Solving the Paradox of Deep Earthquakes

*For decades, geophysicists have known that earthquakes
should not occur at depth inside the earth. But they do.
Finally, we know how and why these events happen*

by Harry W. Green II

On June 8 of this year, a great earthquake rumbled through the earth's mantle more than 600 kilometers below Bolivia. It was the largest earthquake ever recorded at such depths and the biggest of any kind in the past 15 years. The tremors were felt as far away as Toronto. No temblor in history had shaken the earth so far from its epicenter.

The event was truly spectacular and yet paradoxical as well. Although deep earthquakes are as regular as clockwork, they should not, in theory, be possible. The very existence of deep earthquakes has teased geophysicists since their discovery in 1927. Five years ago my colleagues and I in my laboratory at the University of California, first at Davis and now at Riverside, began to unravel the solution to this puzzle. This article gives an account of that discovery and of the new theory of earthquakes that has flowed from it.

Most earthquakes occur within a few tens of kilometers of the earth's surface by the familiar processes of brittle fracture and frictional sliding—the same mechanisms by which glass breaks and

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tires squeal on pavement. Yet almost 30 percent of all earthquakes occur at depths exceeding 70 kilometers, where the pressure reaches upward of two gigapascals (20,000 times that of the atmosphere at sea level); nearly 8 percent happen at depths greater than 300 kilometers, where the pressure is greater than 10 gigapascals. At such high pressures, rock will flow at lower stresses than those at which it will break or slide along a preexisting fault. Earthquakes at depth, then, would seem impossible.

Nevertheless, deep earthquakes do occur, exclusively in thin, planar zones in the earth that begin underneath oceanic trenches and angle down into the mantle. The theory of plate tectonics posits that these locations mark subduction zones, where the cold uppermost layer of the earth (the lithosphere, 50 to 100 kilometers thick) sinks into the mantle. In doing so, it provides the return flow that compensates for the upwelling of molten material and creation of lithosphere at ocean ridges. In these zones, earthquakes show an exponential decrease in frequency from the surface to about 300 kilometers deep. Then their frequency increases again, peaking at 550 to 600 kilometers deep. Finally, earthquakes cease entirely at approximately 680 kilometers deep.

Because the frequency of earthquakes steadily declines down to about 300 kilometers, most geophysicists believe that events originating between 70 and 300 kilometers below the surface (termed intermediate-focus earthquakes) are produced by a mechanism simply related to brittle fracture and frictional sliding. Deep-focus earthquakes (below 300 kilometers), however, follow an entirely different pattern and therefore must stem from a separate mechanism. For more than six decades, the details

of this mechanism remained elusive.

Years of study did provide intriguing information about subduction zones. Near the earth's surface, rocks contain minerals that exhibit a relatively loose packing of atoms. As the pressure on them increases at greater depths within the mantle, the atoms reorganize and yield minerals having progressively greater density. The first such transformation occurs in most parts of the mantle at a depth of about 400 kilometers. In the reaction, olivine, the most abundant mineral of the upper mantle, becomes unstable and changes into a phase having a spinel (cubic) structure that is 6 percent more dense than the original mineral. This shift causes an abrupt increase in seismic velocity at this depth. At 660 kilometers, the spinel form itself becomes unstable and decomposes into two phases, which together are an additional 8 percent more dense. The reaction induces another sharp rise in seismic velocity, marking the boundary between the upper and lower mantles.

The temperature is lower in a subducting slab. Under these conditions, the spinel structure becomes stable at somewhat lower pressures than normal and remains so until reaching slightly higher pressures than normal. Hence, the spinel stability field extends from a depth of about 300 kilometers to a depth of about 700 kilometers. This is exactly the region in which deep-focus earthquakes occur.

Because of this correlation, one of the recurring explanations over the years has been that the distribution of deep-focus earthquakes relates in some unknown way to these phase transformations. Most early suggestions centered around the fact that the reactions involve densification. Several researchers proposed that a sudden transforma-

tion of a significant volume of olivine to spinel would produce an implosion that could radiate the required seismic energy. Later studies refuted this hypothesis, however, showing that the geometric pattern of seismic energy that radiates from deep earthquakes is indistinguishable from that of shallow ones. Moreover, it indicates that movement takes place along a fault.

So what does cause deep earthquakes, and why do the events correlate with the spinel stability field? Direct experimentation of any kind at the extraordinary pressures of the earth's deep interior has become possible only in the past three decades. In 1976 Chien-Min Sung and Roger G. Burns of the Massachusetts
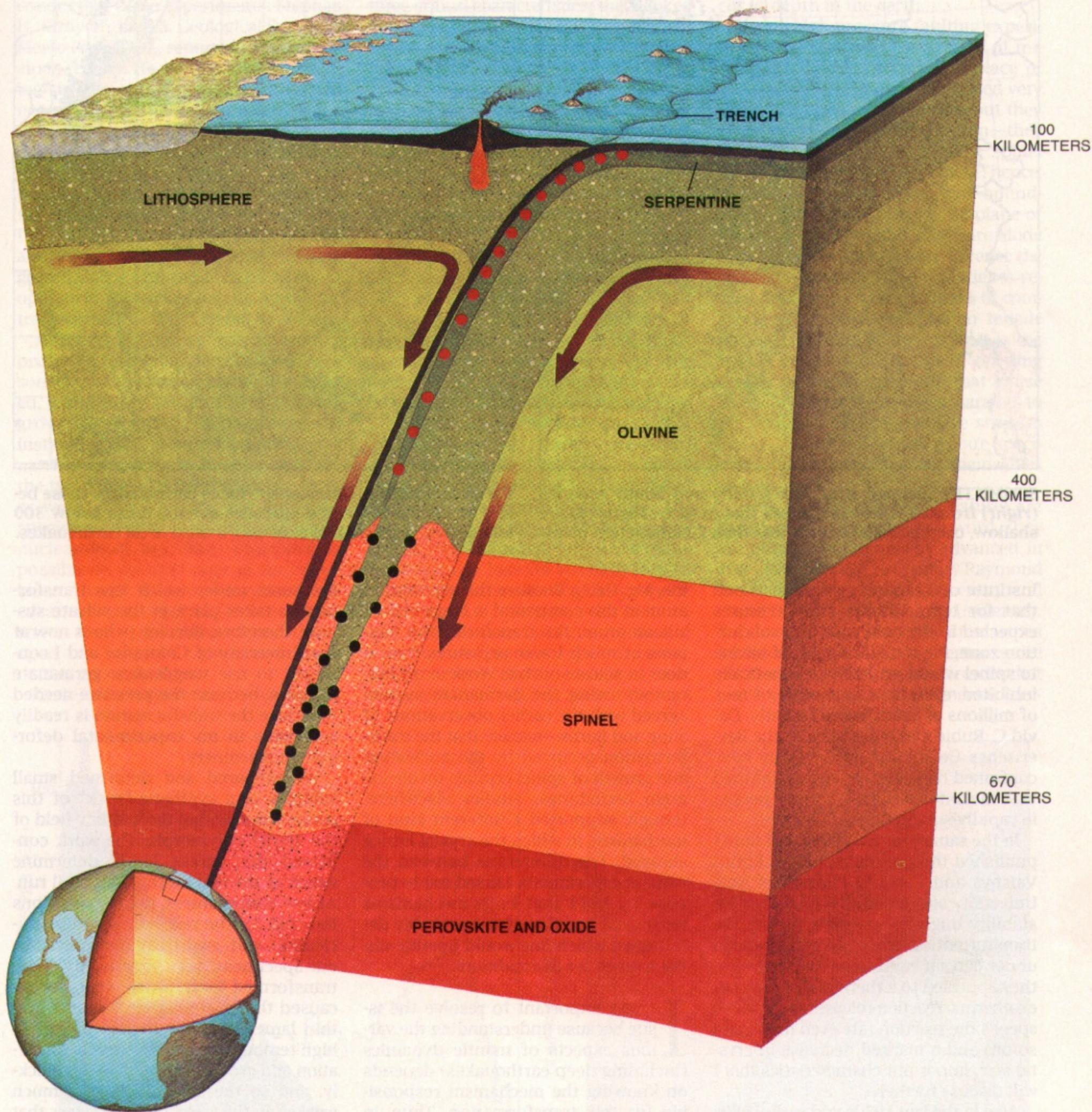
SUBDUCTION ZONES, where tectonic plates meet, are the only places where intermediate- and deep-focus earthquakes occur. Shallow earthquakes happen throughout the world when the brittle rock in the lithosphere fractures and slides. In a cold subducted slab, different mechanisms promote deeper events. Intermediate-focus temblors (*red dots*) occur when serpentine (olivine and water) is dehydrated as it descends into the mantle. Deep-focus quakes (*black dots*) result from the growth and spread of dense microstructures around the margins of the metastable olivine wedge that extends below 400 kilometers. At 700 kilometers, any remaining olivine decomposes silently, and all earthquake activity stops.
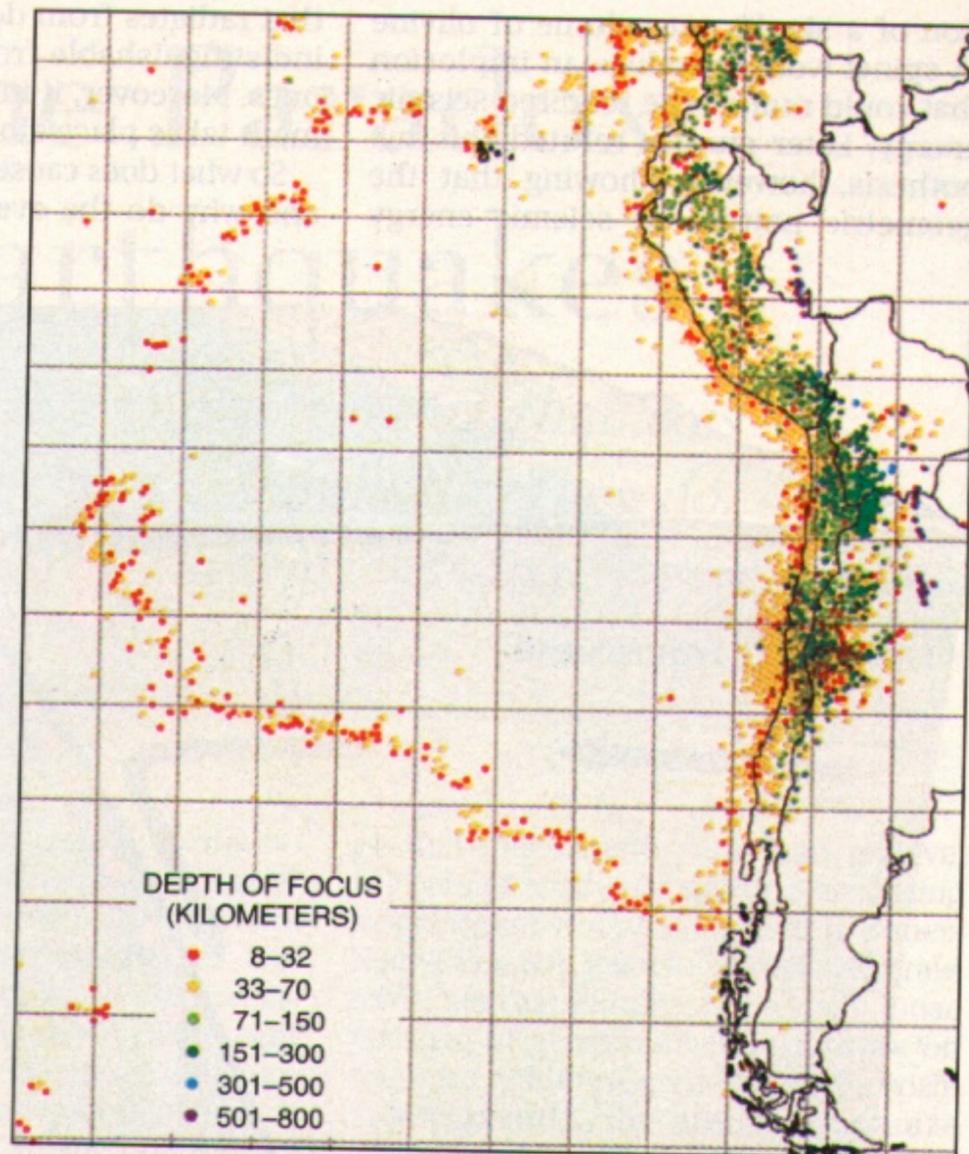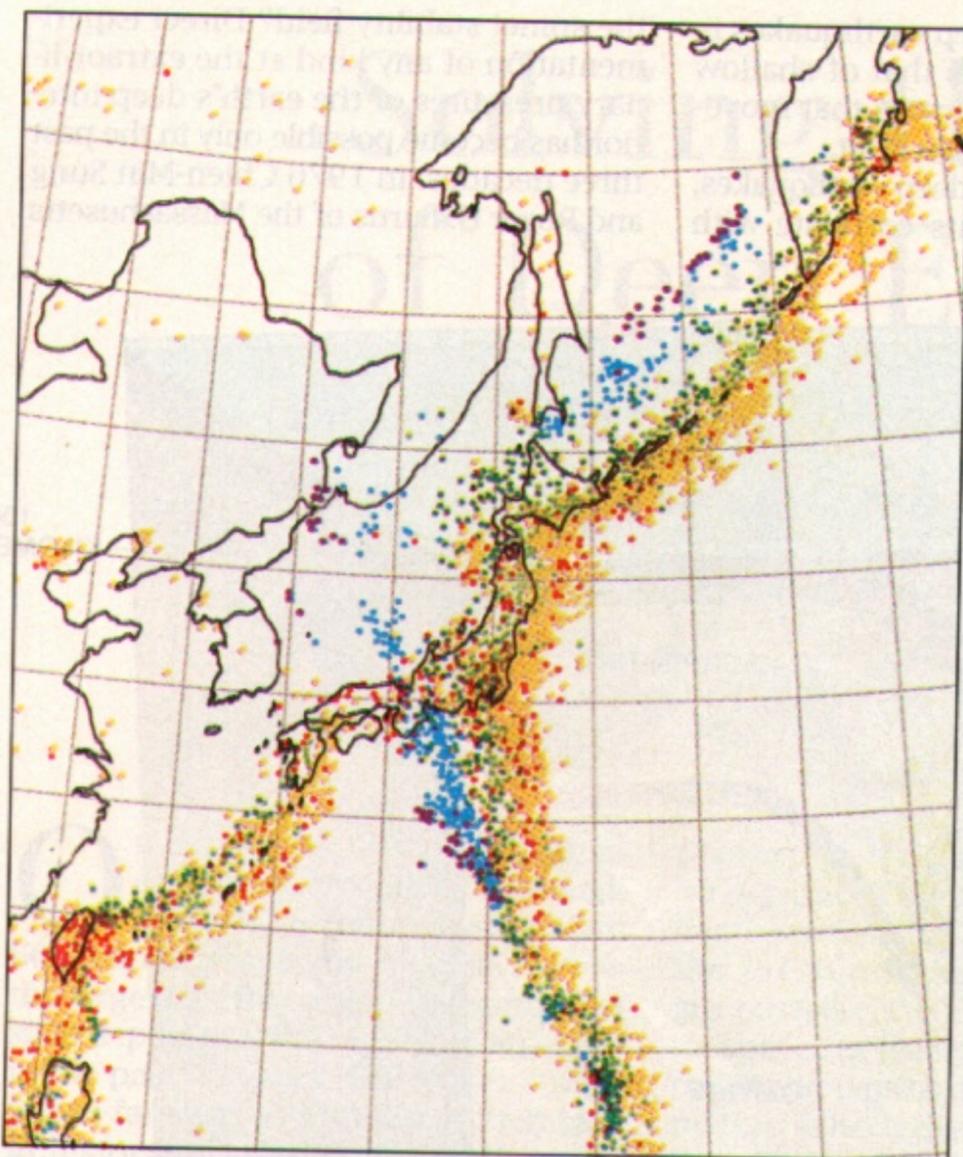
SEISMICITY mapped near Japan (*left*) and South America (*right*) from 1971 to 1986 shows that most earthquakes are shallow, originating at depths less than 70 kilometers below the earth's surface. Intermediate-focus earthquakes, those below 70 kilometers, and deep-focus events, those below 300 kilometers, together make up only a third of all earthquakes.

DEPTH OF FOCUS
(KILOMETERS)

- 8–32
- 33–70
- 71–150
- 151–300
- 301–500
- 501–800

Institute of Technology demonstrated that for temperatures and pressures expected in the cold core of a subduction zone, the transformation of olivine to spinel would probably be kinetically inhibited, even on a time scale of tens of millions of years (more recently, David C. Rubie and colleagues at the Bayerisches Geoinstitut in Germany have confirmed these results and established that metastable olivine should persist in rapidly subducting lithosphere).

In the same year that Sung and Burns published their initial results, J. Rimas Vaisnys and Carol C. Pilbeam of Yale University suggested that a faulting instability might be possible during the transformation from olivine to spinel under certain conditions. In particular, they appealed to a thermal runaway (an exothermic reaction releases heat, which speeds the reaction rate even more, and so on) and a marked decrease in crystal size, important characteristics that I will discuss further.

Also in the late 1970s and early 1980s a controversy arose concerning the exact mechanism by which olivine transforms to spinel. In addition to the silicate olivine of the earth's mantle, $(Mg, Fe)_2SiO_4$, the olivine-spinel transformation takes place in several chemical systems, including germanate oliv-

ine, Mg_2GeO_4. Because the germanium atom in this compound is larger than a silicon atom, the transformation happens at much lower pressures than it does in silicate olivine. Work in my laboratory using the germanate system agreed with the earlier observations of Sung and Burns—namely that the transformation occurred by the nucleation and growth of spinel crystals on olivine grain boundaries. Studies elsewhere, though, supported a different kind of mechanism, in which the crystal lattice sheared. The differences between the various experiments caused me to propose in 1984 that both mechanisms must exist and that stress probably determined which one would operate under a given set of conditions.

It was important to resolve the issue because understanding the various aspects of mantle dynamics (including deep earthquakes) depends on knowing the mechanism responsible for this transformation. Thus, in 1985, Pamela C. Burnley (who was then a graduate student beginning her Ph.D. research) and I began investigating the effect of stress on the transformation. It was not then (and still is not) possible to perform deformation experiments and measure stress at the very high

pressures under which this transformation takes place in the silicate system. Therefore, Burnley (who is now at the University of Colorado) and I continued to use magnesium germanate samples, because the pressure needed to induce the transformation is readily accessible in my experimental deformation machinery.

We prepared and deformed small samples of a synthetic "rock" of this composition within the stability field of the spinel polymorph. The work confirmed that stress levels determine which of the two mechanisms will run. At low temperatures, under conditions too cold for the reaction to run by nucleation and growth of new crystals, our specimens were very strong. They transformed only when high stress caused the crystal lattice to shear into thin lamellae of the denser phase. At high temperatures, however, the nucleation and growth mechanism ran quickly, and so the specimens were much weaker. In this case, the high stress that produced the shearing mechanism was never reached.

These results resolved the controversy over how olivine transforms into spinel. But the stresses required to produce the shearing mechanism are so high that only the nucleation and

growth mechanism should operate in the earth. Moreover, we found no faulting instability associated with the shearing mechanism. Thus, it could be ruled out as a possible mechanism for deep earthquakes as well.

At the same time that Burnley was conducting these experiments, Stephen H. Kirby of the U.S. Geological Survey in Menlo Park, Calif., reported some anomalous results. He was performing faulting studies of two minerals conducted near or above the pressure at which a densification reaction might be expected. Although he found no direct evidence of such a reaction, Kirby proposed that incipient transformation to the stable phases might have caused the faulting he observed. Like Vaisnys and Pilbeam 10 years earlier, he suggested that a faulting instability might operate in the earth's mantle during the transformation from olivine to spinel.

Although we had yet to witness this predicted instability, Burnley and I reasoned that if such an instability existed, it had to involve the nucleation and growth mechanism. Furthermore, the instability had to appear only in the narrow temperature interval between the two ranges tested during our earlier work. Consequently, we deformed specimens under conditions for which nucleation of the spinel phase is just possible on the time scale of the experiment. Bingo! These specimens exhibited an abrupt drop in the amount of stress they could support and developed one or more spinel-lined faults cutting through them.

Detailed examinations revealed a unique set of microstructures within these faulted specimens. Early on, during experiments conducted within the narrow faulting "window," microscopic packets of the high-density phase formed and grew on the olivine grain boundaries. These packets exhibited three critical characteristics: they looked like filled cracks; they ran perpendicular to the stress field; and they contained extraordinarily small crystals of spinel (approximately 10^{-5} millimeter in diameter). The first two characteristics are tantalizingly similar to features that develop in brittle materials before they break. The third offered a potential answer as to how faults can form and slide at high pressures.

From these three characteristics, we formulated a theory of transformation-induced faulting that is analogous to brittle shear fracture but that differs fundamentally in its microphysics. In brittle shear fracture, as the stress rises, large numbers of microscopic tensile cracks open parallel to the maximum compressive stress (S_1). These features are referred to as Mode I cracks because the displacements across them are perpendicular to the plane of the crack. As loading continues, the number and density of Mode I microcracks increase rapidly until the material begins to lose its strength locally. At that time, the microcracks cooperatively organize to initiate shear fracture, and the specimen fails in a fraction of a second. A "process zone" of tensile (Mode I) microcracks develops in front of the growing fault and leads it through
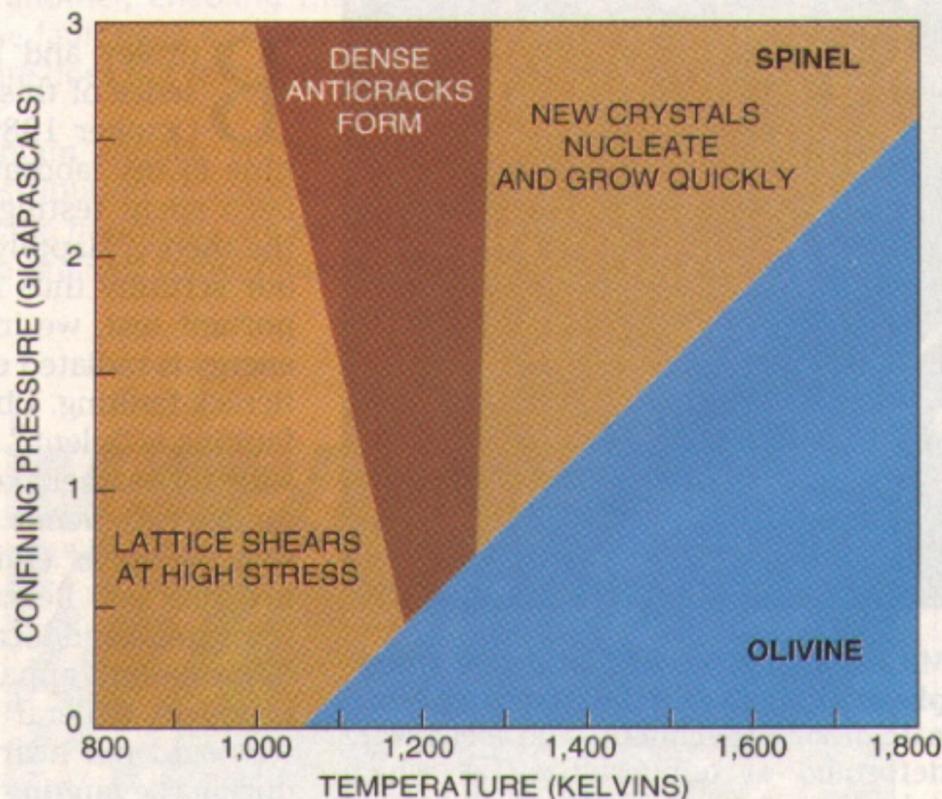
the material. The important point here is that the fault is not a primary failure process; it must be prepared for and led by Mode I microcracks. Because pressure severely inhibits the expansion that takes place when tensile microcracks open, brittle failure cannot occur at depth in the earth.

In our high-pressure faulting experiments, we observed the growth of microscopic lenses of spinel in place of microcracks. The lenses are shaped very much like open tensile cracks, but they have the opposite orientation—they form perpendicular to S_1. The spinel phase is more dense than olivine; hence, the displacements of the lens boundaries move inward toward the plane of the lens. Therefore, the lenses are Mode I features like tensile cracks. Because the displacement of their boundaries is reversed, however, concentrations of compressive stresses, rather than tensile stresses, develop at their tips. It is the tensile stresses at the tips of opening cracks in brittle materials that cause them to orient themselves parallel to S_1; similarly, the compressive stresses at the tips of the lenses in our specimens cause them to orient themselves perpendicular to S_1.

Thus, in every way these features are the inverse of cracks—in a word, they are anticracks, a concept advanced in 1981 in a different context by Raymond Fletcher of Texas A&M University and David D. Pollard of Stanford University. Because of the remarkable similarities between the two Mode I features, we concluded that the microanticracks that precede failure in our experimental spec-
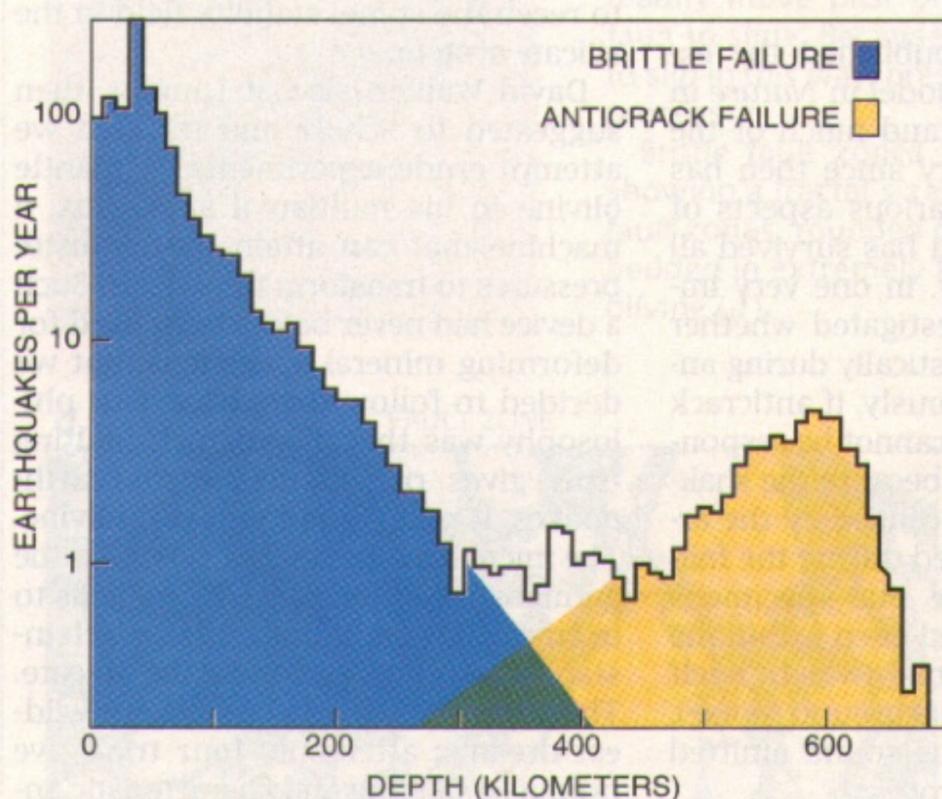

FREQUENCY of earthquakes corresponds closely to the depths at which olivine undergoes phase transformations (*left*). A minimum number of events occur at roughly 400 kilometers, where olivine transforms into a denser spinel (or cubic) phase. No earthquakes arise below a depth of 700 kilometers, where spinel decomposes. Pressure and temperature govern these reactions (*right*). In a germanate olivine at low pressures and high temperatures, olivine is stable, whereas at high pressures or low temperatures, the denser spinel is stable. Anticrack faulting occurs only in a narrow temperature "window."

imens must play the same role in high-pressure faulting as do microcracks in brittle fracture.

The third critical characteristic of our faulted specimens, the very fine grained spinel in the anticracks, gave us insight as to how anticracks can provide a fundamental weakening step and why the process can occur at high pressure. Extremely fine grained materials exhibit a remarkable flow property called superplasticity. Such materials flow by sliding on the grain boundaries between the crystals. This flow is somewhat like the deformation of a bag of sand, but with the all-important difference that the grains of sand are rigid. Therefore, they must slide up and over one another. As gaps open up between sand grains, the dilation must work against the ambient pressure. Hence, this process, like brittle failure, is severely inhibited by pressure. In contrast, grain-boundary sliding is a plastic process in which crystal defects called grain-boundary dislocations move. No expansion happens (as in the granular flow of sand), and so pressure has little inhibitory effect. We postulated that the fine-grained spinel within the anticracks is much weaker than the host olivine and has this "superplastic" flow capacity.
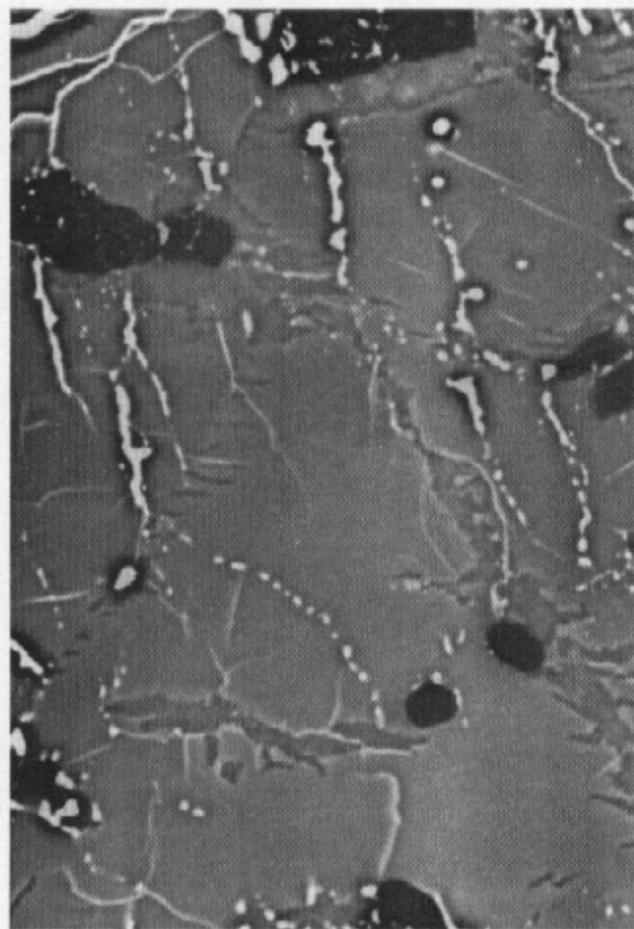
MICROSCOPIC LENSES of dense spinel-phase olivine (*white*) weakened germanate olivine specimens. The rocks were deformed at temperatures at which spinel crystals nucleate sluggishly. At lower temperatures, high stress can induce a smooth transformation from olivine to spinel-phase olivine. Likewise, at higher temperatures, spinel crystals nucleate easily and quickly.

From these observations we formulated the following hypothesis. During loading, under conditions for which the spinel phase grows with difficulty, olivine transforms to spinel. The transformation takes place as new crystals form by repeated nucleation adjacent to one another where stress concentrates. In a nonhydrostatic stress field, the developing packets of spinel tend to grow perpendicular to S_1. This preference leads to their lens-shaped morphology and alignment. These Mode I microanticracks initially form scattered throughout the specimens. But because the fine-grained spinel aggregates within the microanticracks are much weaker than the large olivine crystals, once enough of them have formed, the specimen loses its strength locally.

At this critical stage, large stress concentrations develop around the region of incipient failure, and the growth of anticracks accelerates. Preexisting microanticracks then link up and empty their superplastic contents into the developing fault zone, providing a lubricant along which the fault can slide. The process continues ahead of the tip of the growing fault zone and thereby provides the superplastic material needed to lubricate the fault. The anticracks must grow very rapidly to produce this faulting. We postulated that the speed of their growth resulted from a thermal feedback mechanism: the nucleation of spinel in the anticracks releases heat that locally increases the temperature, which increases the nucleation rate, which raises the temperature further, prompting faster nucleation and leading to catastrophic failure.

Burnley and I published the essence of this model in *Nature* in October 1989, and much of the time in my laboratory since then has been spent testing various aspects of the theory. Happily, it has survived all our scrutiny thus far. In one very important test, we investigated whether energy is radiated elastically during anticrack faulting. Obviously, if anticrack faulting is "silent," it cannot be responsible for earthquakes because the shaking we experience is caused by the arrival of "noise" emitted during the failure process. Because our specimens were small and located deep within the deformation apparatus (which itself produces general background noise), we could not hear the sound emitted during the faulting process.

To overcome this difficulty, I established a collaboration with Christopher H. Scholz of the Lamont-Doherty Earth Observatory of Columbia University, who investigates brittle fracture in the earth. Scholz attaches sensitive piezoelectric transducers to his apparatus to "listen" to the acoustic emissions that precede and accompany brittle failure. We modified one of my high-pressure deformation apparatuses to reduce noise and, working with Tracy N. Tingle and Thomas E. Young from my lab and Theodore A. Kozynski from Scholz's lab, successfully detected acoustic emissions from samples of Mg_2GeO_4 during failure.
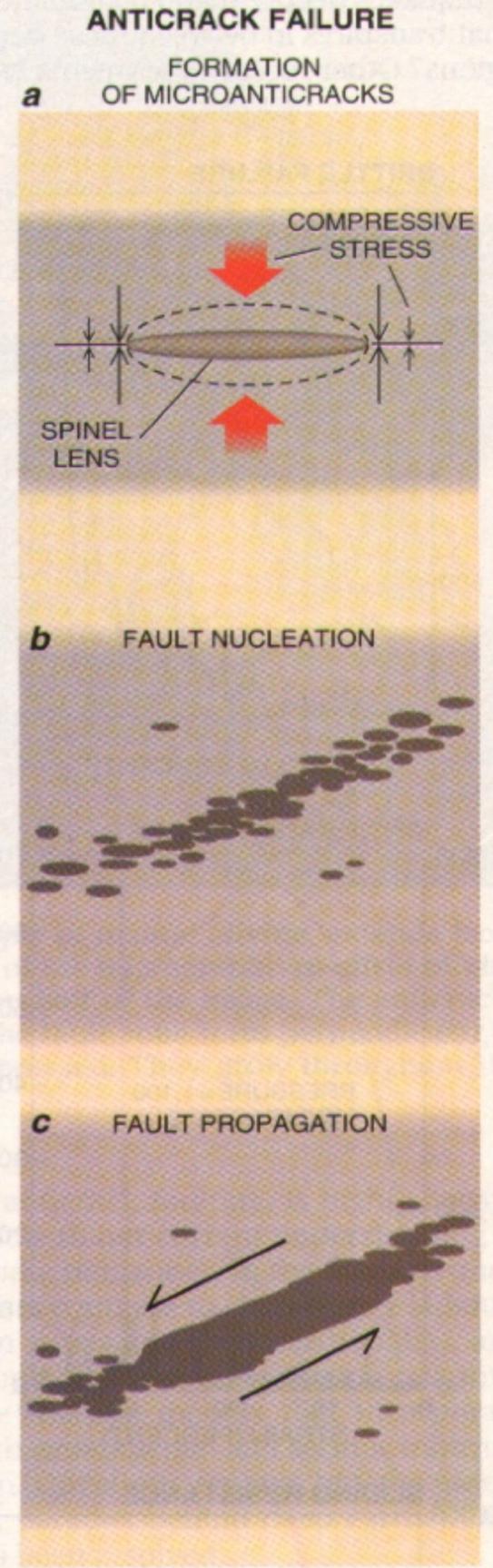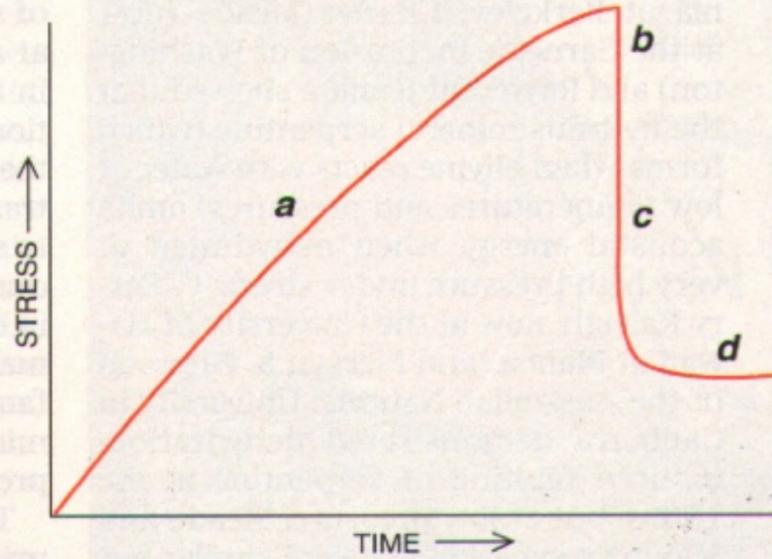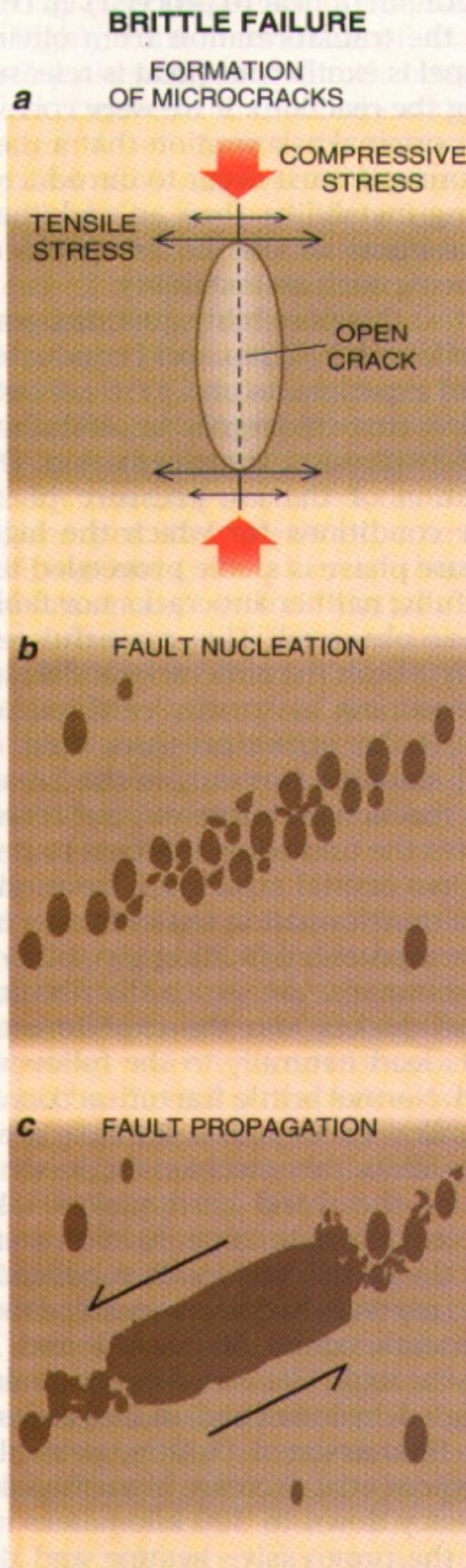
Tingle and I also investigated the flow strength of Mg_2GeO_4 spinel when the crystals are comparable in size to the olivine crystals of the starting material. We then compared that strength to the resistance against sliding present on anticrack-induced faults. Whereas this resistance is much less than the flow strength of the olivine specimens before failure, the flow strength of coarse-grained spinel is twice as great as that of olivine. As a result, one cannot explain the weakness of the fault zones in our specimens by simply replacing olivine with spinel; the flow mechanism must also change. The only known mechanism that can provide such weakening is superplastic flow, consistent with our original speculation.

These tests established beyond doubt that anticrack faulting was a new failure mechanism distinct from brittle failure. Nevertheless, they had one major flaw. We conducted all these experiments on germanate olivine, not the silicate olivine found in the mantle. Of course, as mentioned earlier, none of this work could have been done on silicate olivine; it is still not possible to measure stresses at the high pressures needed to reach the spinel stability field in the silicate system.

David Walker, also at Lamont, then suggested to Scholz and me that we attempt crude experiments on mantle olivine in his multianvil apparatus, a machine that can attain the requisite pressures to transform the silicate. Such a device had never before been used for deforming mineral specimens, but we decided to follow the advice. Our philosophy was that if anticrack faulting truly gives rise to deep-focus earthquakes, it must operate in real olivine. The microstructures we observed in the germanate specimens could guide us to uncover the conditions under which instability would develop in the silicate. The approach worked beyond our wildest dreams; after only four trials, we produced faulting and characteristic anticrack microstructures in mantle olivine at a pressure of 14 gigapascals.

Despite the attractive properties of the anticrack faulting mechanism, it can operate in the earth only if olivine

Brittle versus Anticrack Failure

BRITTLE FAILURE

a FORMATION OF MICROCRACKS

COMPRESSIVE STRESS

TENSILE STRESS

OPEN CRACK

b FAULT NUCLEATION

c FAULT PROPAGATION

d FAULT ZONE

ANTICRACK FAILURE

a FORMATION OF MICROANTICRACKS

COMPRESSIVE STRESS

SPINEL LENS

b FAULT NUCLEATION

c FAULT PROPAGATION

d FAULT ZONE

STRESS

TIME

B rittle failure and anticrack failure, the mechanisms that account for shallow and deep earthquakes, respectively, share many characteristics. Both processes involve the development of microscopic features (*a*) that cooperatively form a fault and allow for movement on it.

As brittle rocks experience mounting stress, microcracks open parallel to the direction from which they are compressed. In rocks found more than 300 kilometers deep, pressure prohibits this dilation. Instead microanticracks (lenses filled with fine-grained, dense spinel-phase olivine) form perpendicular to the direction from which these rocks are compressed.

In each mechanism, at some critical point in time, these microfeatures link up and create a fault (*b*). Movements along the fault then relieve stress (*c*). In brittle failure, the fault is an open fracture. In anticrack failure, the fault contains fine-grained spinel-phase olivine. This material is superplastic—that is, the crystals can readily move past one another, enabling the fault to slide. Because the fault need not dilate to slip in this way, pressure does not restrict the process.

Brittle fault zones contain angular crystals showing a fractal size distribution. In anticrack fault zones, rounded olivine fragments are embedded in extremely fine grained spinel-phase olivine (*d*).
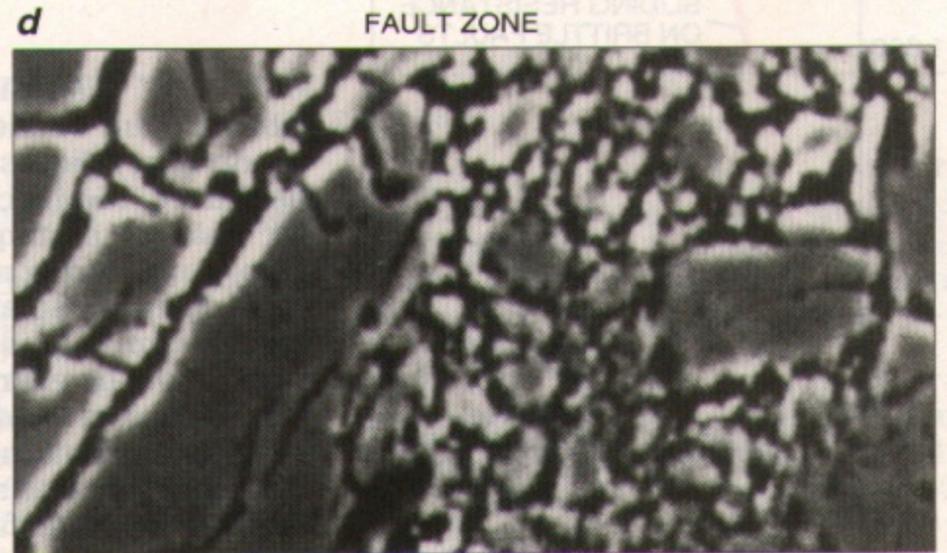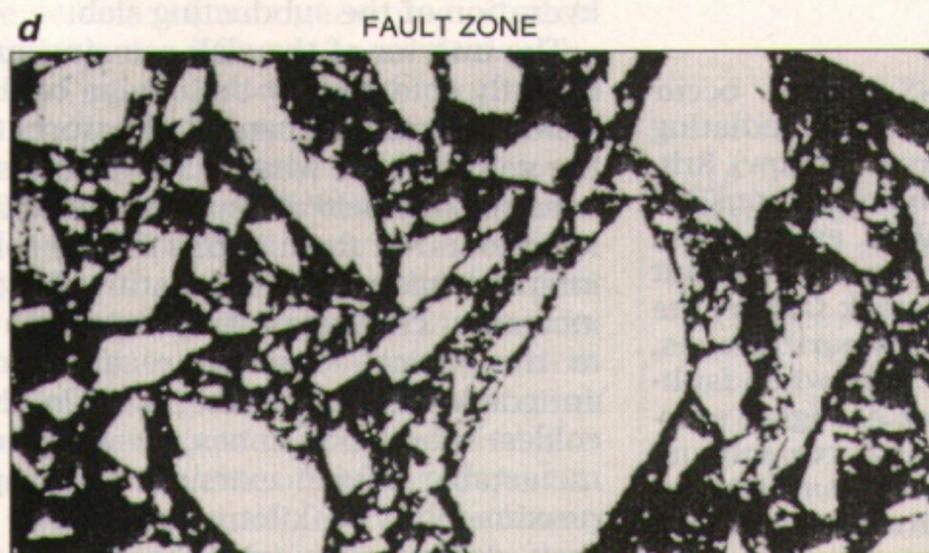
is carried deep into the upper mantle, where the spinel crystal structure is stable. In particular, this mechanism cannot account for earthquakes shallower than approximately 300 kilometers, where olivine is still stable. Normal brittle fracture, though, cannot explain earthquakes deeper than 70 kilometers. What transpires in between these depth regions? Other recent experiments have

neatly provided the explanation for such intermediate-focus earthquakes.

Working at the University of California at Berkeley, Charles Meade (now at the Carnegie Institution of Washington) and Raymond Jeanloz showed that the hydrous mineral serpentine (which forms when olivine reacts with water at low temperatures and pressures) emits acoustic energy when dehydrated at very high pressure under stress. C. Barry Raleigh, now at the University of Hawaii at Manoa, and Mervyn S. Paterson of the Australian National University in Canberra demonstrated dehydration-induced faulting of serpentine in the 1960s, but at low pressure. Meade and Jeanloz's experiments were similar but were carried out instead on sand-grain-size specimens of serpentine in a diamond-anvil cell. The serpentine emitted acoustic energy when it was heated and dehydrated under pressures equivalent to that found 300 kilometers deep in the earth. We can understand this process in terms of the anatomy of brittle fracture. The pressure of the water produced by dehydration pushes open microcracks against the high applied pressure, thereby allowing for brittle failure.

We know from a variety of geophysical and geologic observations that olivine in the uppermost mantle (just below the oceanic crust) becomes partially hydrated as it journeys from an ocean ridge to an ocean trench. Thus, shallow regions in the lithosphere contain the hydrous phases that enable this mechanism to work. The declining frequency of earthquakes in subduction zones down to 300 kilometers most probably represents the progressive exhaustion of the mechanism as the oceanic lithosphere gradually warms up and dehydrates, heated by the surrounding mantle. At about 300 kilometers, anticrack faulting becomes possible, causing an increase in earthquakes there.
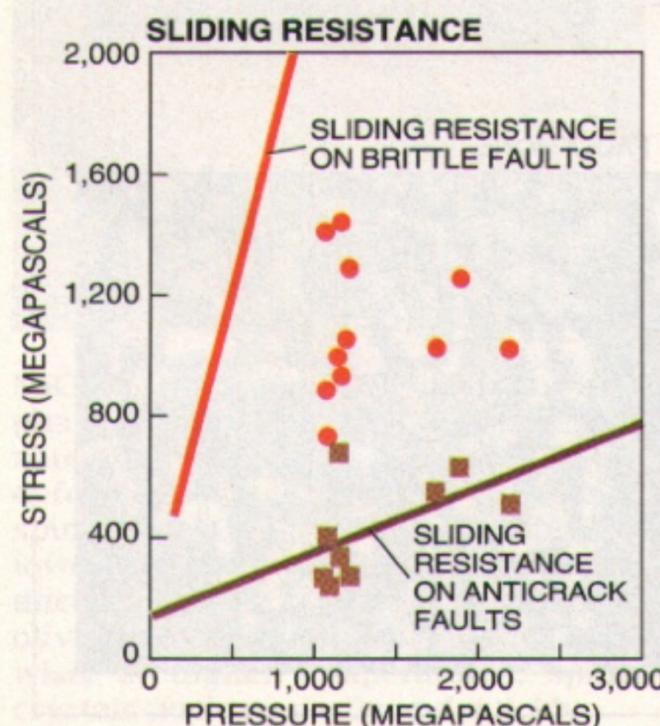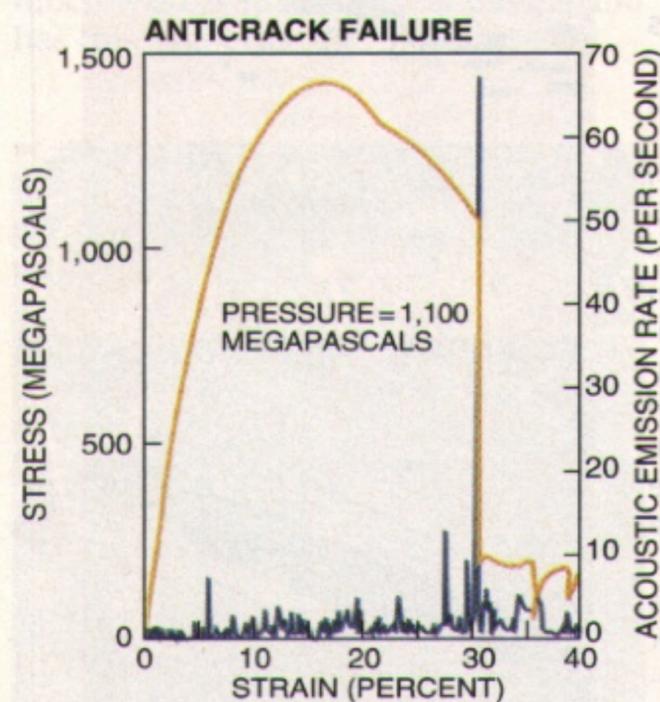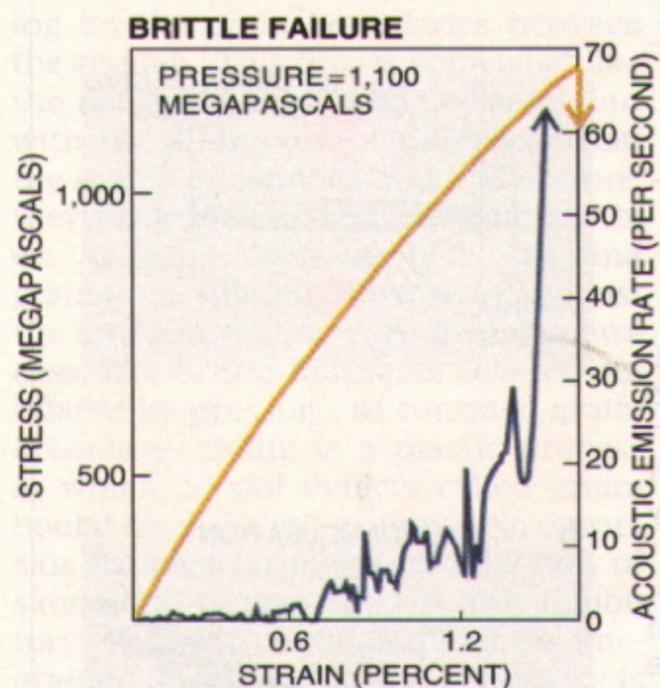
The anticrack faulting mechanism provides an explanation for how and why earthquakes extend to great depth

in the earth. Can this mechanism also explain why they suddenly stop? As mentioned earlier, the decomposition of spinel into two denser phases occurs at approximately 700 kilometers deep in subduction zones. This decomposition reaction is endothermic (it requires the addition of heat to proceed). In contrast, the transformation from olivine to spinel is exothermic (heat is released during the reaction). If we were correct in our original assumption that a thermal runaway must occur to introduce a faulting instability, then an endothermic reaction should be incapable of producing such an instability.

To test this possibility, just this year, my colleague Yi Zhou and I conducted a set of experiments on $CdTiO_3$, a composition that undergoes an endothermic densification transformation. Deformation of the low-pressure phase under conditions for which the high-pressure phase is stable proceeded uneventfully; neither anticracks nor faulting was observed. This powerful test supports both the anticrack model and our reasoning as to why earthquakes cease at the upper pressure limit of spinel stability. Not only is the breakdown reaction endothermic, but it also requires the unmixing of atoms to produce two crystal structures from one. Such a transformation would further inhibit any potential faulting instability.

In summary, the depth distribution of earthquakes and the experimental results lead naturally to the following model. Normal brittle fracture accounts for shallow earthquakes. Because pressure inhibits this mechanism, in most parts of the world earthquakes take place only down to 20 to 30 kilometers below the earth's surface. In subduction zones, partially hydrated oceanic crust and mantle sinks downward and is slowly heated. The water-bearing minerals are dehydrated and, in the process, make fluid-assisted faulting possible. The exponential decrease in earthquake frequency down to 300 kilometers reflects the progressive heating and dehydration of the subducting slab.

The interior of the slab remains sufficiently cold so that the olivine of the subducting mantle cannot transform to the spinel phase when it leaves the olivine stability field at approximately 300 kilometers. At the margins of this cold interior region, the temperature slowly increases. The metastable olivine heats to the critical temperature at which anticrack faulting takes place. In the coldest subduction zones, the wedge of metastable olivine extends down approximately 700 kilometers, where it then decomposes into the two very dense phases of the lower mantle. After

BRITTLE FAILURE

PRESSURE = 1,100 MEGAPASCALS

STRESS (MEGAPASCALS) / ACOUSTIC EMISSION RATE (PER SECOND) vs STRAIN (PERCENT)

ANTICRACK FAILURE

PRESSURE = 1,100 MEGAPASCALS

STRESS (MEGAPASCALS) / ACOUSTIC EMISSION RATE (PER SECOND) vs STRAIN (PERCENT)

SLIDING RESISTANCE

SLIDING RESISTANCE ON BRITTLE FAULTS

SLIDING RESISTANCE ON ANTICRACK FAULTS

STRESS (MEGAPASCALS) vs PRESSURE (MEGAPASCALS)

ACOUSTIC EMISSIONS (*blue*) occur when a fault suddenly slips, radiating energy that relieves stress (*yellow*). Brittle failure, the mechanism responsible for shallow earthquakes, emits noise before and during movement on a fault (*top*). In contrast, anticrack failure, the mechanism behind deep earthquakes, emits acoustic energy only when faulting takes place (*middle*). At higher pressures, brittle faulting can occur only under much greater stress (*bottom*). For this reason, brittle failure cannot explain deep-focus earthquakes. Pressure does not likewise inhibit anticrack failure.

this deep reaction, all earthquakes stop.

The model automatically predicts certain properties for the seismic signals generated in the mantle during intermediate- and deep-focus earthquakes and for the changes in seismic velocity within subducting slabs. First, the seismic signal of these earthquakes should be highly similar to those of shallow earthquakes. In particular, their signals should be consistent with shearing motions on a fault. Indeed, this seems to be the case. Although seismologists have searched for the past three decades, they have found no unambiguous instance of a deep earthquake having a strong implosive component.

Moreover, the seismic velocity of the cold interior of subducting plates should be significantly slower if metastable olivine is present than if the reaction has already run and produced the denser polymorphs. Only Japan experiences a sufficient amount of deep earthquakes and has enough seismic stations to attempt to distinguish between these two possibilities. In 1992 Takashi Iidaka and Daisuke Suetsugu of the University of Tokyo modeled both possibilities for the descending slab underneath Japan and found the telltale slow velocity of a metastable olivine wedge.

If, as we propose, a critical temperature controls the anticrack faulting instability, the faulting will be concentrated at the interface between the metastable olivine wedge and the surrounding, already transformed carapace. If sufficient stress exists on both margins of the wedge, double zones of earthquakes could develop. Two sets of seismologists, one led by Douglas A. Wiens of Washington University and the other by Iidaka, have discovered such double zones during the past year. Iidaka's team found the double zone in the slab that they previously proposed must contain a metastable olivine wedge.

In addition, if there is a change in the fundamental mechanism responsible for earthquakes at 300 to 400 kilometers, one might expect some aspects of the seismic signals generated at such depths to be different from those generated by shallower events. Until very recently, all attempts to identify such distinctions had failed. Still, Heidi Houston and Quentin Williams of the University of California at Santa Cruz recently reported that many deep events seem to start up significantly faster than do intermediate events. Further, Houston and John E. Vidale of the U.S. Geological Survey have now determined that the entire rupture time of such earthquakes is only about half that of shallower ones. Other recent work has shown that young, warm subduction zones experi-
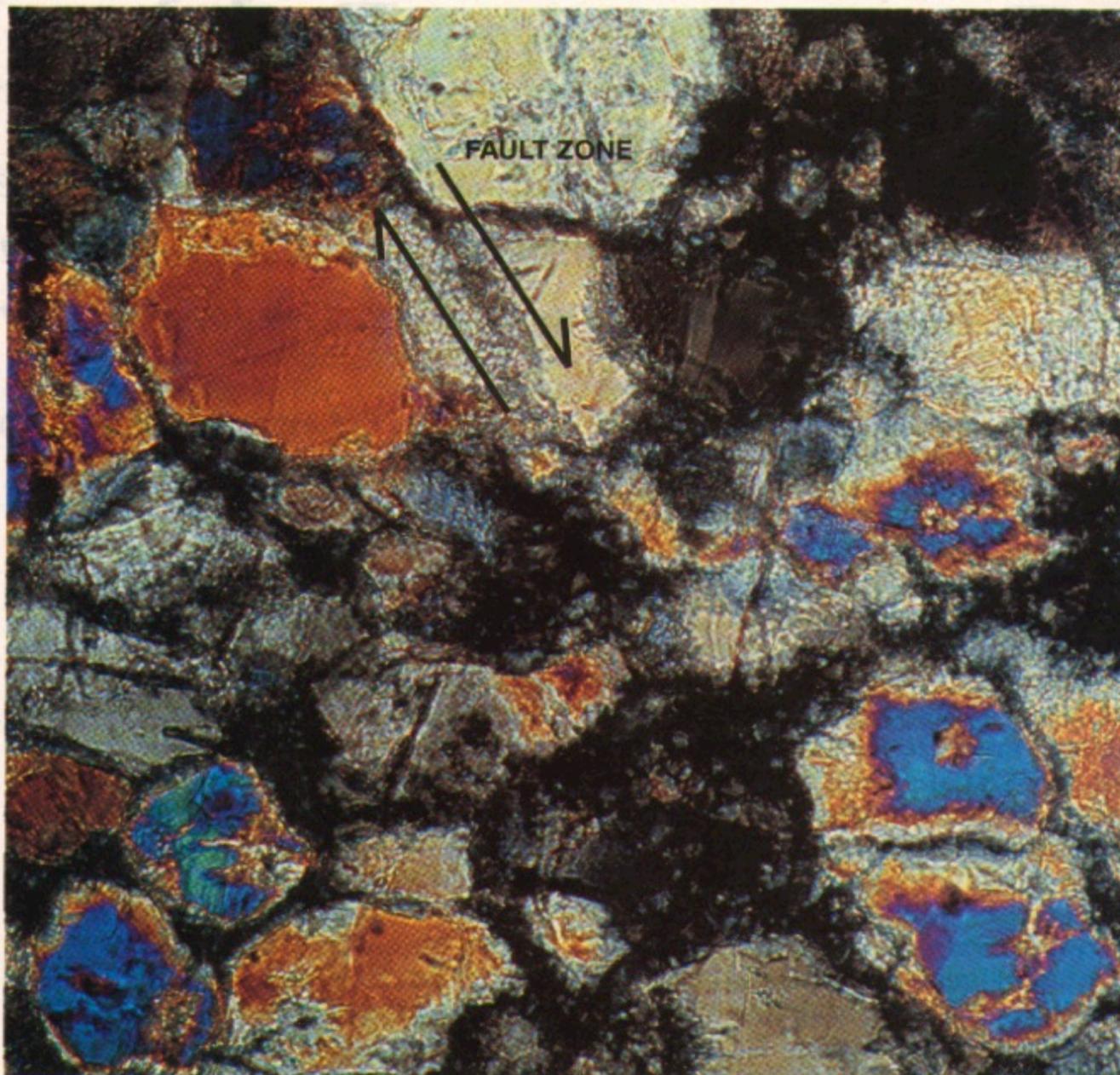
FAULT ZONE, produced by deforming a sample of mantle olivine, extends from the top left corner to the bottom right corner of the micrograph. An offset olivine crystal (*white*) appears on this fault in the top half of the image. The anticracks (*yellow lenses in blue crystal*) that generate the fault zone form perpendicular to the direction from which the sample is compressed. They grow throughout the material parallel to this direction.

ence earthquakes only down to 300 to 400 kilometers; all deep earthquakes are confined to older, colder subduction zones, where metastable olivine is likely to persist to great depths.

The laboratory results therefore explain how earthquakes can happen at very high pressures. The composite model advanced here, in which intermediate-focus earthquakes occur by fluid-assisted faulting and deep events

by anticrack faulting, is highly consistent with our current understanding of subduction zones. In the field, seismologists continue to characterize subduction zones and their earthquakes, and geophysicists are developing quantitative thermal models that incorporate both experimental and seismic information. Questions remain, but the essential paradox behind deep earthquakes has been resolved.

FURTHER READING

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