VENTURA

SIMI VALLEY

1994
Magnitude 6.0

1994
Magnitude 6.7

BURBANK

HOLLYWOOD HILLS

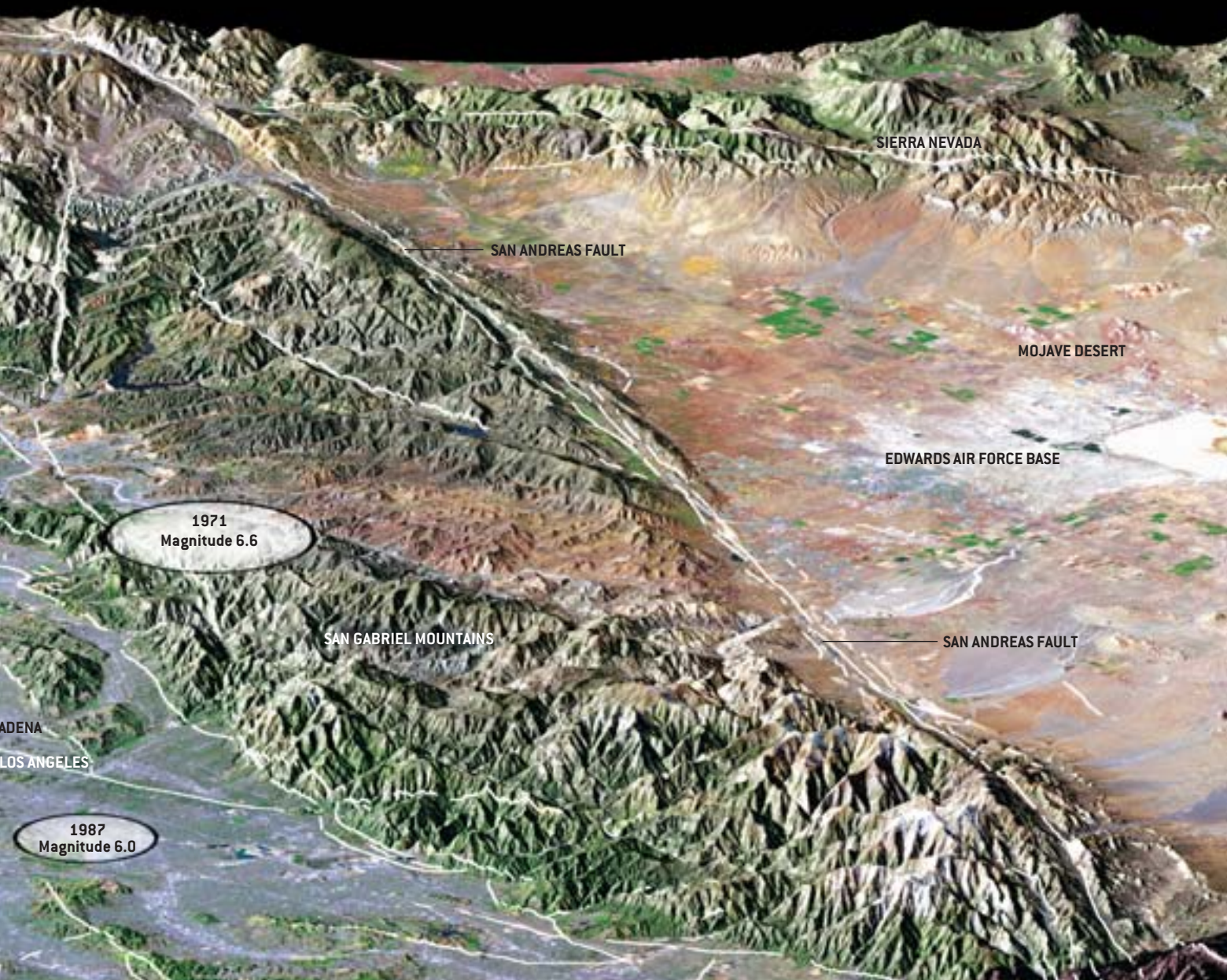SANTA MONICA

PAS

DOWNTOWN

COMPTON

LONG BEACH

THIRTEEN MILLION PEOPLE in and around Los Angeles live among a complex network of earthquake-prone faults (*white lines*), including the famous San Andreas. Some scientists now think that each of the major shocks that have rocked the region since the 1850s (*ovals*) probably influenced the timing and location of subsequent ones.

Earthquake
Conversations

Contrary to prevailing wisdom, large earthquakes can interact in unexpected ways. This exciting discovery could dramatically improve scientists' ability to pinpoint future shocks

By Ross S. Stein

SIERRA NEVADA

SAN ANDREAS FAULT

MOJAVE DESERT

EDWARDS AIR FORCE BASE

1971
Magnitude 6.6

SAN GABRIEL MOUNTAINS

SAN ANDREAS FAULT

ADENA

LOS ANGELES

1987
Magnitude 6.0

For decades, earthquake experts dreamed of being able to divine the time and place of the world's next disastrous shock. But by the early 1990s the behavior of quake-prone faults had proved so complex that they were forced to conclude that the planet's largest tremors are isolated, random and utterly unpredictable. Most seismologists now assume that once a major earthquake and its expected aftershocks do their damage, the fault will remain quiet until stresses in the earth's crust have time to rebuild, typically over hundreds or thousands of years. A recent discovery—that earthquakes interact in ways never before imagined—is beginning to overturn that assumption.

This insight corroborates the idea that a major shock relieves stress—and thus the likelihood of a second major tremor—in some areas. But it also suggests that the probability of a succeeding earthquake elsewhere along the fault or on a nearby fault can actually jump by as much as a factor of three. To the people who must stand ready to provide emergency services or to those who set prices for insurance premiums, these refined predictions can be critical in determining which of their constituents are most vulnerable.

At the heart of this hypothesis—known as stress triggering—is the realization that faults are unexpectedly responsive to subtle stresses they acquire as neighboring faults shift and shake. Drawing on records of past tremors and novel calculations of fault behavior, my colleagues and I have learned that the stress relieved during an earthquake does not simply dissipate; instead it moves down the fault and concentrates in sites nearby. This jump in stress promotes subsequent tremors. Indeed, studies of about two dozen faults since 1992 have convinced many of us that earthquakes can be triggered even when the stress swells by as little as one eighth the pressure required to inflate a car tire.

Such subtle cause-and-effect relations among large shocks were not thought to exist—and never played into seismic forecasting—until now. As a result, many scientists have been understandably skeptical about embracing this basis for a new approach to forecasting. Nevertheless, the stress-triggering hypothesis has continued to gain credibility through its ability to explain the location and frequency of earthquakes that followed several destructive shocks in California, Japan and Turkey. The hope of furnishing better warnings for such disasters is the primary motivation behind our ongoing quest to interpret these unexpected conversations between earthquakes.

Aftershocks Ignored

CONTRADICTING the nearly universal theory that major earthquakes strike at random was challenging from the start—especially considering that hundreds of scientists searched in vain for more than three decades to find predictable patterns in

Overview/*Shifting Priorities*

- Scientists used to think that one large earthquake has no notable influence on the timing or location of the next one, but a surprising new discovery is challenging that perspective.
- Earthquake-prone faults are now proving to be unexpectedly responsive to subtle stresses they acquire during shocks that strike along nearby faults.
- All else being equal, the regions in the earth's crust where the stress rises—even by a small amount—will be the sites of the next earthquakes.
- If this hypothesis turns out to be right, its implications could dramatically improve the ability of nations, cities and individuals to evaluate their earthquake vulnerability.

global earthquake activity, or seismicity. Some investigators looked for changing rates of small tremors or used sensitive instruments to measure the earth's crust as it tilts, stretches and migrates across distances invisible to the naked eye. Others tracked underground movements of gases, fluids and electromagnetic energy or monitored tiny cracks in the rocks to see whether they open or close before large shocks. No matter what the researchers examined, they found little consistency from one major earthquake to another.

Despite such disparities, historical records confirm that about one third of the world's recorded tremors—so-called aftershocks—cluster in space and time. All true aftershocks were thought to hit somewhere along the segment of the fault that slipped during the main shock. Their timing also follows a routine pattern, according to observations first made in 1894 by Japanese seismologist Fusakichi Omori and since developed into a basic principle known as Omori's law. Aftershocks are most abundant immediately after a main shock. Ten days later the rate of aftershocks drops to 10 percent of the initial rate, 100 days later it falls to 1 percent, and so on. This predictable jump and decay in seismicity means that an initial tremor modifies the earth's crust in ways that raise the prospect of succeeding ones, contradicting the view that earthquakes occur randomly in time. But because aftershocks are typically smaller than the most damaging quakes scientists would like to be able to predict, they were long overlooked as a key to unlocking the secrets of seismicity.

Once aftershocks are cast aside, the remaining tremors indeed appear—at least at first glance—to be random. But why ignore the most predictable earthquakes to prove that the rest are without order? My colleagues and I decided to hunt instead for what makes aftershocks so regular. We began our search in one of the world's most seismically active regions—the San Andreas Fault system that runs through California. From local records of earthquakes and aftershocks, we knew that on the day following a magnitude 7.3 event, the chance of another large shock striking within 100 kilometers is nearly 67 percent—20,000 times the likelihood on any other day. Something about the first shock seemed to dramatically increase the odds of subsequent ones, but what?

That big leap in probability explains why no one was initially surprised in June 1992 when a magnitude 6.5 earthquake struck near the southern California town of Big Bear only three hours after a magnitude 7.3 shock occurred 40 kilometers away, near Landers. (Fortunately, both events took place in the sparsely populated desert and left Los Angeles unscathed.) The puzzling contradiction to prevailing wisdom was that the Big Bear shock struck far from the fault that had slipped during Landers's shaking. Big Bear fit the profile of an aftershock in its timing but not in its location. We suspected that its mysterious placement might hold the clue we were looking for.

By mapping the locations of Landers, Big Bear and hundreds of other California earthquakes, my colleagues and I began to notice a remarkable pattern in the distribution not only of true aftershocks but also of other, smaller earthquakes that

BUILDUP AND RELEASE of the stress that accumulates slowly as the earth's tectonic plates grind past one another mark the cycle of all great earthquakes. Along Turkey's North Anatolian fault (*white line*), the land north of the fault is moving eastward relative to the land to the south (*yellow arrows*) but gets stuck along the fault. When the stress finally overcomes friction along the fault, the rocks on either side slip past one another violently. A catastrophic example of this phenomenon occurred on August 17, 1999, when a magnitude 7.4 shock took 25,000 lives in and around the city of Izmit. Calculations of stress before and after the Izmit earthquake (*below*) reveal that, after the shock, the so-called Coulomb stress dropped along the segment of the fault that slipped but increased elsewhere. —R.S.S.

Coulomb stress change (in bars)
Decrease | Increase
−3   0   3
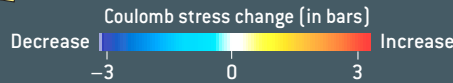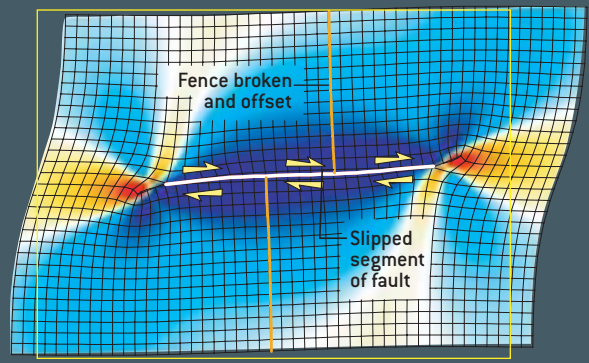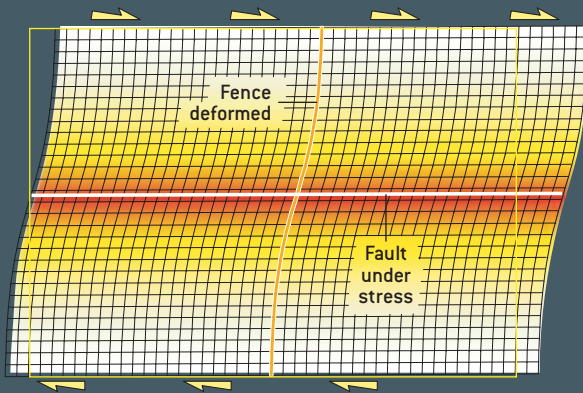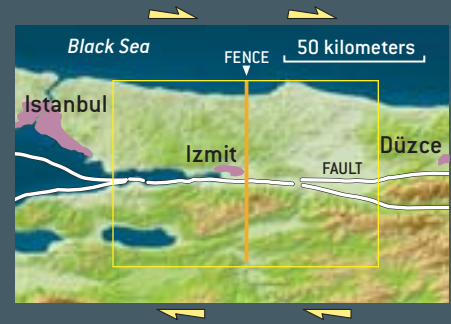
BEFORE THE EARTHQUAKE

The segment of the North Anatolian fault near Izmit accumulated significant stress (*red*) during the 200 years since its last major stress-relieving shock. An imaginary deformed fence and grid superimposed over the landscape illustrate this high stress. Squares along the fault are stretched into parallelograms (*exaggerated 15,000 times*), with the greatest change in shape, and thus stress, occurring closest to the fault.

AFTER THE EARTHQUAKE

The earthquake relieved stress (*blue*) all along the segment of the fault that slipped. The formerly deformed fence broke and became offset by several meters at the fault, and the grid squares closest to the fault returned to their original shape. High stress is now concentrated beyond both ends of the failed fault segment, where the grid squares are more severely contorted than before the shock struck.

follow a main shock by days, weeks or even years. Like the enigmatic Big Bear event, a vast majority of these subsequent tremors tended to cluster in areas far from the fault that slipped during the earthquake and thus far from where aftershocks are supposed to occur [*see box on page 78*]. If we could determine what controlled this pattern, we reasoned, the same characteristics might also apply to the main shocks themselves. And if that turned out to be true, we might be well on our way to developing a new strategy for forecasting earthquakes.

Triggers and Shadows

WE BEGAN BY LOOKING at changes within the earth's crust after major earthquakes, which release some of the stress that accumulates slowly as the planet's shifting tectonic plates grind past each other. Along the San Andreas Fault, for instance, the plate carrying North America is moving south relative to the one that underlies the Pacific Ocean. As the two sides move in opposite directions, shear stress is exerted parallel to the plane of the fault; as the rocks on opposite sides of the fault press against each other, they exert a second stress, perpendicular to the fault plane. When the shear stress exceeds the frictional resistance on the fault or when the stress pressing the two sides of the fault together is eased, the rocks on either side will slip past each other suddenly, releasing tremendous energy in the form of an earthquake. Both components of stress, which when added together are called Coulomb stress, diminish along the segment of the fault that slips. But because that stress cannot simply disappear, we knew it must be redistributed to other points along the same fault or to other faults nearby. We also suspected that this increase in Coulomb stress could be sufficient to trigger earthquakes at those new locations.

Geophysicists had been calculating Coulomb stresses for years, but scientists had never used them to explain seismicity. Their reasoning was simple: they assumed that the changes

Forecasting under Stress

So many features of earthquake behavior are still unknown that scientists have directed their limited insight to playing the odds

HOW PEOPLE PERCEIVE the threat of an earthquake in their part of the world depends in great part on what kind of warnings are presented to them. Most of today's seismic forecasts assume that one earthquake is unrelated to the next. Every fault segment is viewed as having an average time period between tremors of a given size—the larger the shock, the greater the period, for example—but the specific timing of the shocks is believed to be random. The best feature of this method, known as a Poisson probability, is that a forecast can be made without knowing when the last significant earthquake occurred. Seismologists can simply infer the typical time period between major shocks based on geologic records of much older tremors along that segment of the fault. This conservative strategy yields odds that do not change with time.

In contrast, a more refined type of forecast called the renewal probability predicts that the chances of a damaging shock climb as more time passes since the last one struck. These growing odds are based on the assumption that stress along a fault increases gradually in the wake of a major earthquake. My colleagues and I build the probabilities associated with earthquake interactions on top of this second traditional technique by including the effects of stress changes imparted by nearby earthquakes. Comparing the three types of forecasts for Turkey's North Anatolian fault near Istanbul illustrates their differences, which are most notable immediately after a major shock.

In the years leading up to the catastrophic Izmit earthquake of August 1999, the renewal probability of a shock of magnitude 7 or greater on the four faults within 50 kilometers of Istanbul had been rising slowly since the last large earthquake struck each of them, between 100 and 500 years ago. According to this type of forecast, the August shock created a sharp drop in the likelihood of a second major tremor in the immediate vicinity of Izmit, because the faults there were thought to have relaxed. But the quake caused no change in the 48 percent chance of severe shaking 100 kilometers
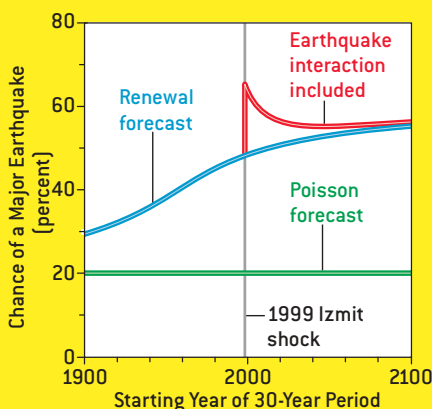
PREDICTED ODDS of a major earthquake striking within 50 kilometers of Istanbul can vary dramatically. The odds, which stay the same or rise slowly with time in traditional forecasts (*green* and *blue*), jump significantly when stresses transferred during the 1999 Izmit earthquake are included (*red*).

to the west, in Istanbul, sometime in the next 30 years. Those odds will continue to grow slowly with time—unlike the Poisson probability, which will remain at only 20 percent regardless of other tremors that may occur near the capital city.

When the effects of my team's new stress-triggering hypothesis were added to the renewal probability, everything changed. The most dramatic result was that the likelihood of a second quake rocking Istanbul shot up suddenly because some of the stress relieved near Izmit during the 1999 shock moved westward along the fault and concentrated closer to the city. That means the Izmit shock raised the probability of an Istanbul quake in the next 30 years from 48 percent to 62 percent. This so-called interaction probability will continue to decrease over time as the renewal probability climbs. The two forecasts will then converge at about 54 percent in the year 2060—assuming the next major earthquake doesn't occur before then.

—*R.S.S.*

CRUMPLED BUILDINGS dot Düzce, Turkey, in the wake of a major tremor that struck in November 1999. Some scientists suspect that this disaster was triggered by an earlier shock near Izmit.

were too meager to make a difference. Indeed, the amount of stress transferred is generally quite small—less than 3.0 bars, or at most 10 percent of the total change in stress that faults typically experience during an earthquake. I had my doubts about whether this could ever be enough to trigger a fault to fail. But when Geoffrey King of the Paris Geophysical Institute, Jian Lin of the Woods Hole Oceanographic Institution in Massachusetts and I calculated the areas in southern California where stress had increased after major earthquakes, we were amazed to see that the increases—small though they were—matched clearly with sites where the succeeding tremors had clustered. The implications of this correlation were unmistakable: regions where the stress rises will harbor the majority of subsequent earthquakes, both large and small. We also began to see something equally astonishing: small reductions in stress could inhibit future tremors. On our maps, earthquake activity plummeted in these so-called stress shadows.

Coulomb stress analysis nicely explained the locations of certain earthquakes in the past, but a more important test would be to see whether we could use this new technique to forecast

and had published it in the journal *Science* two months earlier. Barka's announcement had emboldened engineers to close school buildings in Düzce that were lightly damaged by the first shock despite pleas by school officials who said that students had nowhere else to gather for classes. Some of these buildings were flattened by the November shock.

If subsequent calculations by Parsons of the USGS, Shinji Toda of Japan's Active Fault Research Center, Barka, Dieterich and me are correct, that may not be the last of the Izmit quake's aftermath. The stress transferred during that shock has also raised the probability of strong shaking in the nearby capital, Istanbul, sometime this year from 1.9 percent to 4.2 percent. Over the next 30 years we estimate those odds to be 62 percent; if we assumed large shocks occur randomly, the odds would be just 20 percent [*see box on opposite page*].

The stress-triggering hypothesis offers some comfort alongside such gloom and doom. When certain regions are put on high alert for earthquakes, the danger inevitably drops in others. In Turkey the regions of reduced concern happen to be sparsely populated relative to Istanbul. But occasionally the op-

Even tiny stress changes can have momentous effects, both calming and catastrophic.

the sites of *future* earthquakes reliably. Six years ago I joined geophysicist James H. Dieterich of the U.S. Geological Survey (USGS) and geologist Aykut A. Barka of Istanbul Technical University to assess Turkey's North Anatolian fault, among the world's most heavily populated fault zones. Based on our calculations of where Coulomb stress had risen as a result of past earthquakes, we estimated that there was a 12 percent chance that a magnitude 7 shock or larger would strike the segment of the fault near the city of Izmit sometime between 1997 and 2027. That may seem like fairly low odds, but in comparison, all but one other segment of the 1,000-kilometer-long fault had odds of only 1 to 2 percent.

We did not have to wait long for confirmation. In August 1999 a magnitude 7.4 quake devastated Izmit, killing 25,000 people and destroying more than $6.5 billion worth of property. But this earthquake was merely the most recent in a falling-domino-style sequence of 12 major shocks that had struck the North Anatolian fault since 1939. In a particularly brutal five-year period, fully 700 kilometers of the fault slipped in a deadly westward progression of four shocks. We suspected that stress transferred beyond the end of each rupture triggered the successive earthquake, including Izmit's.

In November 1999 the 13th domino fell. Some of the Coulomb stress that had shifted away from the fault segment near Izmit triggered a magnitude 7.1 earthquake near the town of Düzce, about 100 kilometers to the east. Fortunately, Barka had calculated the stress increase resulting from the Izmit shock

posite is true. One of the most dramatic examples is the relative lack of seismicity that the San Francisco Bay Area, now home to five million people, has experienced since the great magnitude 7.9 earthquake of 1906. A 1998 analysis by my USGS colleagues Ruth A. Harris and Robert W. Simpson demonstrated that the stress shadows of the 1906 shock fell across several parallel strands of the San Andreas Fault in the Bay Area, while the stress increases occurred well to the north and south. This could explain why the rate of damaging shocks in the Bay Area dropped by an order of magnitude compared with the 75 years preceding 1906. Seismicity in the Bay Area is calculated to slowly emerge from this shadow as stress rebuilds on the faults;

THE AUTHOR

ROSS S. STEIN is a geophysicist with the U.S. Geological Survey's Earthquake Hazards Team in Menlo Park, Calif. He joined the survey in 1981 after earning a Ph.D. from Stanford University in 1980 and serving as a postdoctoral fellow at Columbia University. Stein's research, which has been devoted to improving scientists' ability to assess earthquake hazards, has been funded by U.S. agencies such as the Office of Foreign Disaster Assistance and by private companies, including the European insurance company Swiss Re. For the work outlined in this article, Stein received the Eugene M. Shoemaker Distinguished Achievement Award of the USGS in 2000. He also presented the results in his Frontiers of Geophysics Lecture at the annual meeting of the American Geophysical Union in 2001. Stein has appeared in several TV documentaries, including *Great Quakes: Turkey* (Learning Channel, 2001).

EARTHQUAKE CLUSTERS

PLACES WHERE STRESS JUMPS (*red*) after major earthquakes (*filled stars*) tend to be the sites of subsequent tremors, both large (*open stars*) and small (*black dots*). Conversely, few tremors occur where the stress plummets (*blue*), regardless of the location of nearby faults (*white lines*). —R.S.S.

SOUTHERN CALIFORNIA, U.S.
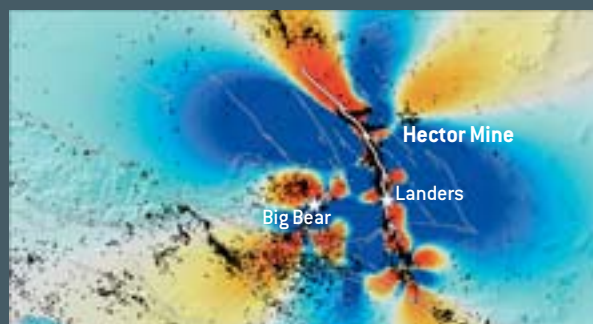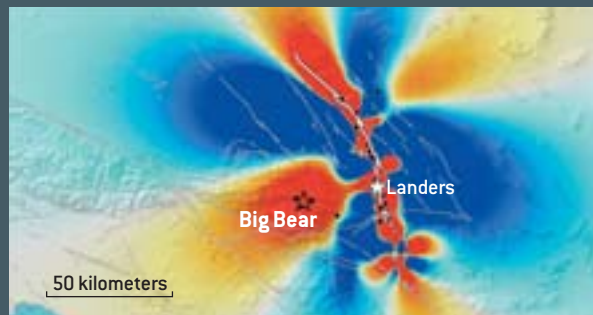
MAGNITUDE 7.3 SHOCK in the southern California desert near Landers in 1992 increased the expected rate of earthquakes to the southwest, where the magnitude 6.5 Big Bear shock struck three hours later (*top*). Stresses imparted by the combination of the Landers and Big Bear events coincided with the regions where the vast majority of tremors occurred over the next seven years, culminating with the magnitude 7.1 Hector Mine quake in 1999 (*bottom*).

KAGOSHIMA, JAPAN
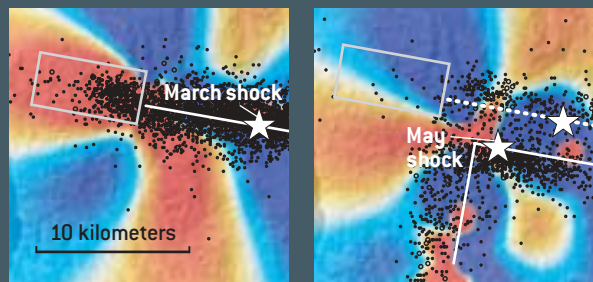
TWIN EARTHQUAKES can turn the rate of earthquake occurrence, or seismicity, up and down in the same spot. In March 1997 a magnitude 6.5 tremor increased stress and seismicity to the west of the ruptured fault (*above left*). Seismicity in that area then dropped along with stress (*above right*) following a magnitude 6.3 shock that struck 48 days later three kilometers to the south.

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the collapsed highways and other damage wrought by the 1989 Loma Prieta shock may be a harbinger of this reawakening.

Bolstering the Hypothesis

EXAMINATIONS OF the earthquakes in Turkey and in southern California fortified our assertion that even tiny stress changes can have momentous effects, both calming and catastrophic. But despite the growing number of examples we had to support this idea, one key point was difficult to explain: roughly one quarter of the earthquakes we examined occurred in areas where stress had *decreased*. It was easy for our more skeptical colleagues to argue that no seismicity should occur in these shadow zones, because the main shock would have relieved at least some stress and thus pushed those segments of the fault further from failure. We now have an answer. Seismicity never shuts off completely in the shadow zones, nor does it turn on completely in the trigger zones. Instead the *rate* of seismicity—the number of earthquakes per unit of time—merely drops in the shadows or climbs in the trigger zones relative to the preceding rate in that area.

We owe this persuasive extension of stress triggering to a theory proposed by Dieterich in 1994. Known as rate/state friction, it jettisons the comfortable concept of friction as a property that can only vary between two values—high friction when the material is stationary and lower friction when it is sliding. Rather, faults can become stickier or more slippery as the rate of movement along the fault changes and as the history of motion, or the state, evolves. These conclusions grew out of lab experiments in which Dieterich's team sawed a miniature fault into a Volkswagen-size slab of granite and triggered tiny earthquakes.

When earthquake behavior is calculated with friction as a variable rather than a fixed value, it becomes clear that Omori's law is a fundamental property not just of so-called aftershocks but of *all* earthquakes. The law's prediction that the rate of shocks will first jump and then diminish with time explains why a region does not forever retain the higher rate of seismicity that results from an increase in stress. But that is only half the story. Dieterich's theory reveals a characteristic of the seismicity that Omori's law misses entirely. In areas where a main shock relieves stress, the rate of seismicity immediately plunges but will slowly return to preshock values in a predictable manner. These points may seem subtle, but rate/state friction allowed us for the first time to make predictions of how jumps or declines in seismicity would change over time. When calculating Coulomb stresses alone, we could define the general location of new earthquakes but not their timing.

Our emerging ideas about both the place and the time of stress-triggered earthquakes were further confirmed by a global study conducted early last year. Parsons considered the more than 100 earthquakes of magnitude 7 or greater that have occurred worldwide in the past 25 years and then examined all subsequent shocks of at least magnitude 5 within 250 kilometers of each magnitude 7 event. Among the more than 2,000 shocks in this inventory, 61 percent occurred at sites where a preceding shock increased the stress, even by a small amount.

Few of these triggered shocks were close enough to the main earthquake to be considered an aftershock, and in all instances the rate of these triggered tremors decreased in the time period predicted by rate/state friction and Omori's law.

Now that we are regularly incorporating the concept of rate/state friction into our earthquake analyses, we have begun to uncover more sophisticated examples of earthquake interaction than Coulomb stress analyses alone could have illuminated. Until recently, we had explained only relatively simple situations, such as those in California and Turkey, in which a large earthquake spurs seismicity in some areas and makes it sluggish in others. We knew that a more compelling case for the stress-triggering hypothesis would be an example in which successive, similar-size shocks are seen to turn the frequency of earthquakes up and down in the same spot, like a dimmer switch on an electric light.

Toda and I discovered a spectacular example of this phenomenon, which we call toggling seismicity. Early last year we began analyzing an unusual pair of magnitude 6.5 earthquakes that struck Kagoshima, Japan, in 1997. Immediately following

pense of others. But our analyses have shown that taking stress triggering into account will raise different faults to the top of the high-alert list than using traditional methods alone will. By the same token, a fault deemed dangerous by traditional practice may actually be a much lower risk.

An important caveat is that any type of earthquake forecast is difficult to prove right and almost impossible to prove wrong. Regardless of the factors that are considered, chance plays a tremendous role in whether a large earthquake occurs, just as it does in whether a particular weather pattern produces a rainstorm. The meteorologists' advantage over earthquake scientists is that they have acquired millions more of the key measurements that help improve their predictions. Weather patterns are much easier to measure than stresses inside the earth, after all, and storms are much more frequent than earthquakes.

Refining earthquake prediction must follow the same path, albeit more slowly. That is why my team has moved forward by building an inventory of forecasts for large earthquakes near the shock-prone cities of Istanbul, Landers, San Francisco and Kobe. We are also gearing up to make assessments for

Taking stress triggering into account will raise different faults to the top of the high-alert list.

the first earthquake, which occurred in March, a sudden burst of seismicity cropped up in a 25-square-kilometer region just beyond the west end of the failed segment of the fault. When we calculated where the initial earthquake transferred stress, we found that it fell within the same zone as the heightened seismicity. We also found that the rate immediately began decaying just as rate/state friction predicted. But when the second shock struck three kilometers to the south only seven weeks later, the region of heightened seismicity experienced a sudden, additional drop of more than 85 percent. In this case, the trigger zone of the first earthquake had fallen into the shadow zone of the second one. In other words, the first quake turned seismicity up, and the second one turned it back down.

A New Generation of Forecasts

EAVESDROPPING ON the conversations between earthquakes has revealed, if nothing else, that seismicity is highly interactive. And although phenomena other than stress transfer may influence these interactions, my colleagues and I believe that enough evidence exists to warrant an overhaul of traditional probabilistic earthquake forecasts. By refining the likelihood of dangerous tremors to reflect subtle jumps and declines in stress, these new assessments will help governments, the insurance industry and the public at large to better evaluate their earthquake risk. Traditional strategies already make some degree of prioritizing possible, driving the strengthening of buildings and other precautions in certain cities or regions at the ex-

Los Angeles and Tokyo, where a major earthquake could wreak trillion-dollar devastation. Two strong shocks along Alaska's Denali fault in the fall of 2002—magnitude 6.7 on October 23 and magnitude 7.9 on November 3—appear to be another stress-triggered sequence. Our calculations suggest that the first shock increased the likelihood of the second by a factor of 100 during the intervening 10 days. We are further testing the theory by forecasting smaller, nonthreatening earthquakes, which are more numerous and thus easier to predict.

In the end, the degree to which any probabilistic forecast will protect people and property is still uncertain. But scientists have plenty of reasons to keep pursuing this dream: several hundred million people live and work along the world's most active fault zones. With that much at stake, stress triggering—or any other phenomenon that has the potential to raise the odds of a damaging earthquake—should not be ignored.   SA

MORE TO EXPLORE

Earthquakes Cannot Be Predicted. Robert J. Geller, David D. Jackson, Yan Y. Kagan and Francesco Mulargia in *Science,* Vol. 275, page 1616; March 14, 1997. http://scec.ess.ucla.edu/~ykagan/perspective.html

Heightened Odds of Large Earthquakes Near Istanbul: An Interaction-Based Probability Calculation. Tom Parsons, Shinji Toda, Ross S. Stein, Aykut Barka and James H. Dieterich in *Science,* Vol. 288, pages 661–665, April 28, 2000.

View earthquake animations and download Coulomb 2.2 (Macintosh software and tutorial for calculating earthquake stress changes) at http://quake.usgs.gov/~ross