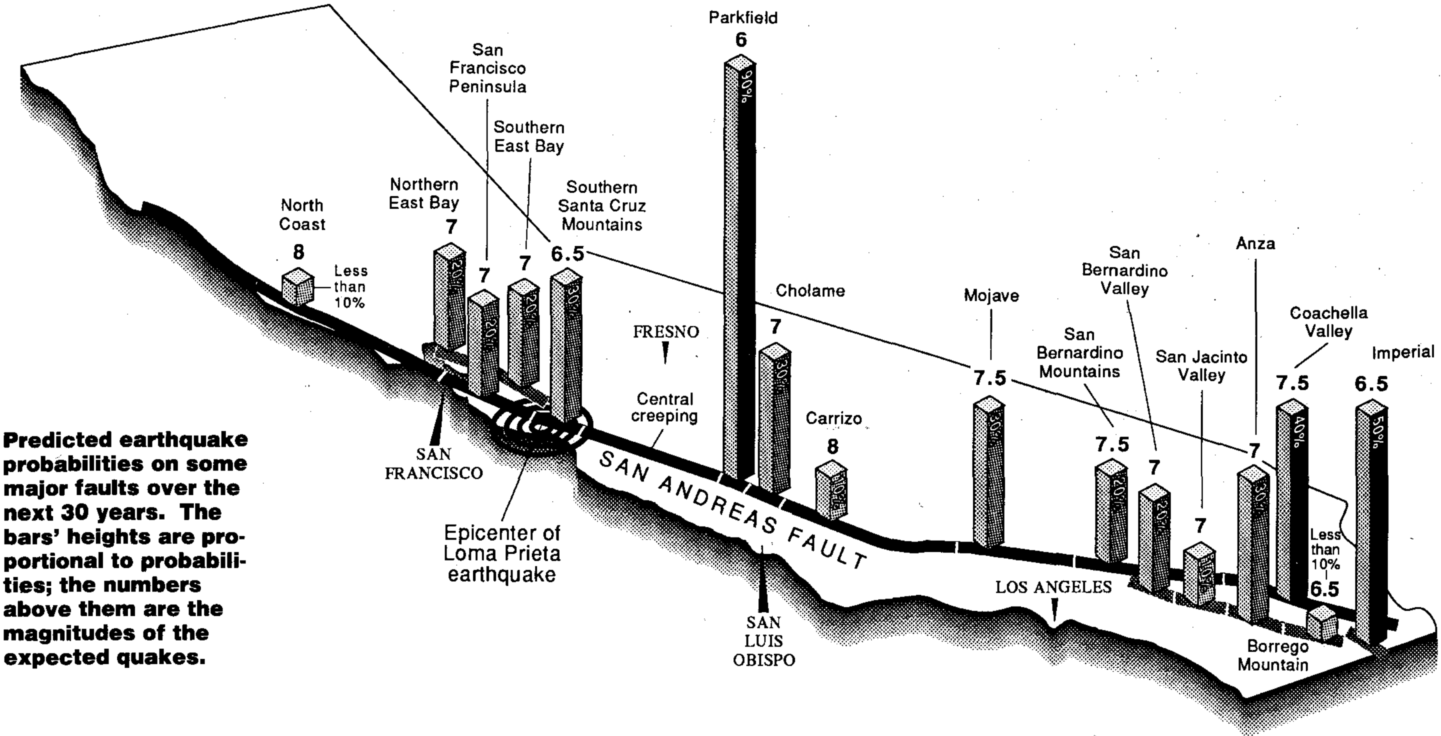
"Now compare them to this other earthquake on the bottom, which is an aftershock of magnitude 4 or so. It also appears similar to the main shock, but if you look at it very carefully, one wave [labeled] is missing. This aftershock is presumably more the strike-slip-type, San Andreas-type mechanism, but 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."

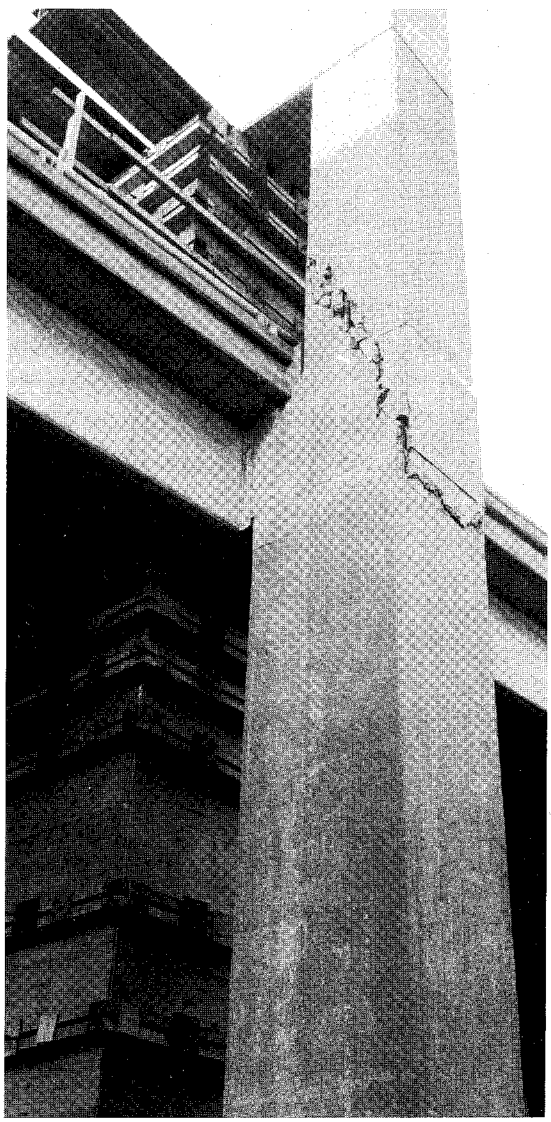
"There are five segments of the fault likely to have a big earthquake in the next 30 years. This was one."

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 Gorgonio 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.

Structural Behavior During the Loma Prieta Earthquake

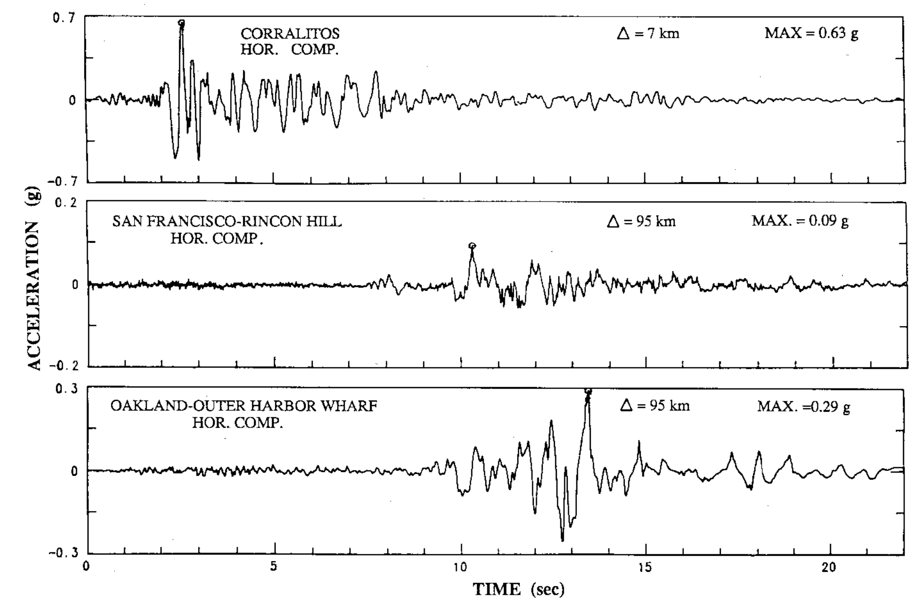
by John F. Hall



The double-deck Embarcadero Freeway, similar to the Cypress Street section of Interstate 880, came perilously close to collapse.

When compared with the magnitude 6.8 Armenian earthquake of December 1988, the Loma Prieta earthquake can be viewed as a demonstration of the success that can be achieved through preparedness and adherence to building codes. In Armenia an estimated 25,000 people died, and whole communities were destroyed. The magnitude 7.1 Loma Prieta earthquake killed 62 persons, and damage was only scattered, with many of the severely damaged structures being older ones built on landfill. Nevertheless, direct losses resulting from the recent earthquake may exceed $10 billion, with damage to more than 100,000 structures. And we must keep in mind that a magnitude 7.1 earthquake is many times smaller than the magnitude 8-plus that the San Andreas is capable of generating when measured in terms of area affected and time duration of strong shaking, important factors in damage potential. Even some of the modern structures that performed well in October 1989 may be vulnerable to a magnitude 8-plus event.

The pictures and discussion that follow present information on the nature of the strong shaking generated by the earthquake and on how some particular and typical structures fared. Emphasis is on those that were built when earthquake effects were poorly understood. Such older structures represent California's most pressing earthquake problem. Source materials for this article include publications by Caltrans, California Division of Mines and Geology (CDMG), Earthquake Engineering Research Institute (EEEI), EQE Engineering, UC Berkeley, and



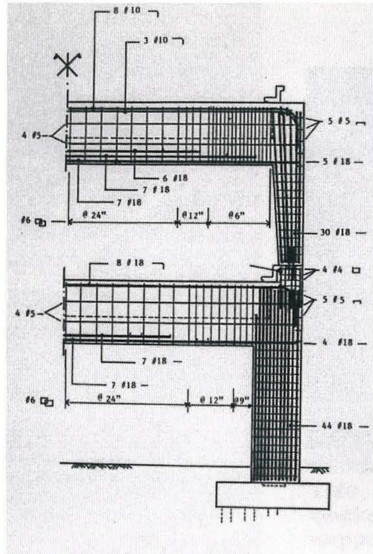
The top accelerogram shows ground motion in terms of acceleration over time at a site 7 kilometers from the epicenter. Comparison of accelerograms from two locations far from the epicenter—on rock in San Francisco (middle) and on mud overlying sand in Oakland (bottom)—illustrates the amplification of ground motion on soft soil.

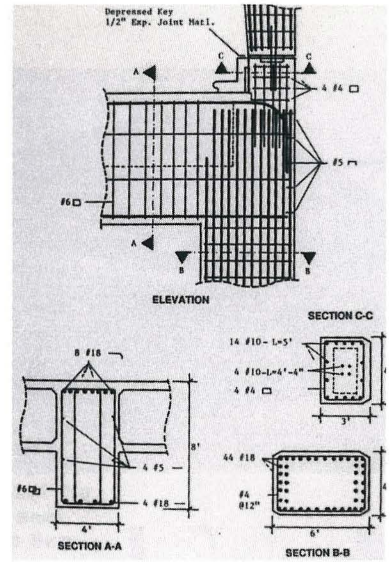
United States Geological Survey (USGS).

A wealth of data was obtained on the nature of the strong shaking generated by the earthquake. These data are records of the motion in terms of acceleration versus time (accelerograms) captured by special vibration recording instruments (accelerographs). Dozens of accelerographs installed over the years by CDMG and USGS triggered during the earthquake. Shown at left are three accelerograms from CDMG; all show a single horizontal component of motion at a particular site on the ground. The Corralitos station was the closest to the epicenter ($\Delta = 7$ km, where $\Delta =$ epicentral distance), and there the ground acceleration exceeded 60 percent of gravity with a strong shaking duration of about six seconds. The other two accelerograms were both recorded 95 km from the epicenter, one on rock (in San Francisco on Rincon Hill) with a 0.09 g peak acceleration, and the other on 10 feet of fill and bay mud overlying sand (at Oakland's Outer Harbor Wharf) with a 0.29 g peak acceleration. These two records illustrate the amplification of ground motion that can occur on soft soil. Such amplification probably played an important role in much of the damage that occurred during the earthquake, such as in the Marina District and the South of Market area in San Francisco and at the Cypress Street section of the Nimitz Freeway (Interstate 880) in Oakland. The Oakland Outer Harbor Wharf station was only 2½ km from the collapsed portion of the Cypress, and the motions at these two locations are thought to have been similar.

The Cypress collapse, which accounted for

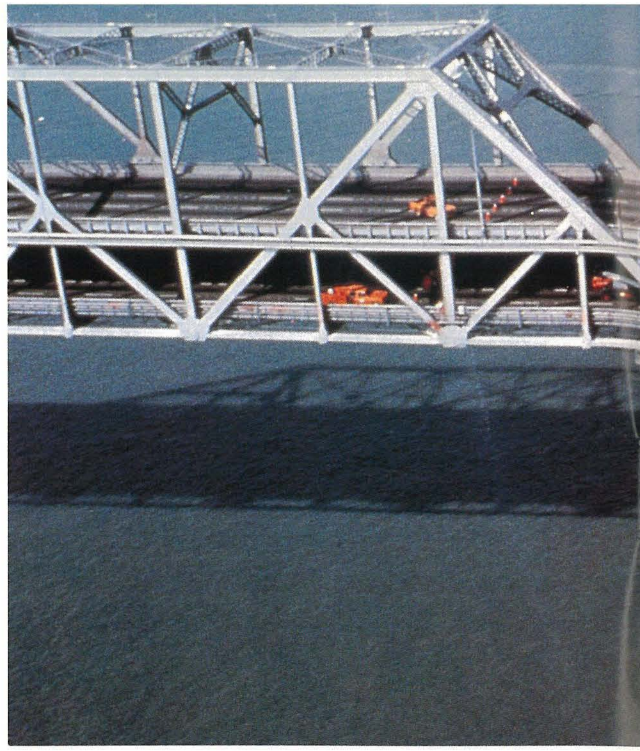
The design of the Cypress Street section of I-880 employed too few wrapping bars around the longitudinal steel reinforcement in the columns as revealed in the original plans (lower-level joint detail at far right; reinforcement layout bent at near right). This led to brittle shear failure at the base of the upper column (below).

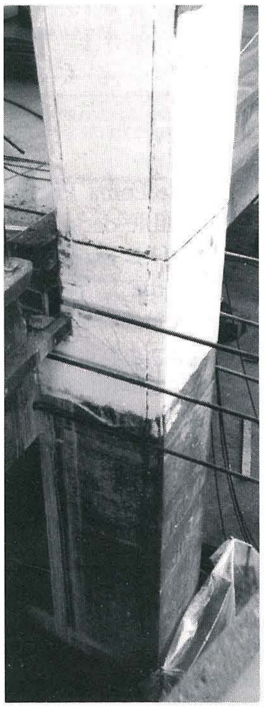




two-thirds of the fatalities from the Loma Prieta earthquake, involved 49 of 85 double-deck spans and extended for 1.2 km. This reinforced concrete structure was designed in the 1950s, before engineers understood very much about earthquake-resistant design using reinforced concrete. In 1971 a number of bridge failures during the San Fernando earthquake led Caltrans to embark on a statewide bridge-retrofit program, the first phase of which involved cabling bridge decks together across expansion joints to prevent the decks from sliding off their joint seats and dropping down during earthquake shaking. The Cypress structure is one of 1,200 bridges statewide that have been so retrofited. Subsequent phases of the state retrofit program deal with column strengthening and are only in their early stages. Many bridges, however, in the area of strong shaking from the Loma Prieta earthquake benefited from the cabling retrofit program.

The drawings above show the pattern of steel reinforcing bars in a typical bent (that is, a frame supporting the decks) of the Cypress structure. The design contains a flaw typical of most older reinforced-concrete structures: an inadequate number of the steel bars, called ties, that wrap around the longitudinal reinforcing bars in the columns. Too few ties make such columns prone to brittle shear failure during earthquakes, which is what happened to the Cypress. The area where the failure initiated is at the base of the upper column, and the failure plane is evident in the photo at left. The deck cabling did nothing to prevent this type of collapse and, in fact, may have helped propagate the failure from one span





Load tests on a surviving section of the Cypress (top) produced the same type of critical shear cracks at the base of an upper column (bottom) that led to the failure of the structure during the earthquake.

to the next by pulling down a bent standing one span away from a collapsed bent. In light of the Cypress experience Caltrans is now reviewing their retrofit program. The future will probably see more complete treatment of important structures with thorough consideration of their entire structural systems.

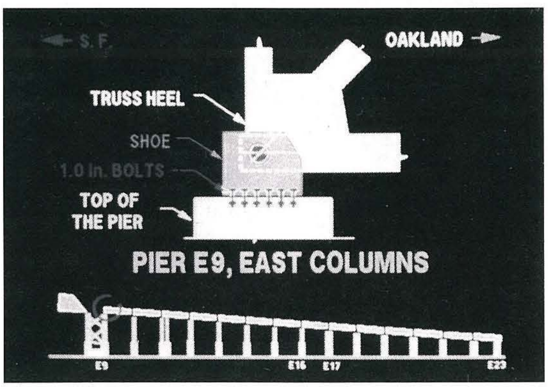
After the earthquake the collapsed and still-standing portions of the Cypress structure were removed except for a two-span, double-deck section south of the part that collapsed. Interestingly, the portion of the Cypress that survived the earthquake was outside the zone of soft soil which underlay the part that collapsed. On the two-span section that was spared demolition, engineers from Caltrans and UC Berkeley recently conducted load tests using jacks placed between the upper deck and massive steel reaction frames, which were installed for this purpose. This type of loading forces the bridge back and forth in much the same manner as it would vibrate during an earthquake, although slower. The test structure was jacked far enough to produce the critical shear cracks at the base of the upper columns (left) confirming this to be the weak point in the design.

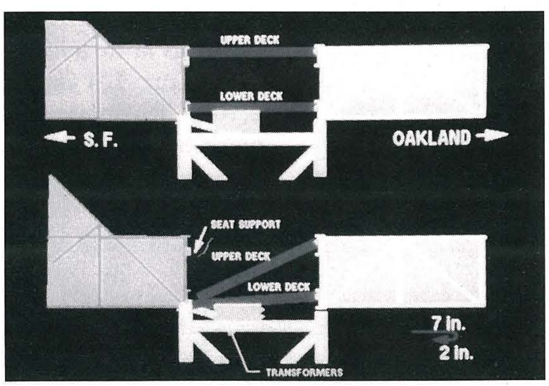
In a later stage of testing, three different methods for strengthening the test structure were tried out. The scheme considered to be the strongest consisted of steel I-sections fastened to the outside of the weakened columns to act as splints. After installation of the trial retrofits, the test structure was reloaded to determine the increase in strength obtained. Caltrans found all three schemes to be effective and plans to use them to retrofit the several freeway structures that remain closed.

A multispan section of the Embarcadero Freeway, a double-deck bridge with similarities to the Cypress structure in Oakland, also came perilously close to collapsing (see photo on page 13). Indeed, the shear cracks in the columns suggest a collapse mechanism similar to that of the Cypress, resulting from a lack of ties in the columns. The Embarcadero remains closed to traffic and is temporarily shored up with timbers, awaiting a more permanent solution, such as retrofiting with the steel splints of the type tested at the Cypress test structure.

In the hours immediately following the earthquake, the most visible symbol of the damage was the collapsed upper and lower roadway decks in the trussed half of the Bay Bridge east of Yerba Buena Island (above). These decks had spanned 50 feet across a massive steel pier (number E9) connecting a 500-foot steel truss on the San Francisco side of the pier with a 300-foot one on the Oakland side. Bolted connections firmly attached these decks to the truss on the Oakland side of the pier, and a 5-inch-wide seat was employed at the end toward San Francisco to permit sliding. During the shaking the forces in the bridge truss on the Oakland side were sufficient to shear the bolts that connected the truss to the pier (top drawing, opposite), after which the truss moved 7 inches on the pier in the direction toward Oakland. This movement caused the decks over the pier, which were bolted to the moving truss at one end, to slide off their seat supports at the opposite end

50-foot upper- and lower-deck spans of the Bay Bridge collapsed across a pier when shaking broke loose one truss to which the decks were attached, resulting in a 7-inch movement toward the Oakland side, which pulled the decks off their seat supports on the San Francisco side.





(bottom drawing). Unfortunately, no cabling retrofit work had been done over pier E9. Similar bolt shearing took place on several other piers closer to the Oakland end of the bridge and, amazingly, the last deck segment came to rest only ½ inch from the edge of its seat without dropping.

The distress suffered by the 55-year-old Bay Bridge from this magnitude 7.1 earthquake 100 km distant has generated concern about the bridge's ability to withstand stronger shaking from maximum earthquakes on the nearby San Andreas and Hayward faults. Caltrans is currently planning for a sophisticated dynamic analysis to be made of the bridge to simulate its response under such conditions. Such an analysis will not be easy because it should account for the numerous sliding joints in the bridge and should consider unsynchronized displacements along the base of the structure as the seismic waves pass by, as well as possible permanent deformation of the foundations.

Damage was sustained by numerous major highway structures, and about half a dozen remain closed. One interesting collapse occurred to the parallel bridges across Struve Slough, a 1964 design, which involved 7 spans on one side and 10 spans on the other. Because of a very weak soil condition consisting of saturated peat, the bridge design employed a pile foundation. To support the bridge decks, the piles were extended upward above the ground and embedded into the undersides of cross beams to which the decks were connected. During the shaking the piles sheared off just below their connection

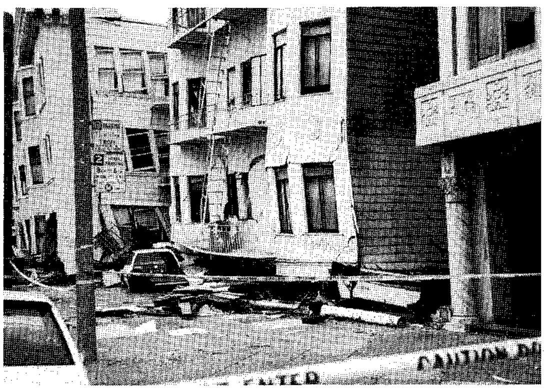
When the parallel bridges across Struve Slough collapsed in weak soil, some of the sheared-off supporting piles punctured the decks as they fell (right). Unreinforced masonry buildings close to the epicenter, such as the one below in the Pacific Garden Mall in Santa Cruz, did not fare well in the earthquake.

with the cross beams, and in a few cases held together enough to puncture cleanly through the deck as it fell, producing a rather eerie sight (above).

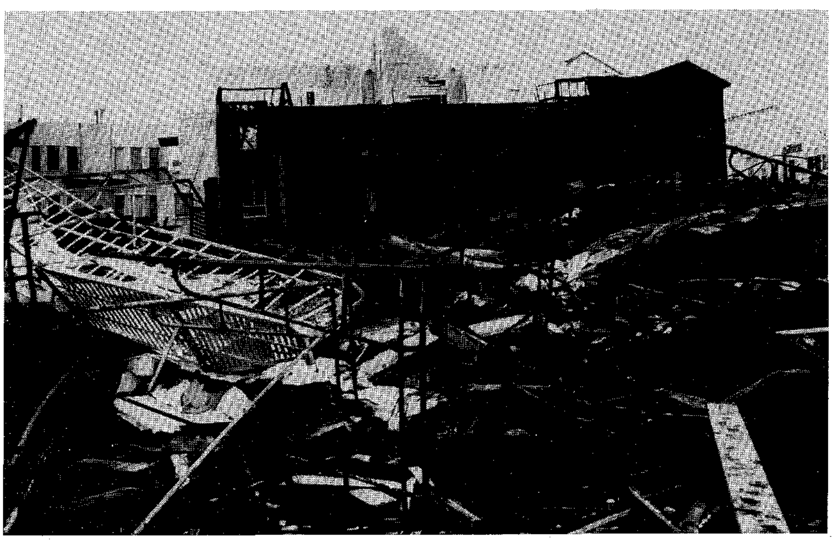
Unreinforced masonry (URM) buildings present a recognized serious hazard to the public during earthquakes. A few cities, such as Los Angeles, have had strengthening programs in effect for several years, and a 1986 California law requires all cities to inventory these old structures and develop mitigation plans by January 1, 1990. The wisdom of such a law was demonstrated by the damage and life-threatening partial collapses suffered by large numbers of URM buildings in the older downtown portions of Santa Cruz, Los Gatos, and Watsonville. The 2,100 URM buildings in San Francisco fared much better; only a few dozen experienced severe damage, with most of these on soft ground in the South of Market area. The majority of San Francisco's URM buildings, located on firm ground or rock, probably saw ground motions on the order of 5 to 10 percent of gravity, not high enough to cause serious damage. But San Francisco, which is still developing its mitigation plan under the 1986 law, should not find solace in the relatively good behavior of its URM buildings. An epicenter closer than the 95-km distance to the Loma Prieta epicenter would have caused much more damage to these brittle structures.

The extensive structural damage in San Francisco's Marina district owed partly to the soil conditions there and partly to the type of construction. Many of the damaged structures were three- to five-story, wood-frame residential buildings dating from the 1920s and contained open first-story parking areas with little bracing (top left). Several of these collapsed in their first story (middle left). The soil in the zone of damage was a loose fill placed in 1915 for the Panama-Pacific Exposition. Evidence from other locations where records of ground motions were obtained indicates that such material amplifies the ground shaking considerably, and this amplification increases the likelihood of damage. The fill material is also prone to liquefaction, and evidence of liquefaction abounded in the Marina. Liquefaction is a type of ground failure and contributed to the structural damage by causing differential settlement of the buildings. Structures similar to those damaged, but located just a few blocks away on firmer ground, sustained little damage.

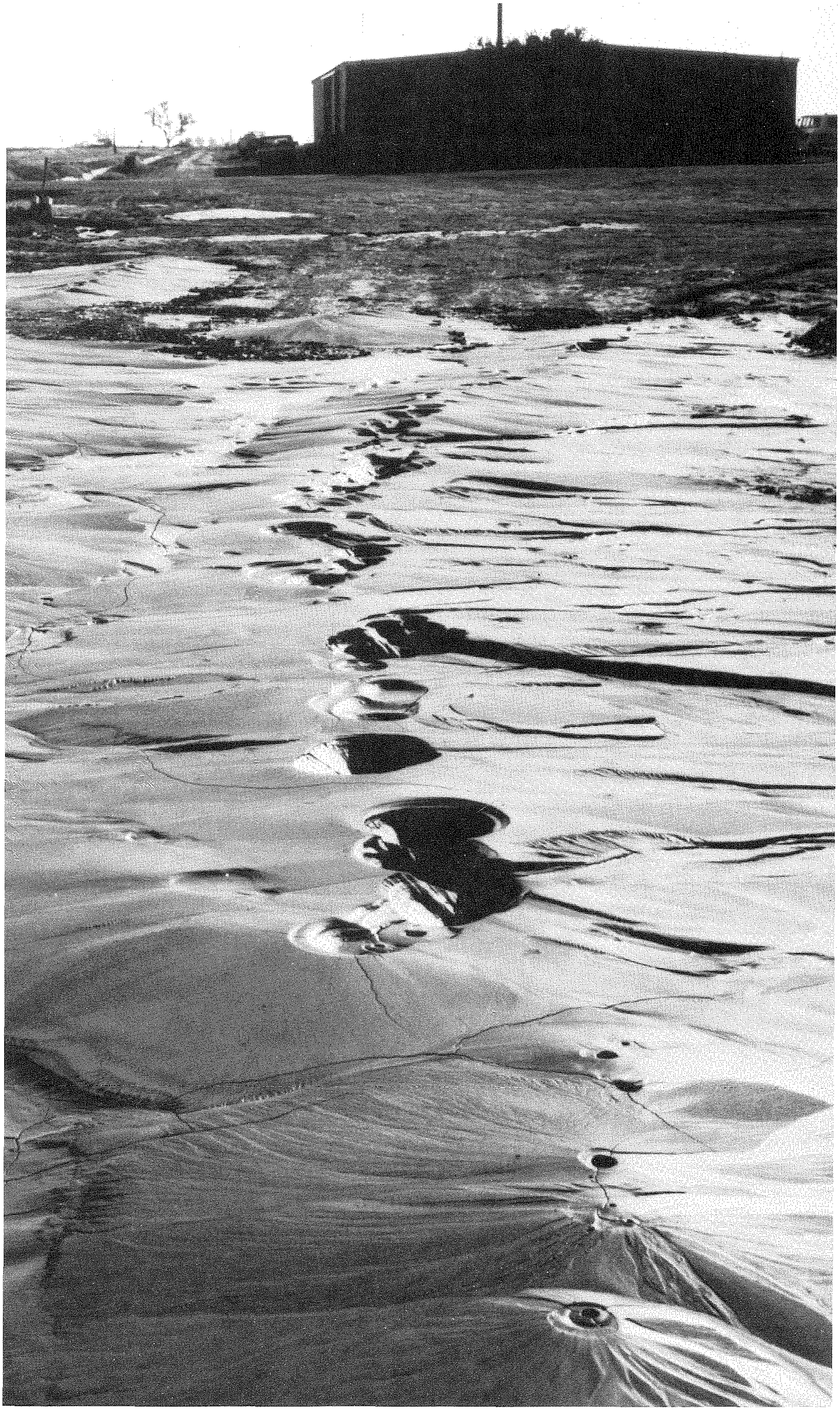
A fire in the Marina district, an area densely populated with wood-frame structures, proved to be particularly troublesome (aftermath shown in bottom photo). Water was initially delivered to the site from a hydrant in front of the building where the fire ignited (until the building collapsed on the hydrant); then from another nearby hydrant (until breaks in the municipal water system and in a high-pressure auxiliary water system dropped the water pressure); then from the lagoon at the Palace of Fine Arts four blocks away (until other buildings collapsed on the fire hose); and finally from Marina Lagoon via the fireboat *Phoenix*. This effort took about an hour, by which time the fire had spread to other buildings and was shooting flames 75 feet into the air. Control of this fire and more than 20 other smaller ones taxed San Francisco's fire department to its full capacity. Just a few more fires or water-pressure problems might have overwhelmed the local fire-fighting capability right after the earthquake and greatly increased the role of fire in the overall damage. □



Damage in San Francisco's Marina district was widespread because of building style, soil conditions, and fire.



John Hall, associate professor of civil engineering, has been a member of the Caltech faculty since 1980, during which time, in addition to the usual faculty duties, he's contributed two other articles to E&S*—on dams and earthquake safety (May 1984) and, with Jim Beck, on engineering features of the Mexican earthquake (January 1986). Currently he's also secretary of the governor's independent board of inquiry into the freeway failures in the recent quake. Hall received his BS from West Virginia University (1972), MS from the University of Illinois (1973), and PhD from UC Berkeley (1980).*



Liquefaction

Liquefaction has progressed since 1964 from the status of a curious, rather mysterious event accompanying earthquakes to a well-documented, fairly well-understood and predictable process.

by Ronald F. Scott

The recent Loma Prieta earthquake brought the phenomenon of soil liquefaction into the public eye in southern California. The damage in San Francisco's Marina area was widely attributed to liquefaction, and there have been dark hints that it may have played a role in the collapse of the upper deck of the Nimitz Freeway. Later reports indicate widespread liquefaction events at Moss Landing, Santa Cruz, and other areas of strong ground motion caused by the earthquake. The term "soil liquefaction," used initially by a few geotechnical engineers and geologists, became a popular media buzz-word for newspaper, radio, and television reporters who besieged the offices of soil engineers (including this one) in the few weeks following the earthquake. What is soil liquefaction? What conditions give rise to it? How hazardous is it? Where can it happen in the Los Angeles area? Are there any palliative measures? If one has a home or other property in an area deemed to be potentially liquefiable, what can be done? Since I've had a lot of practice at this lately, I'll try to provide some relatively nontechnical answers for *E&S* readers.

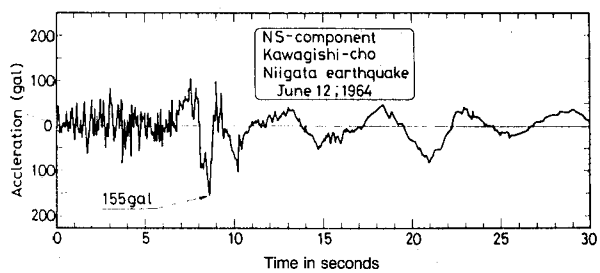
Sand boils were formed as liquefied sand erupted from a fissure in a field during and following the 1979 Imperial Valley earthquake.

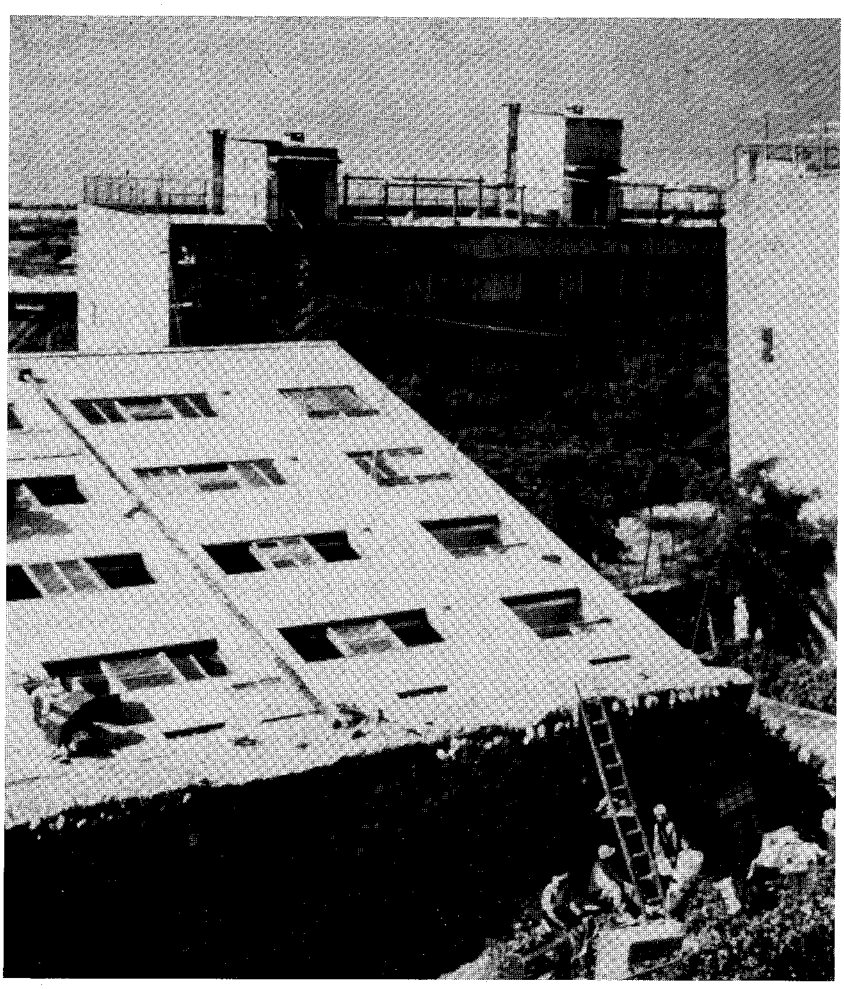
Soil liquefaction has occurred to a greater or lesser extent in all earthquakes; as indicated by contemporary accounts, it has been recognized for centuries without a clear understanding of its mechanisms. Substantial structural damage was associated with liquefaction in the 1960 Chilean earthquake, but detailed engineering attention first focused on liquefaction as a major problem in two 1964 earthquakes—in Alaska (March) and in Niigata, Japan (June). In the United States virtually the entire earthquake engineering community devoted their efforts to the Alaskan event because of its size (magnitude 8.4) and diverse effects, so that the somewhat smaller (magnitude 6.6) but still immensely destructive Niigata earthquake went virtually unnoticed here for some time. Professor George Housner visited Japan later in 1964 (see page 32) and told me about the situation in Niigata, suggesting that I go and see it. I formed a team of soil engineers and applied for a grant from the National Science Foundation to do this. We traveled to Niigata in 1965. Because of its location on alluvial deposits at the coast, Niigata was devastated by widespread liquefaction and its effects. We were deeply impressed by the potential of sand liquefaction for damage, and all of us began to study the phenomenon in diverse ways.

Liquefaction played a role in some of the damage in Alaska and emerged again as a villain in the partial collapse of the Lower San Fernando Dam in the 1971 San Fernando earthquake. Possibly because that failure looked like a more-or-less simple slope failure and involved some highly technical analysis, liquefaction did not catch on then with the media. But with an undiluted form of it in fairly level ground in the Loma Prieta earthquake, liquefaction has now, in 1989, arrived as a hot topic.

What is liquefaction and under what circumstances does it develop? It's a phenomenon associated with fine- to medium-sized (0.1 to 0.5 mm diameter) cohesionless sands when they are in a relatively loose state and saturated with water. If the same material were dry, it would

A strong-ground-motion recorder obtained the accelerations of the 1964 Niigata earthquake in the basement of one of the Kawagishi-cho apartment buildings, which are shown settled and tilted below. The record begins as a typical, high-frequency, firm ground motion, but at about 7 seconds changes to a lower-frequency, sloshing motion as the ground below the building partially or completely liquefies.





become denser and the surface would simply settle on shaking, which causes some of the unstable particles to tumble into spaces between lower, adjacent particles. When the soil is saturated with water, however, propagation of the earthquake waves through it again dislodges some grains, but now their fall into lower spaces is hindered by the water's presence. For a short period of time they are suspended in the liquid. Thus the weight (in liquid) of such particles is no longer borne by the underlying grain structure through solid contacts, but is instead transferred to the liquid, whose pressure rises. In weak shaking only a few grains are moved and the pressure of the water in the pores of the soil rises a small amount. In more intense shaking or shaking of longer duration virtually all of the particles in a mass are disturbed and suspended in the water for a short span of time. In this case almost all solid contact between the particles is lost, so that the soil mass has none of the properties of a solid, which it formerly possessed, but becomes a liquid with the density of the soil/water composite and a viscosity higher than water alone. The liquefied state persists until the particles settle out to form a new, denser structure of contacting solid sand grains, and the water pressure has reverted to hydrostatic once more. The amount of time this takes depends on the size of the grains (smaller grains mean a longer duration) and the dimensions of the liquefied mass (bigger means longer). Typically liquefaction endures for a few minutes but may last up to 10 or 15 minutes.

Besides the presence of a relatively loose, saturated sand and, of course, the strong ground motions caused by an earthquake, another requirement for significant liquefaction is a water table within 10 to 15 feet of ground surface. There is no direct instrumental evidence for the depth to which a soil can liquefy, but calculations indicate that it should generally be limited to the upper 50 to 60 feet of soil profile.

If the soil is fairly uniform all the way to the ground surface, then, depending on the depth of the water table, a general subsidence takes place, and water may appear at the surface. This is unusual in nature since plants and cultivation impose a finer layer of somewhat cohesive soil in the top few feet. In this case, as I view it, if the underlying layer of sand should liquefy, the water has no immediate egress to the surface, since there is an upper confining layer of lower permeability. It finds its way to the surface, however, discontinuously through root or animal holes or cracks, possibly generated by the earthquake. Since it's under pressure from the over-

Liquefaction in the 1989 Loma Prieta earthquake caused lateral spreading of the ground, which tore apart the UC Santa Cruz marine biology building at Moss Landing (top right). Diesel-fuel-filled tanks (top left), also in Moss Landing, settled and tilted on the liquefied sand. The sand boils (above) appeared under the approach spans of the San Francisco Bay Bridge in the same earthquake.

burden, the saturated, liquefied sand will emerge at the surface as fountains as high as a few feet. The remains of these fountains are variously called sand boils, sand volcanoes, and mud fountains, and are a sure indication of liquefaction. The sandy water in the jet falls down around the hole, the sand settles out to form a volcano-like structure, and the water runs off. A subsequent aftershock can reliquefy the material, the fountain is revivified, and the new spout may erode the former volcano feature. Although these are usually ephemeral phenomena, "fossil" sand boils have been identified by Kerry Sieh and his students in his investigations of the San Andreas fault movements at Pallett Creek, and researchers in South Carolina have also found evidence of sand boils presumably caused by the 1884 Charleston earthquake.

The consequences for a structure underlain by a suddenly liquefied sand are fairly obvious—it settles and generally tilts. At the same time, however, the liquefaction of the foundation soil also isolates the building from all but the first few seconds of strong ground motion, so it actually experiences less intense shaking than it would if the ground had remained solid. Frequently, structures that have experienced liquefaction of their foundation soil are relatively undamaged structurally—if you consider settling a few feet and tilting up to 70 or 80 degrees "undamaged." Of course, all connecting utilities are disrupted, and the cost of straightening up the building and reconnecting it may amount to more than half the cost of constructing it from scratch.

Liquefaction, although possibly causing large amounts of property damage to ordinary structures, has not generally been associated with a hazard to life.

In Niigata in 1964 an underground, hollow, reinforced-concrete, sewer junction box floated to the surface when the soil liquefied (top). Lateral spreading in the 1989 earthquake destroyed a coastal highway in Moss Landing (bottom).

Houses and other buildings settle because they are heavier than the liquefied soil, but just the opposite can happen to structures that are buried—pipes for water, sewer, gas, and petroleum, underground storage tanks, and subway tunnels. In most cases the density of these structures is less than that of the suddenly dense liquid in which they find themselves, and consequently they float, tending to rise toward the surface. The amount of movement depends on the relative densities involved, the size and connections of the structure, and the duration of time for which the soil remains liquid.

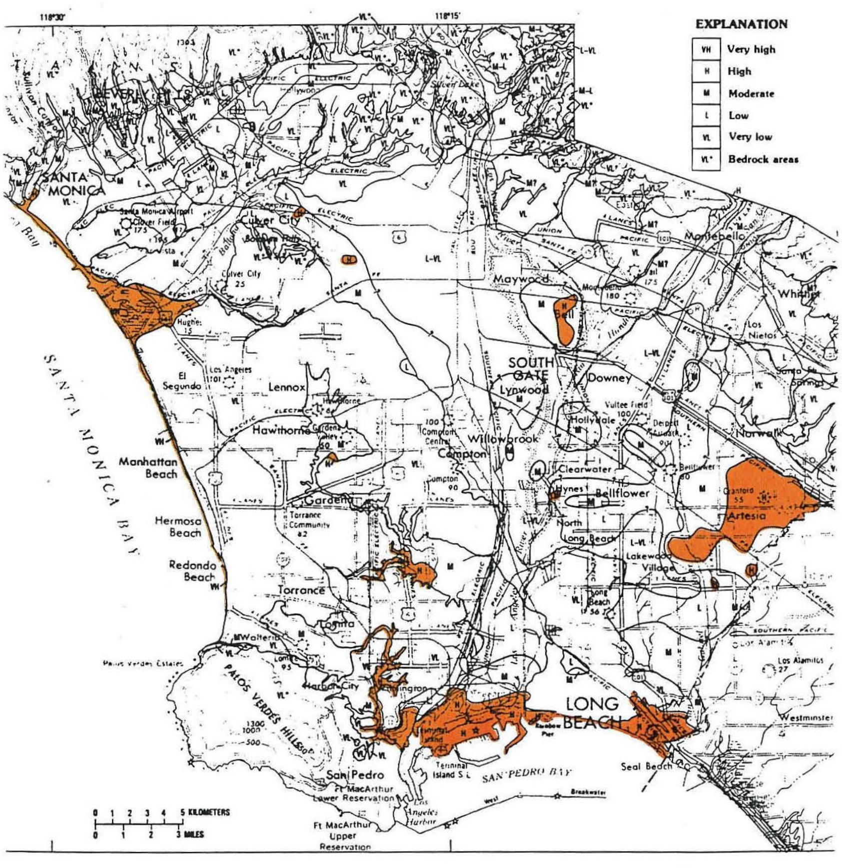
Because of the isolation it affords from the strong ground shaking, liquefaction, although possibly causing large amounts of property damage to ordinary structures, has not generally been associated with a hazard to life. For other structures, however, such as dams, liquefaction can contribute to collapse, with potentially large numbers of casualties, depending on the dam's location. Although the evidence and analyses of the recent event are not all in yet, apparent liquefaction of old fill material in the Marina area of San Francisco caused substantial ground settlements and lateral movements leading to structural damage and breakage of utilities in the soil. So when fire broke out, there was insufficient water to fight it because the water pipes had broken. At Moss Landing, down the coast, lateral spreading of the ground on small slopes accompanied liquefaction and tore apart structures and foundations.

Liquefaction will occur in the Los Angeles area where the above conditions of relatively loose sandy soils, high water table, and seismic potential exist, that is, generally along the coastal zone—Marina del Rey, Manhattan Beach, Redondo Beach, the Long Beach area, and portions of Huntington Beach and Orange County. Isolated regions also exist inland. A US Geological Survey report (noted under the map at left) gives a detailed survey of the liquefaction hazard in Los Angeles and Orange Counties.

Possible mitigating measures range from none to a variety, depending on the structures involved and financial resources available. It would be a good idea, perhaps, not to buy a vacant lot in a liquefiable area for the purpose of constructing a residence. If you already live in a single-family house in a liquefiable area, there is practically nothing you can do except move, if the hazard disturbs you sufficiently. At the other end of the structural and financial spectrum, for large enough structures such as power plants, big buildings, and, say, natural gas storage tanks, several approaches are possible. Sometimes the liquefied soil can be removed by excavation and replaced by a properly compacted fill. Or the liquefied soil may be stabilized chemically, or the structure supported on piles driven to a deeper, firmer layer of material. All of these techniques are expensive, but the expense may be justified by the location and the value of the construction required.

Liquefaction has progressed since 1964 from the status of a curious, rather mysterious event accompanying earthquakes, to a well-documented, fairly well-understood and predictable process. The liquefaction in the San Francisco Marina was predicted for an earthquake of that size, for example. Our research—laboratory, field, and analytical—will continue in the attempt to understand and analyze the phenomenon still better and to arrive at techniques to predict its occurrence and protect against it. □

This US Geological Survey map shows relative liquefaction susceptibility in the Los Angeles area based on current understanding of geology, soil, and water-table conditions.



SOURCE: J. L. Ziony, ed., *Evaluating Earthquake Hazards in the Los Angeles Region—An Earth-Science Perspective*, USGS Professional Paper 1360 (Washington D.C.: US Government Printing Office, 1985).

Ron Scott last wrote for E&S *in the Fall 1988 issue on an entirely different subject—baseballs. But studying soil behavior is what he* really *does, and he's been particularly busy since the implication of liquefaction in damage caused by the recent Loma Prieta earthquake. Scott holds a BSc (1951) from Glasgow University and ScD (1955) from MIT. He joined the Caltech faculty in 1958 and is currently the Dotty and Dick Hayman Professor of Engineering.*

George W. Housner: How It Was

Seismologists are interested from the ground surface down, and engineers are interested from the ground surface up.

Known as the father of earthquake engineering, George W. Housner first came to Caltech after graduating from the University of Michigan in 1933. He earned his MS here in 1934, then worked for five years as an engineer designing structures in Los Angeles before returning to finish his PhD at Caltech in 1941. He wrote his dissertation on the earthquake behavior of buildings. In 1945 he returned once again as assistant professor, and it was in those early postwar years that he developed spectral analysis, decomposing the complex patterns of an earthquake's ground-motion "signal" into its component frequencies. Housner spent the rest of his distinguished career at Caltech and was named the Carl F Braun Professor of Engineering in 1974. Most recent among his many honors was the 1988 National Medal of Science.

Housner became professor emeritus in 1981, but he never really "retired." And when Gov. Deukmejian needed someone to head an independent inquiry into the collapse of sections of the Nimitz Freeway and the San Francisco Bay Bridge during the October 17 Loma Prieta earthquake, Housner was the perfect choice. His four-decade reputation in making structures safe from shaking had already inspired the Times *of London, two days after that quake, to laud him as "the man who kept Frisco standing."*

The Oral History Project of the Caltech Archives recorded Housner's remembrances in 1984 in three days of interviews with Rachel Prud'homme. The following excerpts from that oral history trace the development of earthquake-safe building standards in California—and probably the rest of the world as well.

George Housner exhibits his shaking machine, which simulates the effect of an earthquake on the model "highrise building" at right. Calculations of how a real building will react when shaken and vibrated have made it possible to develop procedures for designing safer structures. The photo was taken in the early 1960s.

Rachel Prud'homme: Can you give me a bit of the background on the difference in the work done here in seismology and in earthquake engineering research?

George Housner: Seismologists primarily study the earth's interior by recording earthquake waves which take various paths through the interior of the earth. Their instruments are very sensitive. I can explain that with an anecdote: For our purposes—we want to measure the very strong shaking that does the damage—but in this case the seismologists' instruments would be off-scale. We had a lot of instruments—when I say "we," I mean the community here in southern California—installed in buildings prior to the 1971 earthquake, and it was sort of an eye opener to the engineers to see what these motions of the ground and of the buildings were. And we had a meeting up in San Francisco to show these records and explain them to the engineers. Afterwards, one of the engineers approached Perry Byerly, who was a famous seismologist and had just become professor emeritus at Cal Berkeley—and said, "Perry, *these* are the kind of records we engineers always wanted. Why haven't you gotten them for us before?" "Oh," he said, "If I had specialized in strong motions, I'd now be *assistant* professor emeritus." And there's a lot of truth to what he said. One way of distinguishing the difference is that seismologists are interested from the ground surface down, and engineers are interested from the ground surface up. The dividing line is maybe 100 feet down. But we're interested in very strong shaking and the nature of strong

A Housner-Hudson shaking machine, the first modern earthquake-simulation device, is hoisted to the top of a 110-foot intake tower at the Encino reservoir in the San Fernando Valley for the first field test of the machine in 1961. Although this tower was scheduled for replacement and could be shaken with the energy equivalent to a fairly strong earthquake, a similar machine on Millikan Library jolts that structure only gently for student projects.

shaking—where it might occur, and so on. Byerly once told me that the only precise definition of an "epicenter" was that it's "a mark made on a map by a man who calls himself a seismologist."

RP: When was earthquake engineering research started at Caltech?

GH: Well, that was started by R. R. Martel, who got very interested. He had gone to Japan to attend a world engineering conference in the late 1920s and had seen what had happened to Tokyo in the '23 earthquake and had noticed that some of the Japanese were interested in earthquake engineering.

RP: The big earthquakes in Tokyo and Santa Barbara, and then Long Beach were precursors in a sense to finding out what potential hazards there were in earthquakes. And then there's a jump to the '64 quake in Alaska.

GH: Well, there were other quakes, but they didn't happen to hit the big cities. An earthquake gets famous for killing people, not for its real size.

RP: So your job is to keep people from getting killed, basically.

GH: Right. There was a very important earthquake at El Centro, California, which for many years held the record for the strongest recorded shaking. It was 7.1 on the Richter scale. So in earthquake engineering circles, worldwide, the El Centro earthquake is well known. We've had Japanese visitors who tell me, "Oh, I'm going down to El Centro and see what it's like there."

Then there was a damaging earthquake in 1935 at Helena, Montana. There was a rather big earthquake in 1952 up by Tehachapi. There was a big earthquake in '49 near Tacoma, Washington, and the one in Alaska in '64. Although the Alaskan quake didn't kill many, it was such a large earthquake, by far the largest in modern times in this country, that it was very important. The National Academy of Sciences put out a big report, and the fattest of all the volumes is the one on engineering. I was chairman of that engineering committee and Paul Jennings was also a member. We put a lot of effort into that; it's a monumental report.

RP: So you're recording and studying ground motion.

GH: We also record and study the motion of buildings during an earthquake. The objective is—given, let's say, the ground shaking—to be able to calculate what a building will do with sufficient accuracy so you can design it properly.

RP: Do you deal with soil condition or is that the seismologist's responsibility?

GH: No, that's in engineering. Really, I should not have said from the ground surface but from the rock surface. For instance, here we're sitting on 900 feet of alluvium, so the seismologist's interests would only start 900 feet down. But our interests would be in the behavior of the ground as well as the behavior of buildings. Ground behavior is a matter of soil mechanics. Ron Scott is our expert at Caltech on soil mechanics.

From our research on ground motions and the mathematical analysis of the vibrations of structures, we develop procedures for designing buildings, not with a building code but from a more rational approach. Paul Jennings and I were consultants on the earthquake design of the Arco twin towers, as well as of the Union Bank building, the Security Pacific Bank building, and what used to be called the Crocker National Bank building.

The building code merely says that you should design to resist a certain force pushing on the building. But in reality the building is vibrated. To do it right you need to know how it will be strained. So what we did for these buildings is identify those faults in the general region that might generate strong shaking at the site. This included faults such as the San Andreas, which is about 35 miles from the site and could generate a magnitude 8-plus earthquake. Then there are closer, smaller faults which would generate smaller earthquakes. So, on the basis of earthquakes we had recorded, we were able to develop methods of generating earthquake ground motions that corresponded to these earthquakes at different distances. And we computed for each of them how the building would vibrate and what the forces and stresses would be, and then the engineers designed accordingly. So in a sense those buildings had experienced some four or five earthquakes before they were built.

Housner, shown here in 1958, and Don Hudson designed this compact earthquake recorder, 50 of which were installed in buildings in the Los Angeles area and 50 in San Francisco.

RP: What was the state of the art of earthquake engineering before, when you started?

GH: Well, for example, when we were doing this work on these high-rise buildings, they were the first ever done. And after the San Fernando earthquake, we took records obtained in some of these buildings and computed from the recorded basement motions the corresponding roof motions. These were then compared with the recorded roof motions and we got very good agreement. The Los Angeles building department then said, "Well, good. From now on, all buildings over 16 stories high must be designed on the basis of dynamic analysis, taking into account realistic ground shaking." So it made a big change in the way things were done.

RP: Do you think that Caltech has pretty much become the leader in this field?

GH: It was the leader for many years. Now some of the other schools have also built up their efforts; notably UC Berkeley and the University of Illinois. Earthquake engineering is an extremely interesting subject, so it has attracted a lot of people now. We're not claiming that right now Caltech is the leader, but I think it's certainly one of the leaders.

RP: Since 1947 you and Professor Martel were on an Advisory Committee of Engineering and Seismology, set up by the Coast and Geodetic Survey. Can you tell me about that?

GH: That only lasted a certain number of years, but it was a precursor to the Earthquake Engineering Research Institute. In the early days those of us interested in earthquakes—we were a very small number—were highly critical of the Coast and Geodetic Survey because they weren't really doing enough. The leader of the group that installed and maintained the strong-motion instruments here on the West Coast, Franklin Ulrich, got the idea that if there were an advisory committee to his operation, then its recommendations might carry more weight in Washington. So that was why it was set up. As it turned out, it didn't carry more weight, and in sort of desperation—frustration—we

formed the Earthquake Engineering Research Institute.

Originally its function was to do research, to develop the instruments and get them installed, and that sort of thing. And in the very early days we actually did some of that. I think we developed the first modern shaking machine that you put on buildings to shake them.

RP: You actually shake the building?

GH: That's right. We have a machine on top of Millikan Library now and shake that. But we obviously are under restraint because we can't shake it hard enough to feel. That's part of the student lab work; they shake the building and measure what it does, and so on. Before the library staff moved into the building we shook it real hard once. And we had the top going back and forth about one-eighth of an inch. This was before the San Fernando earthquake. Jennings noticed that the library shelves were not braced properly, so he wrote a memo to the building and grounds people saying, "These bookshelves are not right; you have to strengthen them so that they won't come down during an earthquake." Well, they didn't do anything. So he wrote another memo. They still didn't do anything. And when the earthquake came, down the shelves went. It was a real mess.

Bookshelves on the eighth floor of Millikan Library (below) did not fare well in the 1971 San Fernando earthquake— despite warnings.

RP: And then they did it.

GH: Yes. Now, if you look up, you can see that they're braced. In fact, all the bookshelves on campus are supposed to be fastened to the walls so they don't fall down on the occupants of the room.

RP: Computers must have had an extraordinary effect on your research.

GH: Oh yes, they did—enormous. Without the development of the digital computer, we wouldn't be anywhere near where we are. It's an enormous calculating job to take an earthquake accelerogram and compute the response of a building. One standard kind of calculation we make from an earthquake record is to compute what we call the response spectrum. I first did that for my thesis. And the very first time we calculated it—we did it by pencil and paper, which involved drawing the accelerogram and multiplying and integrating—it took about a day for one point on the spectrum. That was at the very beginning of my thesis research. Then we developed a small mechanical analog computer, and that speeded it up from one day to about 15 minutes, an improvement of about 30 times. But then later we developed an electrical way of doing it, and we'd get a point in maybe 15 seconds. Now we get 500 points in 15 seconds on the digital computer.

RP: You have developed machines to measure ground shaking, and have spread them over a far greater area than before. And you now work with the seismologists who also record data.

GH: Right. Actually, after the San Fernando earthquake, the seismologists saw that our records could also throw light on the fault mechanism, the slip of the fault. So they got interested in our records. When the fault slips, it may slip like the San Andreas fault, which slides horizontally over a depth of six or seven

In the April 1964 Alaska earthquake (magnitude 8.4) a section of bluff near Anchorage (visible in the lower right of the photo at left) slipped into the sea, continuing during the earthquake until damage extended a half-mile inland. About 35 houses were destroyed in this landslide, including those in the picture at right.

This earthquake was the event that got the attention of the government. And the money.

miles. Over that fault area, it's jumping and sending out stress waves. And our instruments are close, giving information on this process of slipping. That was of great interest to the seismologists, so they're interested now in our records from that point of view.

There are some seismologists who work more closely with engineers than others do. Here at Caltech we work in particular with Clarence Allen, Hiroo Kanamori, and Kerry Sieh. For a seismologist the distinction is whether he's interested primarily in seismology or primarily in earthquakes.

RP: In '64 there was the great Alaska quake. And then there was the Niigata in the same year. Would you describe them?

GH: Alaska was the big earthquake with a magnitude of 8.4. We figure that the fault slipped over a length of about 450 miles. If you had the same kind of an earthquake in California, that would go from below Los Angeles to beyond San Francisco, but of course we don't have the same kind of earthquakes. It was a monstrous earthquake. If there had been large cities in the region, it would have been a great disaster. Because of its size it was extremely interesting, and it's really unfortunate that there weren't any instruments to record the ground shaking. The nearest instrument was in Seattle. It was an earthquake well worth studying for the ground behavior and its landslides. One slide was of a size never previously conceived of. The ground at Anchorage extends to the ocean, where there was a bluff of about 100 feet. And during the earthquake the bluff slipped down. Then, as the earthquake continued, additional ground continued slipping until the landslide extended about a half-mile back from the bluff and extended along the coast for a couple of miles. It was on the outskirts of the city, fortunately, but 35 houses were destroyed.

This earthquake was the event that got the attention of the government. And the money. Before that the National Science Foundation didn't have any special earthquake engineering program. But after that they did set up a program with special funding in earthquake engineering.

RP: Isn't it true that after the Alaska quake, President Johnson tried to set up an earthquake research program that would call for extensive surveys of faults and so on?

GH: Yes, he was apparently interested in getting something going, but unfortunately his term came to an end too soon. So the earthquake didn't have a lasting influence in that sense. It was really the 1971 earthquake that finally got Congress to move.

The magnitude-7 Niigata earthquake wasn't such a large earthquake as Alaska, but it had remarkable soil behavior. Like most Japanese cities, it's on an outwash plain of a river. It's so mountainous, and that's about the only place they can build. And the top 100 or 150 feet of ground was sand that had been washed down and deposited, and there was high ground water. When the shaking came, there was a tendency for the sand grains to reorient into closer packing. When that happens (because the spaces are full of water), for a while all the weight on the surface is supported by the water—until it oozes out. During that time the sandy soil has little strength and the damage to their buildings was mainly due to that. Tremendous damage was sustained in Niigata due to settlement and cracking and tilting. This phenomenon, which we call liquefaction—for a while the material is kind of like a liquid, what used to be called quicksand—came to the attention of engineers for the first time as a possible, serious thing. So now it's watched very carefully when putting up buildings or power plants or things of that sort.

At the time of the Niigata earthquake I was a member of the board of directors of the International Institute of Seismology and Earthquake Engineering in Tokyo. It was a school set up cooperatively by UNESCO and the Japanese government, and I was the UNESCO representative on the board of directors to help it get started. Every year we had a meeting over there, and in '64 when I heard about the earthquake I went to visit Niigata. Of course, that isn't my specialty, but when I came back, I told Ron Scott that he would have to go over and see it—he should organize a group and get funding from NSF to go over. So they went over, and I noticed when they came back they were in sort of a state of shock about what could happen.

When the 1971 earthquake came . . . we got more records on that earthquake than out of all the earthquakes in the world before that.

RP: You've done a tremendous amount of work with state and federal governments. How do you work with the government of the state of California? How have you worked with them to help plan for earthquakes?

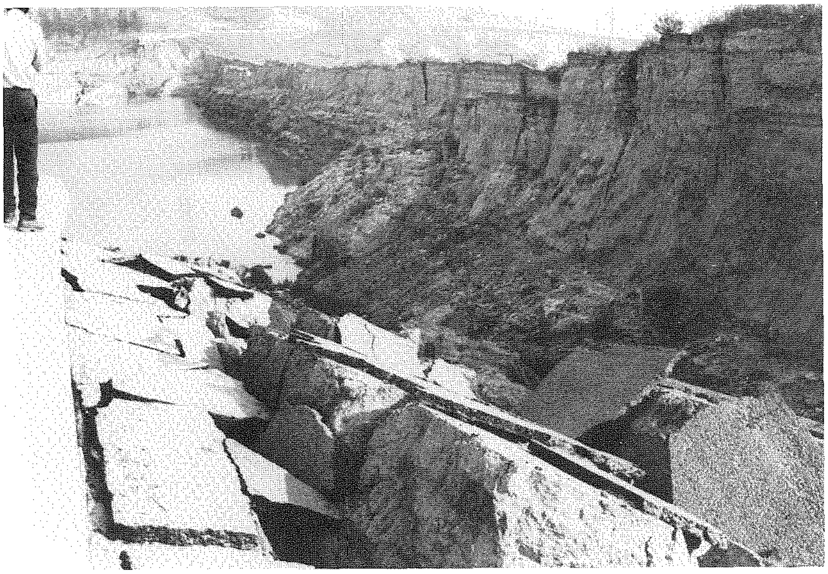
GH: I was president of the Earthquake Engineering Research Institute when the big Feather River project was planned—I think it must have been in the middle or late 1950s—that I first realized there was going to be an earthquake problem. They were going to build this system of dams and aqueducts and pumping plants real close to the San Andreas fault. In fact, the project crosses the fault three times.

The project brings water from the Feather River. North of Sacramento, where the Feather River comes out of the Sierras, a large dam has been built, the Oroville Dam, which provides the main reservoir for the system. From Oroville Dam the water comes down the American River and on through Sacramento and out to the delta region of the bay. Then, at the southern end of the delta region there is a pumping plant which takes water out of the delta and starts it south in the aqueduct—sort of an artificial river—along the western edge of the valley to near Bakersfield. Then about half of it gets pumped up over the mountains into Los Angeles, and the rest skirts around east of the mountains and goes down to San Bernardino. This is an enormous system—some 20 big dams, several big pumping plants, and the aqueduct. At the time it was built, I think it cost about $3 billion, but I think to do it now would be $10 billion. We felt we had to tell them that they were facing big earthquake problems.

As president of the Earthquake Engineering Research Institute, I wrote the letter to Harvey Banks, who was the director of water resources. Then in due course I got a telephone call from Larry James, chief geologist up there, who said that some of them would like to come down and talk to us. So Sam Morris, Don Hudson, and I met here at Caltech with Larry James, Bob Jansen, and Don Thayer. And we explained the problem and how they would have to face up to the risk and so on. They seemed impressed by that, but they couldn't sell it to the boss. They went ahead and built Oroville Dam. Then Banks retired and a new head was appointed, Alfred Golzé, who had been at the Bureau of Reclamation. Apparently these three fellows we'd talked to had gone to Golzé and said, "We think we ought to do something." So they came back here—this was, of course, a number of years later—and said, "We'd like to have you on an advisory committee on earthquakes."

They had designed the dam and were building it, and were just getting ready to start designing the rest of the system—it took maybe six years to build the dam and fill the reservoir. I remember talking with Larry James, who decided who the advisory committee members should be. Hugo Benioff, a Caltech seismologist, was chairman; I was on; Nathan Whitman, a Caltech graduate and practicing engineer in the local area; and Harry Seed of UC Berkeley. We prepared a recommendation based on my research and told them what the strong shaking would likely be and what they should do. And they adopted that procedure. That was the first time such modern procedures had been used on dams and pumping plants. We set a precedent; now all over the world they do it the way we had recommended.

It's kind of ironic. This project is sort of a leader in earthquake safety; it's being held up as a model all over the world. Yet, after the project was essentially completed, Ralph Nader's group came out with a report denouncing the whole project, saying particularly that it hadn't been designed for earthquakes and wasn't safe! It turns out, apparently, that's standard practice,



Dams hold a great potential for destruction and loss of life in an earthquake. Although a large section of the Van Norman dam (built in 1916) failed and slid into the reservoir during the 1971 San Fernando earthquake, the dam itself survived. This was not part of the Feather River project, whose earthquake engineering standards, developed by Housner, set a precedent eventually adopted worldwide.

and when Nader's been asked why he does this, he says, "Well, that's the way to make an impact." He doesn't *want* to check, you see; he wants to make the impact. I'm really annoyed at that.

RP: You were chairman of the Geologic Hazards Advisory Committee for the organization of the California State Resources Agency in the late 1960s. And you were chairman of the Panel on Aseismic Design and Testing of Nuclear Facilities for the International Atomic Energy Agency.

GH: Yes, we drew up reports. I suppose these reports on geologic hazards and atomic energy circulate around and people see them; and maybe they don't do anything immediately, but in the long run something comes out of it.

RP: And of course we had the San Fernando earthquake in February 1971.

GH: Yes, there we were, with an earthquake in our backyard. We prepared a report at Caltech. A number of us were on the Los Angeles County Earthquake Commission; Harold Brown, president of Caltech, was the chairman, and there were Charlie Richter, Don Hudson, Hardy Martel, and myself.

RP: What changes in engineering came out as a result of that earthquake? You said before that the old structures are still unsafe in spite of the 1933 building codes and so on.

GH: Even at that date it wasn't enough to move people to do anything about the old buildings. But the thing simmered on the back burner. All the other cities looked to Los Angeles. Los Angeles was the only city big enough to have a good building department with competent people, and so they always looked to LA for leadership. Well, we recommended to the city council that they should do something about hazardous old buildings. And it was kind of a hot potato; they always had some reason for not taking action—more studies, and this and that. And it kept on that way but it didn't die, which you might have expected. And finally, 10 years after the earthquake, they passed an ordinance to get rid of the old hazardous buildings. Of course, they don't try to get rid of them all at once. At that time they estimated there were about 8,000. Well, if you try to tear them all down at once, that would be worse than an earthquake economically. So what they're doing is to identify the most hazardous, and each year notify maybe 50 people that their buildings must be strengthened or torn down. Of course, they don't want to notify too many at once, because they don't want 500 or 1,000 irate building owners coming at them. So the building department people were somewhat nervous; they didn't know if they could get away with it. If there were a big outcry, they would have to back off. But so far, there hasn't been; they've been doing this and the owners have been cooperating. One building owner did bring suit a year or so ago and asked for an injunction against it, and the judge said, "No, you can't have an injunction against this." So that has sort of settled it now. (The 1985 Mexico earthquake

President Ronald Reagan presents the National Medal of Science to George Housner in 1988 at the White House.

speeded up the process, and by 1989 about two-thirds of the buildings had been taken care of.)

RP: What can you do about the hidden hazards—the water mains, the gas lines?

GH: Those are all problems. The governor of California has some advisory committees, which I presume are still in effect—this was before Deukmejian's time—to look at various aspects. On the water supply for southern California, there was a committee of people who were involved with water supply systems. They came over to talk to us about the general problem. Several were Caltech alumni. They were to size up the situation should the big earthquake occur on the San Andreas fault: what would happen to the water supply to the homes? A big amount of our water comes from outside—the *majority* of our water comes from the other side of the San Andreas fault. And then the question of what happens to the distribution system has to be considered. So they're looking at these things. I myself think it isn't too hazardous a situation. There'll be some damage and interruption with the distribution but not anything in the nature of a crisis.

For many years people interested in earthquakes have pushed the idea that more instruments should be out there to record what's happening. And it was very difficult in the early days to get any money or get anything done. We saw one problem was that there weren't any instruments commercially available. So in the 1960s Hudson and I got hold of one of the instrument companies—Teledyne, a local company making geophysical instruments—and convinced them they should build a strong-motion earthquake recorder, which they did. We advised the company on what kind of instrument it ought to be and the kind of cost it should have and so on. After that, you could recommend to people, "You ought to have one; you can *buy* one right here." We thought that perhaps 100 instruments could be sold, but now Kinemetrics, the successor to Teledyne Seismic Instruments, has sold 5,000 worldwide.

Then a Caltech graduate, John Monning, became chief of the Los Angeles building department in the 1950s. He was a very able man, and it was clear that he had the confidence of the city council, the mayor, everybody. He saw that our recommendation for more instruments, especially in buildings, was very important. So he talked to the councilmen and got their approval, and they put in the code that all new buildings over 10 stories high should have three recording instruments in them—at the roof, at mid-height, and in the basement. With Monning getting it into the code, many buildings got these instruments, and when the 1971 earthquake came, we were able to get all sorts of records. We got more records on that earthquake than out of all the earthquakes in the world before that. And new computer technology made it possible to do something with the records. It was because these instruments were there and we got the records that we were able to show that it was possible to compute what buildings do.

RP: Your implication is that, in earthquake

Cranston got his bill approved by the Senate . . . and it went to the House. And who should get up and denounce it . . . but the representative from Palmdale—sitting right on the fault!

matters, Los Angeles is the leading city in the world, over and above San Francisco.

GH: For earthquakes, yes. I'm sure that the Los Angeles building department is one of the most competent in the country and, as far as earthquakes go, *the* most competent. Usually what happens is that Los Angeles puts something in their code on earthquakes, and then a few years later, it goes into the Uniform Building Code. Monning tried to get this instrument thing into the Uniform Building Code right away. It's the function of what is called the International Conference of Building Officials. But when Monning made his proposal, he was voted down. But I think that now, while the Uniform Building Code doesn't require it, it recommends it. And quite a number of cities have done something.

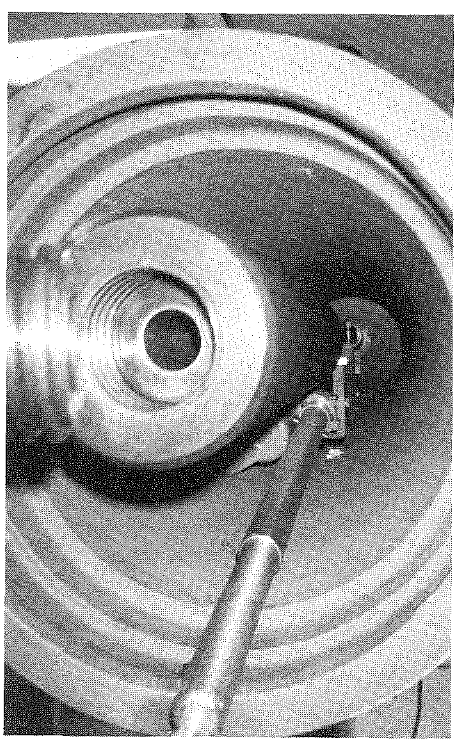
RP: You received a large grant in '74 from the National Science Foundation for a new research program.

GH: Yes. That's, of course, the result of the 1971 earthquake. We had thought that the NSF ought to be putting more money into earthquake engineering research, but it's very difficult to pry money loose when it's already allocated to somebody else. And while they did have a little to put into earthquake engineering, it wasn't much. Then—I think it was just a little before the '71 earthquake—I got a call from one of the assistants in Sen. Alan Cranston's office who said that Sen. Cranston was interested in leading a bill through Congress on natural disasters and wanted advice. We were just finishing a report on earthquake engineering research, funded by NSF, on what the problem was, what you ought to do, and so on. Fortunately, I had a copy and sent it to this assistant, and in due course she got back to me and said, "Well, that's just what we want. And we'll try to put through a bill on it." Of course, you can't keep anything secret there, and the Geological Survey got hold of it and said, "Well, you have to also put in seismology."

So Cranston's office drew up a bill which had two parts: one for funding research in seismology and one for funding research in earthquake engineering. The scheme they use is that when the Senate draws up a bill the House does too, and vice versa. Well, Cranston got his bill approved by the Senate, and then they had the corresponding House committee work one up, and it went to the House. And who should get up and denounce it on the grounds that they didn't need to do anything about earthquakes in California but the representative from Palmdale—sitting right on the fault! And that killed it; they didn't get enough votes. So then they had to put it away and start again.

Well, in between came the San Fernando earthquake. And Sen. Cranston—I guess he wanted a little publicity—called and said he'd like Clarence Allen and me to meet him at such and such a place and show him around. So we did. Of course, by "coincidence," wherever we went there were TV people waiting for us. So Sen. Cranston made hay on that. Then he went back and got the bill through both houses, got it approved and implemented. So that's where the big grant came from, because the bill directed the National Science Foundation to put a certain amount of money into earthquake engineering research. I think it was at that time something like $6 million. It's been a very important thing because it funds earthquake engineering research at many universities, and it's had a reinvigorating effect on civil engineering because it suddenly brought them all into the 20th century. □

The cannon's breech. The cannon itself is sheathed in a 16-inch-diameter cast-iron pipe as a safety precaution.



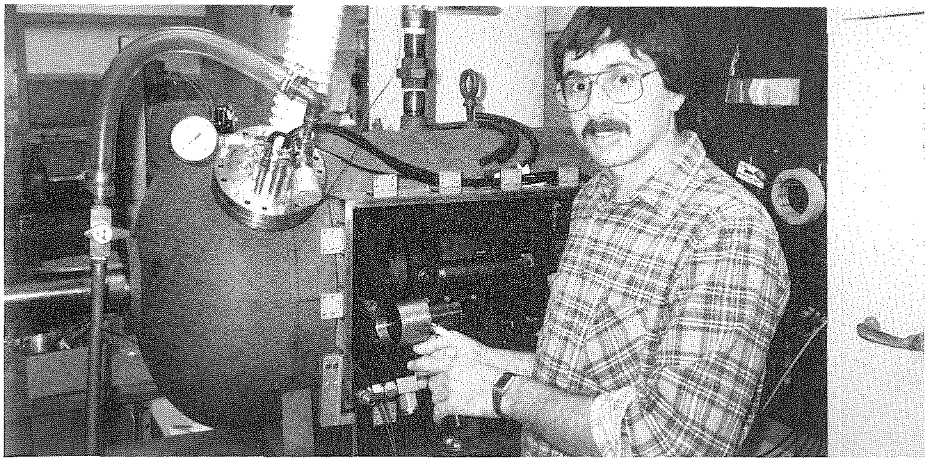
The Glass Menagerie

A "metallic glass" isn't a tin cup. A tin cup, like every ordinary hunk of metal, is crystalline—its atoms packed in a neat, orderly arrangement that repeats itself over and over throughout the material. A glass, however, is amorphous—its atoms are all jumbled together higgledy-piggledy, with no repeating order. A metallic glass is composed of metallic atoms, such as nickel, that have forsaken crystallinity for amorphism.

Metallic glasses have several useful properties. They are very strong under tension; a metal fails when stretched because dislocations (tiny crystal defects—missing atoms or planes of misaligned atoms) migrate through the crystal until they link up to become fractures. But an amorphous material has no set structure, so either dislocations don't form easily, or they don't travel well—the reason isn't clear yet, but metallic glasses will pull enormous loads. Metallic glasses also have superior magnetic properties. A magnetizable crystal—a chunk of iron, for example—consists of magnetic "domains," within which every atom has the same magnetic orientation. Each domain normally pairs with an equal-sized domain of opposite polarity, and their magnetic fields cancel. Apply an external magnetic field, and the domains aligned with it grow at their partners' expense. But any one atom can't easily realign itself because its reactionary neighbors—the other atoms in the domain, whose magnetic moments are bound in lockstep along the crystal axes—wield great influence. Thus a strong field must be applied before magnetic *perestroika* can occur. In the anything-goes disorder of an amorphous material, however, atoms can easily align themselves with a weak or fast-changing field. Thus metallic glasses would make ideal electric motor and transformer cores, and, on a smaller scale, Sony is already making tape decks with metallic-glass heads.

The trick to making metallic glass is to cool molten metal so rapidly—about 1 million degrees per second—that the atoms don't have time to crystallize. Ribbons averaging 40 microns (millionths of a meter) thick have been commercially available since 1973, manufactured by squirting liquid metal onto a spinning copper wheel, but it's been very difficult to make anything thicker.

Until now. Joseph Bach, now a junior in aeronautical engineering, took up the problem on his Summer Undergraduate Research Fellowship (SURF) last summer with Brent Fultz, assistant professor of materials science, and graduate student Barry Krueger. "There are a lot of things about bulk metallic glasses that aren't well known," says Fultz. "We wanted to study compression behavior, for example. Well, you can't compress something that's 40 microns thick and four feet long." So they devised a scheme to make thick samples using the Keck Dynamic Compactor—a 35-millimeter howitzer donated to Caltech by Aerojet Ordnance and adapted to its new life in the Keck



Bach at the cannon's business end. The target receptacle, which can be seen inside the safety enclosure, is mounted on shock absorbers. (The enclosure also serves to contain the gunsmoke.) The fitting he's holding screws onto the cannon's muzzle, and contains the fiber-optic and radar feeds as well as the vacuum connection.

The trick to making metallic glass is to cool molten metal so rapidly—about 1 million degrees per second—that the atoms don't have time to crystallize.

Laboratory by Thad Vreeland, professor of materials science, and graduate student Andy Mutz. It now resides on the third floor, where it is shared by several research projects, Vreeland's general studies of powder-consolidation mechanics among them.

Bach and Fultz figured that a projectile with just the right velocity would, upon slamming into a powdered metallic glass, generate a shock wave that could fuse the powder grains into a solid mass without altering their internal structure. Too little oomph wouldn't stick the grains together; too much would shove the atoms into a crystalline array. "The trick is to melt just a thin layer of the grains' surface so they'll stick together," says Bach. Adds Fultz, "We had reason to believe shock-wave consolidation would work, because it's a very rapid heating and cooling process. If you heat a metallic glass, it crystallizes before it melts. But others have found that if you increase the heating rate, you raise the crystallization temperature, so it doesn't crystallize quite so easily. You also lower its viscosity, so it flows a little bit better. So we were shooting for that window where the crystallization temperature is high enough to keep the material amorphous, but at the same time it flows and consolidates well, with no unfilled cracks."

Each shot followed the same general procedure. Bach ground store-bought glass ribbon (nickel-chrome alloy with a dash of boron to enhance glassiness) into a fine powder, and sifted it to get uniform-sized grains. Then he checked it by x-ray diffraction to be sure the heat of grinding hadn't crystallized it, and tamped it down into the sample container with a hydraulic press, using up to 30,000 pounds of pressure. Says Bach, "We tried to pack the particles as tightly as possible. We wanted to use as little energy as possible overall, so the less energy used to push the grains together, the better. And we didn't want the powder flying all through the gun when we turned on the vacuum." The sample container, an inch-thick hardened stainless steel ring, was sealed to the gun's muzzle, and the gun barrel evacuated to remove air resistance to the projectile, or "flyer plate"—a flat cylinder that slid down the barrel face first, like a quarter into a coin wrapper.

The upshot of each firing was a disk about the size of an Oreo cookie and half as thick; plenty thick for a compression test, and with material to spare for hardness tests, x-ray diffraction studies, and microphotography.

The group reduced the propellant charge with each shot to find the minimum workable flyer-plate velocity. Two independent systems measured the impact velocity—a Doppler radar like the one that bags speeders, and a fiber-optic system that shot two beams of light across the flyer's path and measured the time difference between the flyer's interruption of each beam.

The first shot had too much punch. The sample wound up half amorphous and half crystalline. It would have crystallized completely, but for the fact that the flyer hitting the powder produces two shock waves. One travels forward into the powder, compacting and fusing it. The other propagates backward into the flyer plate, bounces off its rear wall, and heads forward again. The wave's character changes upon reflection, becoming a "release wave" that pulls the material apart rather than compacting it.

"These are not the largest samples ever made, but they are certainly the easiest to make."

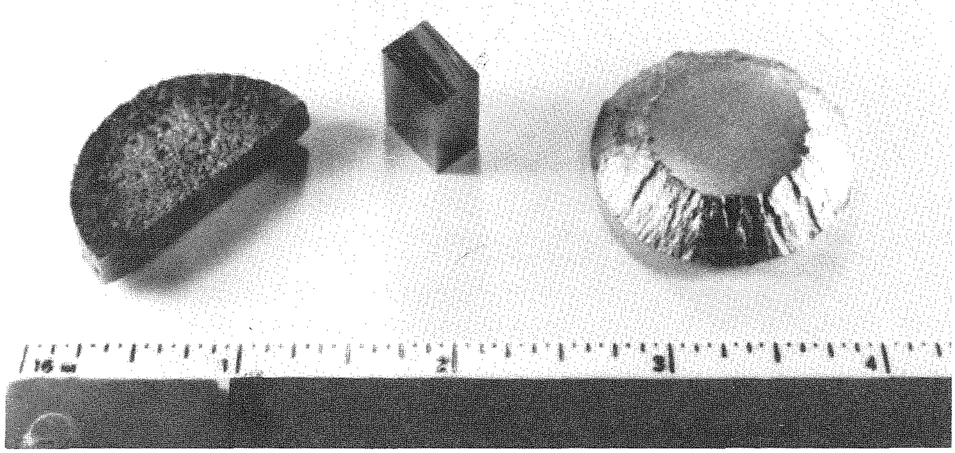
The release wave enters the now-consolidated powder about a microsecond after the shock wave. Because waves travel faster through denser material, the release wave rapidly overtook the shock wave and partially canceled it, leaving the powder beyond amorphous. "We learned a lot from that first shot," says Bach. "The crystalline and amorphous zones were perfectly flat and parallel, so we knew that the shock was planar and propagating very evenly through the powder. Then for the next shot, we doubled the plate's thickness to nine millimeters so that it would take longer for the release wave to reach the powder. We also reduced the propellant charge to lower the flyer velocity."

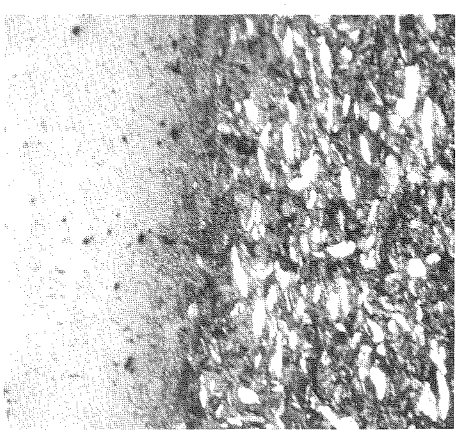
The second shot crystallized all the way through. The flyer plate was still going too fast and giving the shock wave too much energy, but at least the release-wave problem had been solved. So they cut back on the powder again.

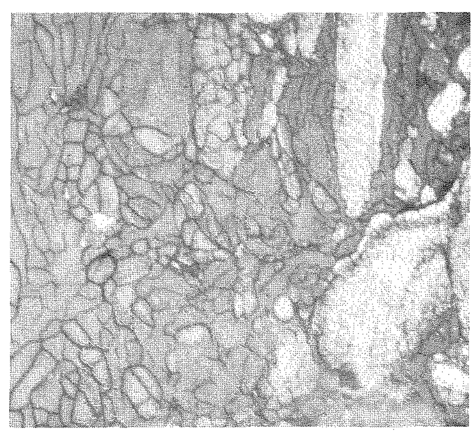
The third shot was a bang-up success, as were three more. The x-ray diffraction and hardness tests showed that the material was amorphous, and photomicrography didn't reveal any cracks or voids. The compression tests are under way.

"These are not the largest samples ever made, but they are certainly the easiest to make," says Fultz. "A Japanese group is fusing ribbons by heating them and running them through a rolling mill very quickly. But you have to be very nimble with your torches. It's a big nuisance to set up and very tricky to make work. We just load and fire, and the process is very controllable—you can predict what you're going to get. It's been a big success for a small SURF project."□—*DS*

Top: Metallic glass samples. The cube in the middle is ready for compression tests. Bottom left: Cross section of the first sample, magnified 50×. The sample is amorphous on the left side, crystalline on the right. Bottom right: Close-up of the transition zone, magnified 400×.







"Things with a degree of order to them should be controllable to some extent."

Taming Turbulence

What do a helicopter rotor spinning, your heart beating, and a dolphin swimming have in common? Give up? They are all examples of unsteady, turbulent flow being exploited for useful ends. And while humans aren't nearly as adept at getting the mileage out of unsteady flow as nature is, we are learning something about it.

In the early 1970s, Garry Brown, then a senior research fellow, and Anatol Roshko, now the Theodore von Kármán Professor of Aeronautics, performed a series of landmark experiments that proved that one type of unsteady flow, shear flow, had a definite internal structure. A "shear flow" is like the traffic at an expressway on-ramp. Two streams of liquid, both flowing in the same direction but one traveling much faster than the other, merge. The flows can retain their separate identities for some distance downstream, separated by a "shear layer"—a turbulent region where the streams mix. Brown and Roshko discovered that the shear layer is dominated by a series of large eddies, or "vortices." These vortices swirl in the same direction; when a fast-moving stream on top joins a slow-moving stream on the bottom, for example, the vortices spin clockwise. They act as a series of roller bearings, taking up the velocity difference between the two streams while mixing them together.

Says Paul Dimotakis, then a graduate student and now professor of aeronautics and applied physics, "The classical view of turbulence at the time was that it was a random mess. I recall that close to a year was spent searching for troubles with the Brown-Roshko flow facility, trying to get rid of those vortices. It was so against the party line on what turbulence was supposed to be like. But after a year of trying, the conclusion was that that's what turbulence must really look like."

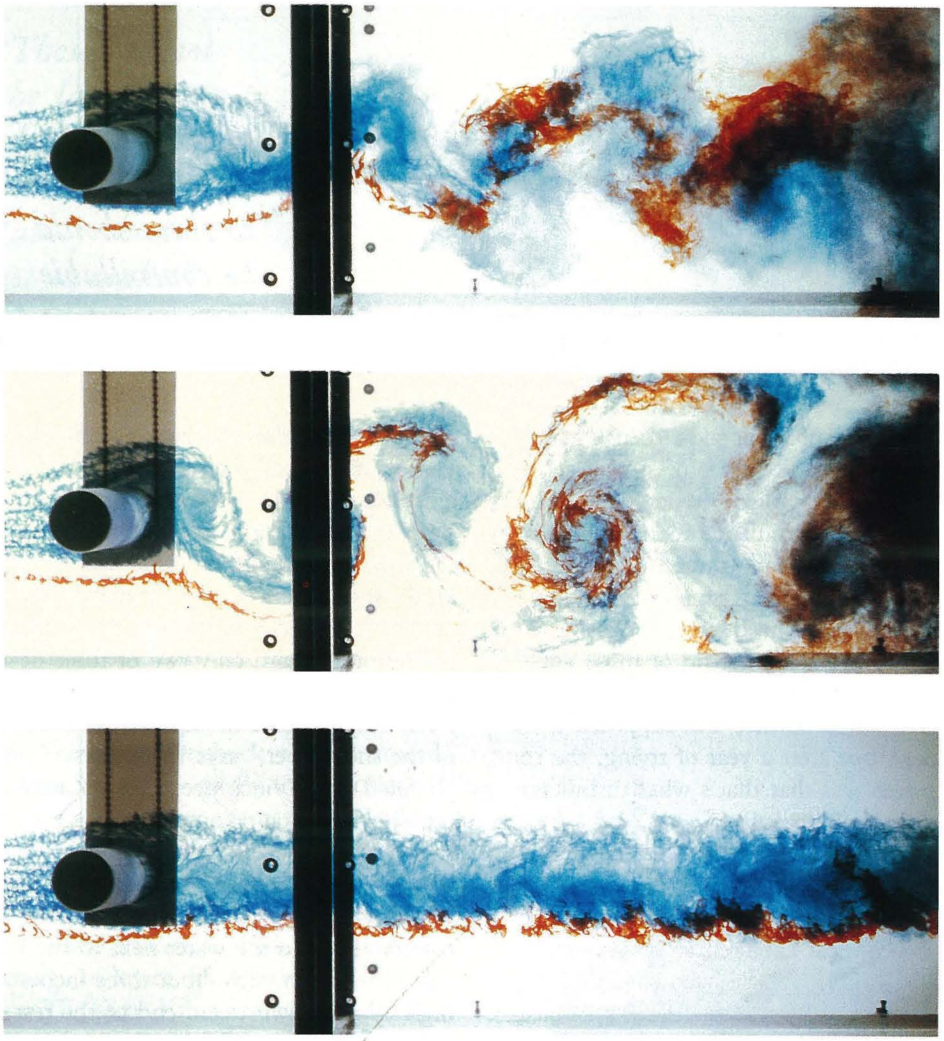
Brown and Roshko were in turn building on the work of Theodore von Kármán, founder of the Graduate Aeronautical Laboratories at Caltech (GALCIT), who had shown earlier that the wake behind a cylinder perpendicular to the direction of flow is dominated by a series of vortices with alternating spins. These vortices were thought to be peculiar to cylinders, however. Only after Brown and Roshko's discovery of similar vortices in shear-flow turbulence was it realized that order exists in all turbulent flows.

There was an important conclusion to be drawn from all this. Says Dimotakis, "Things with a degree of order to them should be controllable to some extent—if there is a semi-organized motion, you should be able to enhance it, inhibit it, or, better yet, program it. So if the flow has a tendency to form these vortices, in principle you can exploit that tendency to your own ends, like in judo, where you use your opponent's strength against him. But when we started trying to control turbulent flow 12 years ago, it was a very high-risk undertaking."

The work on shear layers continued, and Dimotakis and Manoocher Koochesfahani, now at Michigan State University, discovered that a gently moving airfoil (a winglike shape) placed in the shear zone where the two streams meet can have a profound effect. A pitching airfoil sheds vortices off its trailing edge at the frequency it is driven. By cycling the airfoil through only two or three degrees of pitch amplitude, "we got what I can only describe as explosive growth of the shear layer," says Dimotakis. "It filled the 20-inch-deep channel very rapidly. We don't know how much more we could have made it grow if its flow were unbounded." The shear layer, which was made visible by injecting colored dye into the water next to the airfoil, was normally about three inches high by the downstream end of the test section. (This work is usually done in wind tunnels, but "In the last decade, a host of new techniques have made water a particularly convenient medium. Our hydro lab is a unique facility, and we're very lucky to have it.")

Now Dimotakis is applying this technique to the type of turbulence where order was first discovered. He and graduate student Phillip Tokumaru have been experimenting with cylinder wakes. They have found that by rotating the cylinder on its axis, the wake's spread downstream can be narrowed or broadened by a large factor. Furthermore, when they narrowed the wake, they were able to reduce the cylinder's drag—its resistance to the flow around it—by as much as a factor of six.

"It seemed clear that if we oscillated the cylinder at something like its natural vortex shedding frequency we could strengthen the vortices," Dimotakis says. "It wasn't clear what would happen at much higher or lower frequencies."



Top: Normal wake behind a stationary cylinder.
Center: The cylinder is rotating to produce maximum dispersion.
Bottom: The cylinder is rotating to produce minimum dispersion.

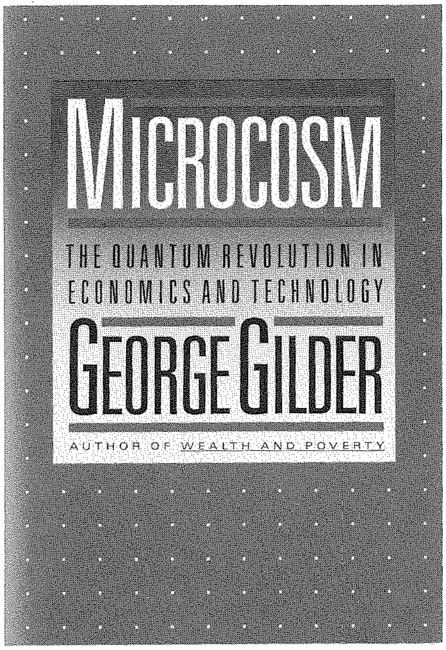
"We've only scratched the surface of being able to make the flow and turbulence do what we want, instead of having to accept what it does."

So Tokumaru tried these other frequencies, and at the same time varied the amplitude of oscillation. He quickly discovered that the frequency affected the spacing between vortices, while the amplitude controlled the strength of each individual vortex. From there it was a short step to trying to program the vortices, setting the oscillation to launch the vortices with a spacing and strength that would cause them to approach each other downstream or to draw apart. And this, in turn, altered the rate at which the wake spreads.

Nobody is likely to try to narrow a motorboat's wake by fitting it with an oscillating cylinder, but Dimotakis hopes this work will address a number of fundamental phenomena of turbulent fluid flow. "We want to understand in detail exactly how the vortices leave the cylinder. That's what we're doing now. The separation of unsteady flow from a body to which it is attached is not a very well-documented chapter in fluid mechanics today, and here we have a highly controlled flow in which we can measure practically everything that needs to be known. We could use that information to develop criteria for computational models of separating unsteady flow, which we really don't know how to simulate very well now. And unsteady flow is paramount to so many natural phenomena. A heart valve works for a lifetime with no maintenance because the vortex it sheds helps close it with very little muscular expenditure—it just starts the motion. I've watched dolphins overtake a destroyer doing 30 knots while swimming at a 45° angle to its course. The dolphin was doing at least 40 knots with no trouble at all, just playing. It probably couldn't swim that fast if the flow was steady.

"We've only scratched the surface of being able to make flow and turbulence do what we want, instead of having to accept what it does. It could be exploited to make anything from supermaneuverable aircraft, to more efficient mixing and combustion devices, to better sailboats, to a whole slew of applications we really haven't yet imagined, because this behavior is so counter-intuitive."□—*DS*

Books



Simon and Schuster, 1989
$19.95
426 pages

George Gilder, supply-side economist and author of the best-selling *Wealth and Poverty* and of *Spirit of Enterprise*, is a provocative thinker and entertaining writer who also understands technology. In his latest book, *Microcosm: The Quantum Revolution in Economics and Technology*, Gilder presents an inside view of the history of the semiconductor industry to support his thesis that fundamental but largely unrecognized changes have occurred in the world economy. This new scientific materialism dictates that a nation's wealth and consequent standard of living depend less on its natural resources and manufacturing skills than on its ability to handle information and foster innovation.

Where should we seek this new source of wealth? Gilder argues that we must look within the microcosm, the domain ruled by quanta and lying beyond human senses and common experience. The microcosm is not only where scientific understanding begins, but is also the frontier of technology in the information age. Integrated circuits and the information-handling structures of life dwell in the microcosm because the storage, processing, and communication of information are cheaper and faster in a world of smaller dimensions and energies. The "overthrow of matter" by quantum theory was the precursor to the microelectronic chips that have made possible today's proliferation of low-cost, high-performance computing and communication systems. These machines exist to manipulate information rather than matter or energy; have no moving parts, friction, or wear; and are constructed principally of silicon, oxygen, and aluminum, the most abundant elements in the earth's crust.

Gilder's premise that economic power today flows principally from information rather than material resources leads in several steps to the implication that, to be successful, economies must be guided by the principles of the microcosm. As Gilder states so eloquently in his opening chapter:

> Today, the ascendant nations and corporations are masters not of land and material resources but of ideas and technologies. Japan and other barren Asian islands have become the world's fastest-growing economies. Electronics is the world's fastest-growing major industry. Computer software, a pure product of mind, is the chief source of added value in world commerce. The global network of telecommunications carries more valuable goods than all the world's supertankers. Today, wealth comes not to the rulers of slave labor but to the liberators of human creativity, not to the conquerors of land but to the emancipators of mind.

Those areas of information technology that create the largest added value belong, according to Gilder, to free-market economies. The United States has long been the world leader in information technology, and will extend that lead not by pursuing routine and capital-intensive high-definition-TV and memory-chip manufacturing, but by creating the programming and software that will make them useful.

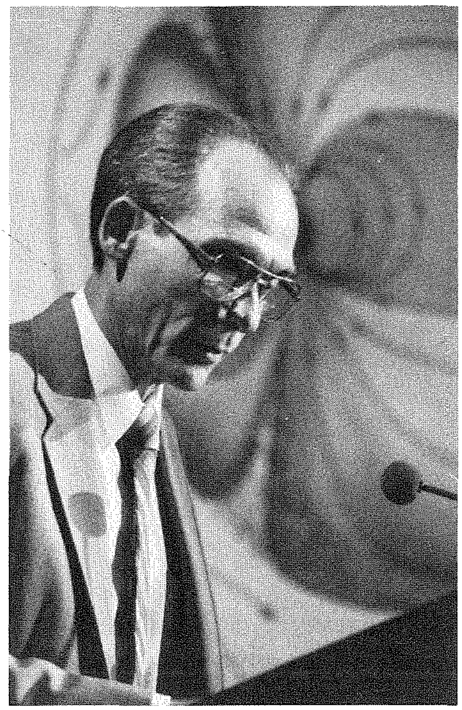
The reactions in the national press to *Microcosm* focus predictably on Gilder's economic thesis and its meaning to competition in microelectronics with Japan. Caltech readers will be at least equally interested in the inside story of the semiconductor industry and the fascinating glimpses of the personalities who have pioneered its development, including many who are Caltech alumni, faculty, and students. Gilder's accounts often go well beyond a person's influence on and contributions to microelectronics to describe working habits, backgrounds, and personal lives. It was certainly not Gilder's plan to write a complete history of the semiconductor industry; rather, he has concentrated on the pivotal innovations that have shaped this industry.

Caltech's Carver Mead, upon whom Gilder bestows the title of "prophet of the microcosm," is the hero of this story. The title of "prophet" is well justified by Mead's early work with tunneling devices; his characterization of Schottkybarrier devices built from a variety of III-V materials; his theoretical predictions with his graduate student, Bruce Hoeneisen, of the limits of scaling of silicon metal-oxide-semiconductor field-effect transistors; his contributions to design methods for high-complexity microchips, such as microprocessors; his pioneering development with his graduate student, David Johannsen, of silicon compilers; and his most recent efforts with high-complexity, biologically inspired analog chips. Many other Caltech people enter the story as Mead's teachers, students, friends, and co-workers, including Max Delbrück, Richard Feynman, John Hopfield, Misha Mahowald, Amr Mohsen, Linus Pauling, Ivan Sutherland, and John Wawrzynek.

Carver Mead is the Gordon and Betty Moore Professor of Computer Science at Caltech; Gordon Moore is a Caltech alumnus and trustee who plays another prominent role in Gilder's accounts as co-founder of Intel Corporation, the company that pioneered the dynamic memory chip, the electrically programmable read-only memory, and the microprocessor. Technical developments such as these, as well as later developments in silicon compilation, analog circuits, and neural computers, are described accurately, but in a style that will be readily understood by people outside of the fields of computing and microelectronics. *Microcosm's* extensive bibliographical notes are interesting reading in themselves, and refer the reader to an eclectic but well-selected collection of related writings.

Charles L. Seitz
Professor of Computer Science

Ed Stone reveals the romance of Neptune's magnetic field to the media in August 1989.



Romancing E. Stone

Ah, those legendary figures of romance. Antony and Cleopatra, Heloise and Abelard, Heathcliff and Cathy, Cyrano de Bergerac, Garbo, Gable, Elvis, and Edward C. Stone.

Yes, it's true. For his role in "revealing the uncommon romance of the heavens to the common man," the Voyager project scientist and Caltech's vice president for astronomical facilities has been named one of the Top Ten Romantic People of 1989 by Korbel Champagne Cellars, purveyors of fine California champagne, wines, and brandy since 1882. Although he was on the road in Australia and unavailable for comment, Stone was said by his administrative assistant, Susan McCurdy, to be delighted with the honor, and with the complementary bottle of Korbel Natural Champagne bestowed on him.

According to Rebecca Sydnor, newly designated director of romance of Korbel's department of romance, weddings, and entertaining, Korbel's selections were based "on a definition of romance in the broadest, most noble sense of the word. This year's honorees represent a wide-ranging cross section of individuals—both human and animated—who have in their respective ways, given new meaning to the ideals of love and romance."

Stone's fellow exemplars of the romantic ideal for 1989 include Tom Cruise and his wife, Mimi Rogers; the cartoon-strip character Charlie Brown; quarterback Joe Montana; ballerina Suzanne Farrell; the rescue workers of the San Francisco earthquake and Hurricane Hugo; Chris Evert; Michelle Pfeiffer; and the late Lucille Ball and Laurence Olivier. All now become part of a noble tradition dating back to 1986, the year Korbel began selecting superstars of romance.

Of course, Stone's appearance in this illustrious lineup is no real surprise, for the romantic possibilities of travel have always piqued the human imagination. Or, as the great bard of romance, Shakespeare himself, wrote, almost 400 years before Stone waved Voyager off on its grand tour, "Journeys end in lovers meeting."

Reprinted from *On Campus*

New Trustees

Three new members have been elected recently to Caltech's board of trustees: Richard M. Ferry, president of Korn/Ferry International; Richard M. Rosenberg, vice chairman of the board of BankAmerica Corporation in San Francisco; and Frank G. Wells, president and chief operating officer of the Walt Disney Company.

Honors and Awards

John E. Bercaw, Shell Distinguished Professor and professor of chemistry, received the 1990 Award in Organometallic Chemistry from the American Chemical Society.

Harry B. Gray, Beckman Professor of Chemistry, been named the ARCS Foundation Man of Science for 1990, and has also received the 1990 Alfred Bader Award in Bioinorganic or Bioorganic Chemistry.

Leroy E. Hood, Bowles Professor of Biology, has received the 1989 Beering Award, from Indiana University.

Donald E. Hudson, professor of mechanical engineering and applied mechanics, emeritus, has been awarded the 1989 Newmark Medal from the American Society of Civil Engineers.

Hans W. Liepmann, von Kármán Professor of Aeronautics, Emeritus, was named honorary member of the American Society for Mechanical Engineers.

THE ASTROLOGICAL OBSERVATORY AND LABORATORY 107

policy. The organization of the Observatory Council and the personnel of its Advisory Committee are shown on page 47 of this Catalogue.

The Observatory Council, supported by the unanimous opinion of the Advisory Committee and of others consulted, decided to use fused silica for the 200-inch mirror and other mirrors of the large telescope. President Gerard Swope and Dr. Elihu Thomson of the General Electric Company promised the full cooperation of that company in this undertaking; and much progress has already been made in the preliminary work.

The extensive investigation of auxiliary instruments, which forms a prime feature of the general scheme, has been begun. ...e Eastman Kodak Company has ...any of the special photographic ...rophotometer has been ordered,

VOLUME XXXVII NUMBER 121

BULLETIN

OF THE

CALIFORNIA INSTITUTE

OF

TECHNOLOGY

ANNUAL CATALOGUE

PASADENA, CALIFORNIA

DECEMBER, 1928

Centennial or Millennial?

Page 107 from the 1928 Caltech course catalog (above) was sent to *E&S* with the comment: "Note this relic of medieval science—clear evidence that Caltech was actually founded in the Middle Ages!"

Lee Carleton, BS '33, of Huntington Beach happened upon this 60-year-old typo (or was it?) while nostalgically paging through the catalog from his freshman year. It should read "*Astrophysical* Observatory and Laboratory," and refers to a provision by the International Education Board for construction of a "200-inch reflecting telescope and many auxiliary instruments . . . to be erected on the most favorable high-altitude site that can be found within effective working distance" of Caltech and its partner in astronomy, the Carnegie Institution of Washington. This was to become the Hale Telescope on Palomar Mountain, eventually dedicated in 1948, which has been the source of many of the major astronomical discoveries of the last four decades.

Did some anonymous typesetter perhaps have other plans for it?

Jennings Named Provost

Paul Jennings, professor of civil engineering and applied mechanics, has been named vice president and provost of the Institute, succeeding Barclay Kamb, professor of geology and geophysics. Like several of the authors in this issue, Jennings in an authority on earthquake engineering. He has been involved in a variety of projects aimed at developing more earthquake-resistant structures and at understanding how the ground moves in destructive quakes.

Some of his role in the development of earthquake standards in California is mentioned in George Housner's oral history, beginning on page 26. Jennings is also a member of the Independent Board of Inquiry, headed by Housner, which was set up by the governor to investigate the failure of the Nimitz Freeway and the Bay Bridge in the Loma Prieta earthquake.

Jennings received his BS in 1958 from Colorado State University and earned his MS (1960) and PhD (1963) from Caltech. He joined the Caltech faculty in 1966 as assistant professor of applied mechanics and was appointed associate professor in 1968 and professor in 1972. He was chairman of the Division of Engineering and Applied Science from 1985 to 1989. Jennings is a member of the National Academy of Engineering and past president of the Seismological Society of America and of the Earthquake Engineering Research Institute.

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