Weak Faults: Breaking Out All Over

Studies of the Loma Prieta quake have finally laid to rest the fundamental premise that all faults are strong; now the problem is to figure out how weak faults work

EARTHQUAKES USED TO BE SIMPLE. Generating them took just two blocks of rock—huge ones, to be sure, squeezed together with crushing force—trying to slide by each other along a fault. Tremendous friction built up along the fault, locking it until the stress reached such high levels that it overcame the fault's great strength and unleashed an earthquake. That was the theory, anyway, and in the laboratory you could make little "quakes" by squeezing two pieces of rock together to create a strong "fault" and then pushing them by each other. Nice idea, but it now seems that faults aren't always strong.

A spate of new findings from the San Andreas and other faults is forcing researchers to swallow the notion that something comes between the great crustal blocks to let them slip as if they were as slick as banana peels. Speaking of the San Andreas (but you could apply this everywhere), geophysicist Mark Zoback of Stanford University says: "We've thrown off our high-stress paradigm."

Bad news for seismologists, and not just for those who clung to strong faults in the face of accumulating evidence of fault weakness. "It puts us all on shaky ground," says Zoback, who quickly adds: "No pun intended. We fundamentally don't understand how earthquakes work. After all these years, we don't have a clue." And that bodes ill for the search for seismology's Holy Grail—earthquake prediction. With the collapse of traditional models of fault behavior, "we don't have a basis on which to build a strategy" for prediction, says Zoback. Others are less pessimistic, but everyone agrees that understanding earthquakes now hinges on learning how the strong bond of rock against rock can be weakened, either permanently or perhaps only once it begins rupturing in earthquakes (see box).

Doubts about the strength of faults have been mounting for some 20 years, but studies of Loma Prieta helped settle the issue by showing that faults do not carry the great load of stress implied by high strength. To be sure, nobody had ever detected all the stress the traditional models had called for—earthquakes release only modest amounts of stress, far less than required by lab experiments with bare rock-on-rock sliding. Indeed, if big quakes worked the way bench experiments do, one seismologist half-jokingly speculates, "everything would die—even the insects." So how have researchers accounted for the shortfall? By arguing that only part of the stress built up along a fault was released in an earthquake, when it could be readily measured, but most of it was still there afterward.

R. E. WALLACE, U.S. GEOLOGICAL SURVEY

Weakened but still dangerous. *A gash marks the San Andreas, where pressurized fluids may be at work.*

Because Loma Prieta struck such a densely instrumented region, seismologists Andrew Michael, William Ellsworth, and David Oppenheimer of the U.S. Geological Survey (USGS) in Menlo Park were able to test that assumption. They analyzed small shocks that took place before and after the main quake to find out how stress along the fault had changed during the event. If the main event had dissipated only part of the stress, the aftershocks should have been aligned with all the earlier shocks, because much the same stress field would be generating them. But the USGS team found that aftershocks located near the main shock were oriented every which way. The overall stress that had driven the main shock was gone, or nearly gone, the USGS researchers concluded. Although fault stress may have varied from place to place, the nearly complete stress drop suggested that the average stress on the fault was modest to start, and the fault had given way more easily than strong-fault dogma would suggest.

The San Andreas isn't the only fault showing distinct signs of weakness. In the aftermath of Loma Prieta, the number of small earthquakes changed markedly along other faults, as well as along segments of the San Andreas well away from the main rupture. In pursuing the possibility that Loma Prieta triggered those changes, USGS seismologists Paul Reasenberg and Robert Simpson in Menlo Park found they could best explain the response of faults up to 100 kilometers away if they are weak. In their model for how Loma Prieta could have produced the observed seismicity changes, they found that the link was strongest when they assumed that the coefficient of friction along the distant faults is low—more like that of the inside of a banana peel than the high friction of rock on rock measured in the lab.

And like any slippery object, faults seem able to slide even when they're mostly squeezed rather than pushed. Studies of stress orientation are now showing that faults have slipped in response to stresses that are oriented across the fault instead of along it—the direction that would result in the maximum "push." Just as a melting ice cube will skate across a counter top even when it's being pushed from above, a weak fault should move even when the stress is close to perpendicular to the fault.

Stress fields oriented at a high angle to the faults they drive are turning up all over. At Loma Prieta, Zoback and Gregory Beroza of Stanford, a specialist in stress and a seismologist, respectively, have taken a closer look at the Loma Prieta aftershocks, many of which took place on small fractures in the rock near the San Andreas. They found that the aftershocks near the main fault and more or less paralleling it were responding to stress that is nearly perpendicular to the fault. That finding suggests that not only the main fault but also the faults in the surrounding rock were weak.

At the other end of the San Andreas, on Southern California's now-extinct San Gabriel and Punchbowl faults, geologist Frederick Chester of St. Louis University recently concluded from the arrangement of nearby geologic features that the stress driving slippage was oriented as much as 60° and 80° away from the main faults. Farther afield from the San Andreas, Van Mount and John Suppe of Princeton University have found from studies in wells near the Great Sumatran fault of Indonesia that stress is oriented at 70° to 80° to the fault, and preliminary studies suggest the same may be true of the Philippine fault and New Zealand's Alpine fault.

Now researchers are trying to figure out what could be making the faults weak

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—Mark Zoback

enough to respond to the feeble pushes that would result from high-angle stress. Some seismologists are considering the possibility that faults become temporarily weak only after slippage starts (see box). But other theorists are looking for ways to weaken faults permanently. Simply lubricating them with ground rock or clay won't work. At the pressures and temperatures 5 to 15 kilometers down, where quakes get started, potential lubricants become as strong as rock. But high-pressure fluids could do the job, weakening a fault not by lubricating it but by pushing back against the enormous pressures squeezing it shut (*Science*, 8 January 1988, p. 145).

To judge by the looks of faults exhumed by erosion, there is plenty of water around deep in a fault, but confining it until it reaches the necessary pressures had seemed a problem. Now two new means of maintaining fluid pressures have been proposed. Fault mechanics specialist James Byerlee of the USGS in Menlo Park suggests that fluids now lubricating the San Andreas were trapped there when the fault formed, either by impermeable clays or by pore-filling minerals deposited from the fluids. Once the fluid was confined, the weight of the overlying rock could pressurize it.

James Rice of Harvard University suggests a more dynamic system for pressurizing the San Andreas, in which processes at even greater depths would actively pump

Are Only Moving Faults Weak?

For Lawana Knox, being caught a few hundred meters from a rupturing fault was a once-in-a-lifetime experience. For seismologists, what she reported was a revelation. Standing near the epicenter of the magnitude 7.2 earthquake near Borah Peak, Idaho, in 1983, she saw one side of the fault shoved a meter or more into the air in just one second. According to the conventional theory of how faults rupture, the slip on the Borah Peak fault should have taken 10 times as long.

This startlingly abrupt rupture and others like it are pushing seismologists to reconsider how faults work. The traditional picture of faults that slip only when tremendous stress overcomes high rock friction is already under assault from studies showing that many faults may be inherently weak (see main text). But reports like Knox's have led researchers to suspect that the act of rupturing can temporarily weaken a fault further—or momentarily sap its strength if it is strong to start. Like the notion of inherently weak faults, the new evidence for dynamically weakening faults is likely to enfeeble the already less-than-robust art of earthquake prediction.

Signs that something unexpected is happening on breaking faults are surfacing all over. In a study of seven earthquakes, including Borah Peak, seismologist Thomas Heaton of the U.S. Geological Survey in Pasadena compared the rupture duration indicated by seismic records with that predicted by conventional theory. He found that, at any one spot on the fault, the rupture lasted only 10% to 15% of the theoretical duration.

To account for the disparity, Heaton is reviving a long-discussed alternative to conventional fault mechanics that he calls a self-healing rupture. In the traditional picture of fault rupture, a zone of slippage expands along the fault until the entire rupture zone is slipping at once. In a self-healing rupture, by contrast, a rupture pulse races along a fault. At any one time, most of the fault is not slipping; the full amount of slip takes place as the rupture pulse sweeps by. That picture would explain the very rapid slip observed in the earthquakes Heaton studied. But a rupture pulse could only be sustained if there were some process for briefly weakening the fault as it starts to slip, then locking it up again ("healing" it) after the rupture passed.

Several ways of weakening a fault as it slips have been proposed. They range from heating fluids by fault friction, producing a cushion of steam, to the exotic process of acoustic fluidization, in which the grinding of rock on rock makes such a horrifically loud noise that the sound energy forces the fault apart and lets it slip more freely. The newest mechanism to be proposed involves a more mundane phenomenon. Seismologist James Brune of the University of Nevada suggests that the rupturing fault develops ripples, rather like the rumples that develop in a car's tires when it squeals around a curve. And just as those rumples can weaken a car's grip on the road, the ripples, says Brune, can separate the fault faces, if only by a millimeter, and thereby weaken it. With his colleagues Rasool Anooshehpoor and John Anderson, Brune has observed such "separation waves" in laboratory "earthquakes" generated when two blocks of foam rubber are pushed by each other along a "fault," and he is now looking for them in experiments with granite blocks.

No matter how a fault manages to do it, weakening during an earthquake "probably bodes ill for earthquake prediction," says Heaton. The interaction between slip and frictional strength is liable to be unsteady, even chaotic, he says. As a result, the slip on any one patch of fault could vary dramatically from quake to quake, contrary to the regularity predicted by a currently popular earthquake model. Such variability would mean that the prediction of quake size and timing would be difficult, if not impossible. Predicting the damage done by a large quake might be complicated as well, notes Heaton. A weakened fault means faster slip, as Lawana Knox learned first-hand. In a major earthquake, fault motion totaling perhaps several meters could occur in several seconds rather than the expected tens of seconds. For some buildings near the fault, that could be a sharper jerk than their designers had anticipated. ■ **R.A.K.**

ADDITIONAL READING

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fluid into the fault. His model relies on the fact that at depths greater than about 15 kilometers, below the fault itself, heat and pressure make rock flow like putty rather than break. This ductile flow, says Rice, would tend to squeeze high-pressure fluids out of the rock at those depths and into the fault above. There the fluids would be confined by the relatively impermeable rock surrounding the fault until they leaked away and were replaced by more fluids pumped up from the ductile region. From their inspection of exhumed faults, Chester, James Evans of Utah State University, and Ronald Biegel of Columbia University's Lamont-Doherty Geological Observatory tend to favor Rice's model of flowing fluids rather than Byerlee's static version; they see mineral deposits in the form of veins—a strong indication of fluid flow.

The notion that faults might be wedged open by high-pressure fluids pumped in from below is a long way from the idea that the high friction of rock on rock makes faults strong. But if researchers can figure out where fluids get into faults and just how they weaken them, they may be able to rebuild their understanding of fault mechanics into a foundation for earthquake prediction. Knowing how the fluid-induced weakening varies along a fault, for example, could be crucial to forecasting the next damaging quake. And a picture of how fluids weaken faults might help seismologists understand how some faults—nearly horizontal ones such as those beneath the Basin and Range province of Nevada and Utah, for example—slip at all (*Science*, 3 June 1983, p. 1031).

But the new picture of weak faults may also help heal a rift—the intellectual rift between laboratory experimentalists, whose work on fault mechanics had seemed increasingly at odds with the behavior of real faults, and some of their colleagues doing the fieldwork that conflicts with the laboratory data. If invoking high fluid pressures can eliminate "the discrepancy between what we learn in the lab and what Nature does on a large scale," says Rice, "then it would mean lab mechanics would be useful for learning what the precursors might be" for the next big quake. Odd that peacemaking might emerge from such violence as Loma Prieta. ■ RICHARD A. KERR

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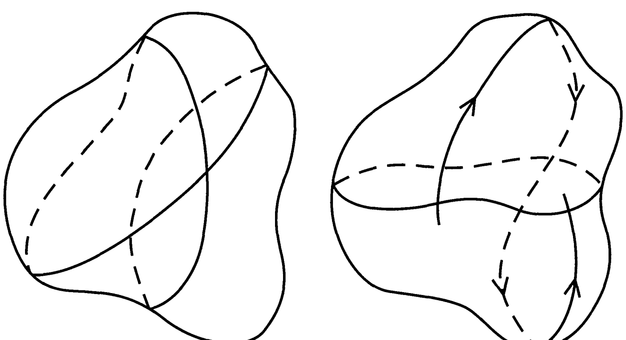
What Goes Around Comes Around

An unlikely partnership of two mathematicians has solved one old problem and suggested ways to solve many new ones

IF THERE IS AN ODD COUPLE IN MATHEMATICS, it would surely have to be a differential geometer hooking up with an expert in dynamical systems. One mainly studies the structure of stationary objects, while the other is interested primarily in change. Normally those two views of the world don't mix. But don't try telling that to John Franks and Victor Bangert.

Franks, an expert in dynamical systems at Northwestern University, and Bangert, a differential geometer at the University of Freiburg in Germany, recently teamed up to solve a problem that had vexed differential geometers for decades: How many closed geodesics are there for any Riemannian metric on a sphere—or, to put it differently, if Arnold Schwarzenegger crushes a basketball, how many unbroken rubber bands can Magic Johnson wrap around it?

The answer—that there are infinitely many conceptual rubber bands (closed geodesics) that can be wrapped around any distorted sphere—comes from an entirely new theorem Franks and Bangert developed, and it not only solves Magic's basketball puzzle, it is also pregnant with "offspring" from the marriage of mathematical disciplines that could have implications for a variety of scientific fields from plasma physics to new materials.



Distorted basketballs. *On a crushed sphere, some curves close up* (left), *while others may wrap around forever.*

SOURCE: BARRY CIPRA

The new theorem is especially good news for geometers, who consider closed geodesics worth their weight in gold. A geodesic, whether it's wandering about on the surface of a sphere or cruising through the gravitationally curved space-time of Einstein's theory of general relativity, is essentially just a curve that follows the curvature of whatever surface or space it lies in. "Following the curvature" means that geodesics have a "shortest path" property: Taken in segments, a geodesic connects points in the most direct way possible, just as a rubber band tries to make itself into as short a loop as possible. By analyzing the lengths of these loops, mathematicians can deduce many properties of the surface they lie on.

On an ordinary, undistorted sphere, the geodesics are all great circles, such as the earth's equator. And they are all "closed," meaning that traveling along one of them always brings you around the sphere, back to where you started. But on other surfaces—ones that Schwarzenegger has worked over, for example—geodesics are typically not closed. They are more like broken rubber bands stretched to an infinite length and wrapped endlessly around the surface. Looking for closed geodesics among this tangle of curves is a bit like searching for the proverbial needle in a haystack. But Bangert and Franks' result shows that there are infinitely many needles in this particular haystack.

To prove that there are an infinite number of closed geodesics for any closed surface, Bangert started with a single closed geodesic, which served as an equator. The only property an equator must have—aside from being closed—is that it not cross itself. For any geodesic that does cross the equator, one of two things must happen: Either it crosses the equator again, or it doesn't.

Several years ago, Bangert proved that if a geodesic crosses the equator, but afterward stays in one "hemisphere," then there are infinitely many other geodesics that are closed. He did this using classical techniques in differential geometry. But the other case, where each south-north crossing is followed by a north-south crossing, defied his geometer's bag of tricks.

So he turned to an approach first suggested by American mathematician George David Birkhoff in the 1920s. Birkhoff showed that