

# New Light on Deep Earthquakes

Until about 15 years ago, it was a mystery how deep earthquakes could occur. Recent results have now demonstrated mechanisms for such rock failures at great depths

By Harry W. Green II

ON JUNE 7, 1994, a great earthquake rumbled through Earth's mantle more than 600 kilometers beneath Bolivia. It was the largest earthquake ever recorded at such depths. The tremors were felt as far away as Toronto. No other quake in history had been felt so far from its epicenter.

The event was truly spectacular and yet paradoxical as well. Although deep earthquakes are as regular as clockwork, in theory they should be impossible. Indeed, the very existence of deep earthquakes has teased geophysicists since their discovery in 1927. In 1989 my colleagues and I began to unravel the solution to this puzzle in the laboratory. This article gives an account of that discovery, the new theory of earthquakes that has flowed from it, and recent developments in our understanding.

Most earthquakes are shallow events that occur within a few tens of kilometers of Earth's surface by the familiar processes of brittle fracture and frictional sliding—the same mechanisms by which glass breaks and tires squeal on pavement. For example, last year's devastating Indonesian earthquake was a shallow quake only 16 to 18 kilometers beneath the Indian Ocean. But almost 30 percent of all earthquakes originate much deeper, occurring at depths exceeding 70 kilometers, where the pressure reaches upwards of two gigapascals (20,000 times that of the atmosphere at sea level); nearly 8 percent happen at depths great-

er 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 that begin beneath oceanic trenches and angle down into the mantle. The theory of plate tectonics tells us that these locations mark subduction zones, where the cold uppermost layer (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 new 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.

## Elusive Mechanism

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), howev-

er, follow an entirely different pattern and therefore probably 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 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, atomic reorganizations occur that yield new minerals having progressively greater density. The first such transformation occurs in most parts of the mantle at a depth of about 410 kilometers. In the reaction, olivine, the most abundant mineral of the upper mantle, becomes unstable and changes into a new 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 new phases, which together are an additional 8 percent denser. The reaction induces another sharp rise in seismic velocity.

At lower temperatures, such as in a subducting slab, the spinel structure becomes stable at somewhat lower pressures than normal and remains so until subjected to slightly higher pressures than normal. Hence, in subduction zones the spinel stability field extends from a depth of about 300 kilometers to about 700 kilometers. This is exactly

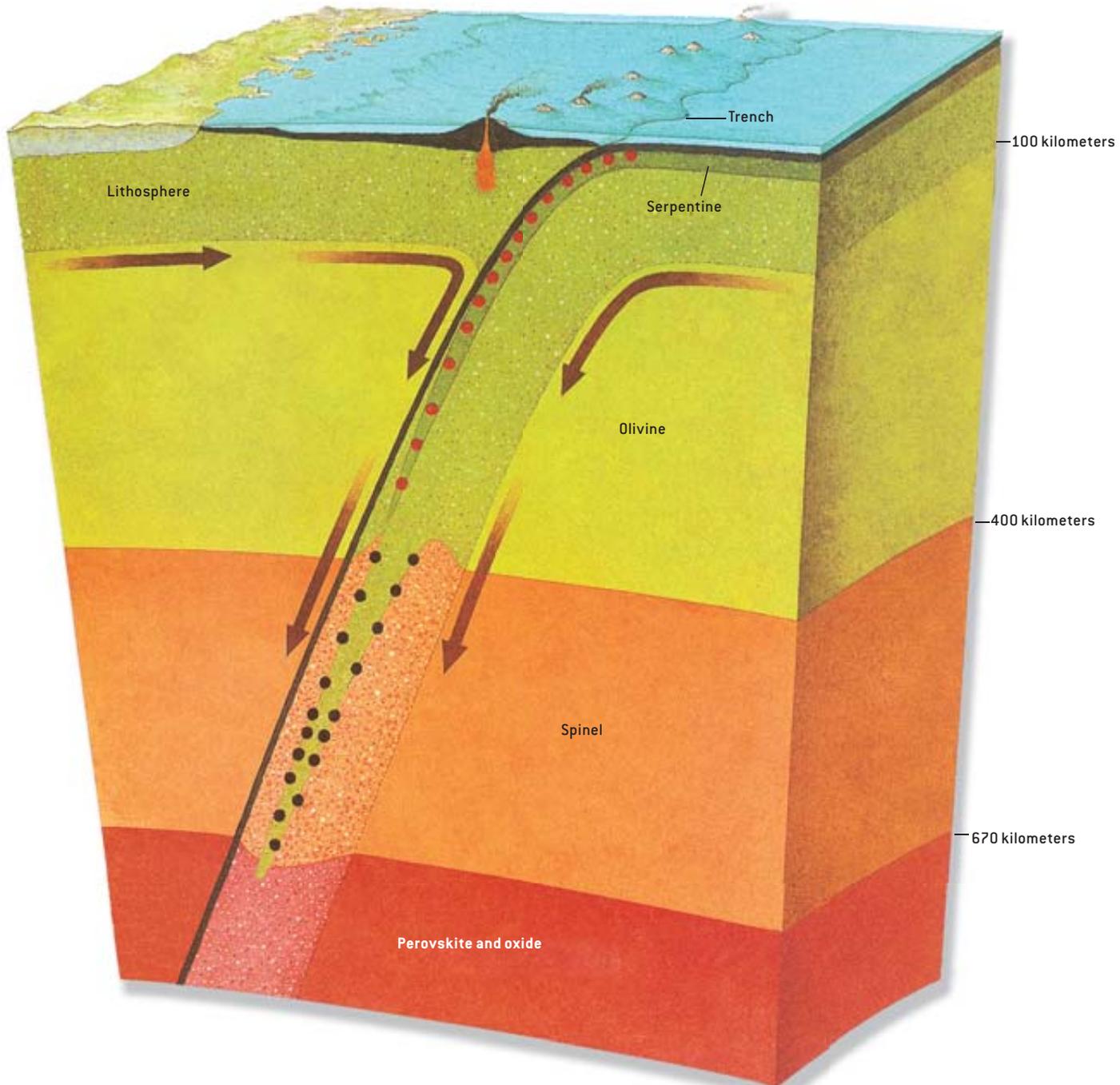
the region in which deep-focus earthquakes occur.

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 transfor-

mations. Most early suggestions focused on the fact that the reactions involve densification. Several researchers proposed that a sudden transformation of a significant volume of olivine to spinel would produce an implosion that could radiate the required seismic en-

ergy. Later studies refuted this hypothesis, however, showing that the geometric pattern of energy radiated from deep earthquakes is indistinguishable from that of shallow ones and indicating that movement takes place along a fault.

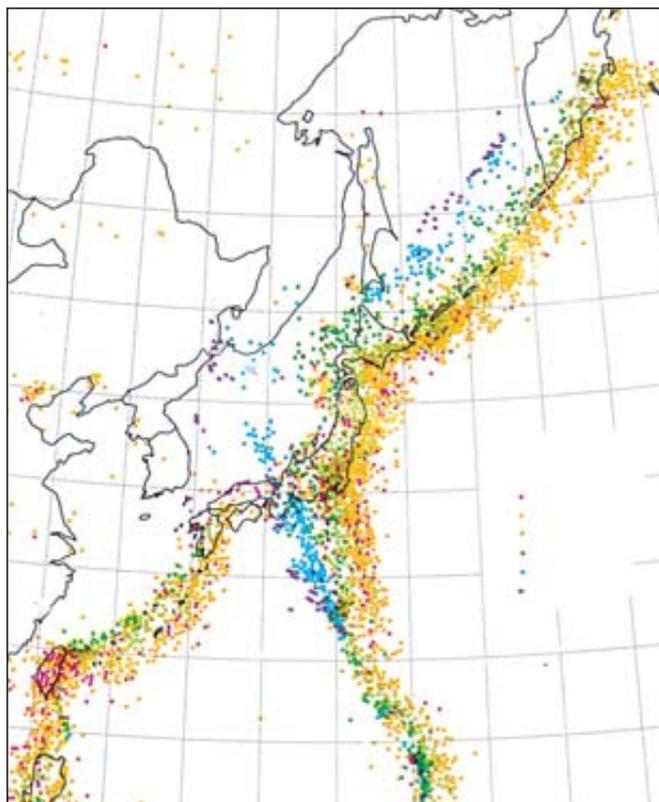
So what does cause deep earth-



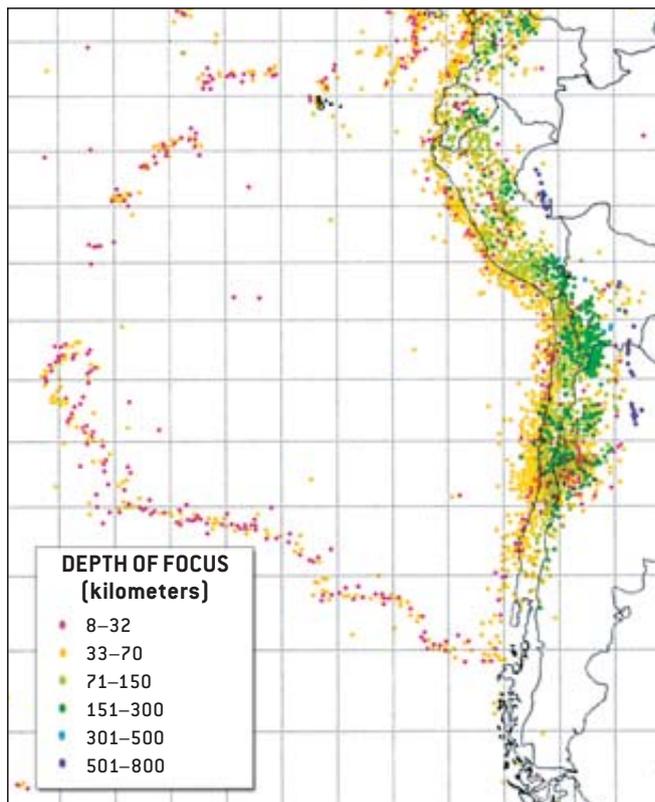
SUBDUCTION ZONES, where tectonic plates come together, are the only places where intermediate- and deep-focus earthquakes occur. In contrast, shallow earthquakes happen throughout the world when the brittle rock in the lithosphere fractures and slides. In a cold subducted slab, different mechanisms promote deeper events. Intermediate-focus tremors (red dots) occur when serpentine [a hydrous mineral

generated by reaction of water and olivine) 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 (green) that extends below 400 kilometers. At 700 kilometers beneath the surface, any remaining olivine decomposes silently, and all earthquake activity stops.

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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 beneath the earth's surface.



Intermediate-focus earthquakes, those below 70 kilometers, and deep-focus events, those deeper than 300 kilometers, together make up only a third of all earthquakes.

quakes, and why do the events correlate with the spinel stability field? Direct experimentation of any kind at the extraordinary pressures of Earth's deep interior has become possible only in the past few decades. In 1976 Roger Burns and Chien-Min Sung of the Massachusetts Institute of Technology showed 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 timescale of tens of millions of years. More recently, debate has arisen as to how cold a subduction zone would have to be to preserve such metastable olivine. Seismic evidence for the existence of metastable olivine, however, is now strong.

In the same year that Sung and Burns published their initial results, J. Rimas Vainys and Carol 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, which generates more heat, and so on) and a marked decrease in crystal size, important characteristics that I will discuss further.

Despite such progress, 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 Earth's mantle,  $(\text{Mg,Fe})_2\text{SiO}_4$ , the olivine-spinel transformation takes place in several other chemical systems, including germanate olivine,  $\text{Mg}_2\text{GeO}_4$ . The latter compound has the advantage that the larger germanium atom causes the transformation to occur 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 mechanism of nucleation and growth of spinel crystals on olivine grain boundaries. Studies elsewhere, though, suggested a different kind of mechanism, involving shearing of the crystal lattice. The differences between the various experiments caused

me to suggest in 1984 that both mechanisms must be real and that stress probably determined which one would operate under a given set of conditions.

### Looking for the Mechanism

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 possible at that time to perform deformation experiments and measure stress at the very high pressures under which this transformation takes place in mantle olivine. Therefore, Burnley (who is now at Georgia State University) and I continued to use magnesium germanate samples, because the pressure needed to induce the transformation was 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 the level of stress determines the choice between the two mechanisms. 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. They appeared in faulting studies of two minerals conducted near or above the pressures at which densification reactions might be expected. Although he found no direct evidence of such reactions, 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 Earth’s mantle during the transformation from olivine to spinel.

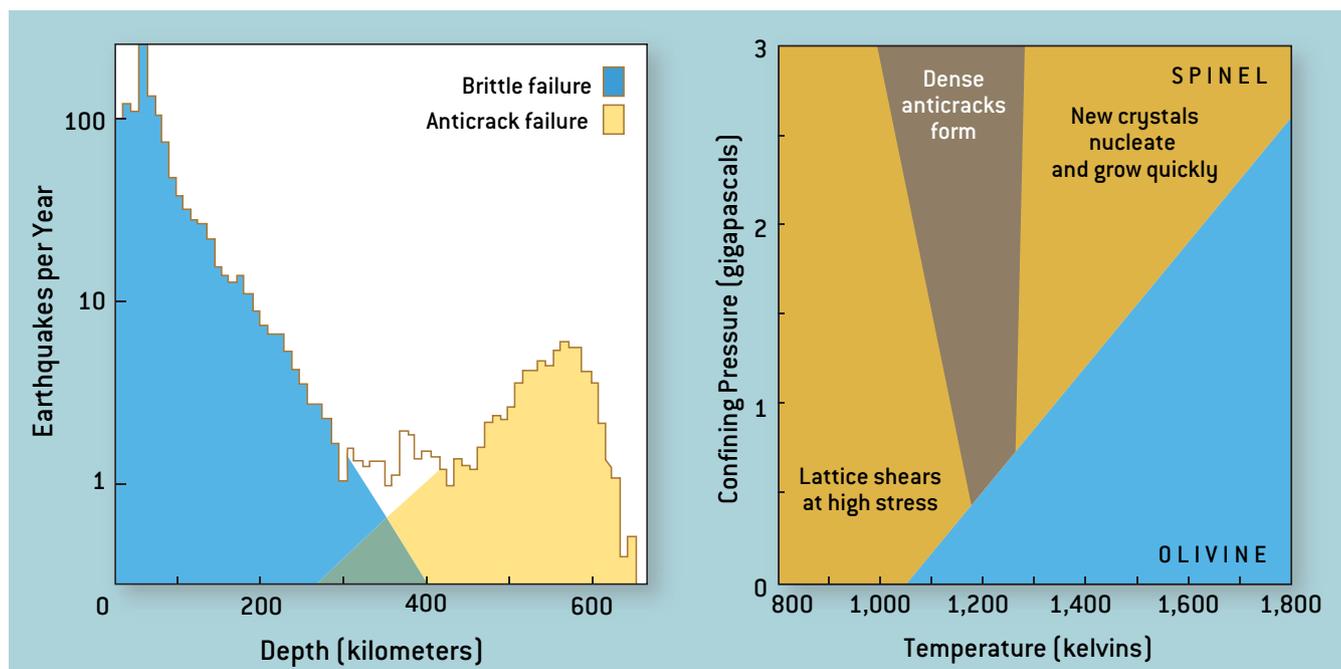
Although we had yet to witness this predicted instability, Burnley and I reasoned that if such an instability existed, it had to involve the nucleation and growth mechanism. Furthermore, the instability had to appear only in the narrow temperature interval between the two ranges tested during our earlier work. So, we deformed specimens under conditions for which nucleation of the spinel phase is just possible on the timescale 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. In the early stages of 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 were oriented perpendicular to the maximum compressive stress; 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.

## Forming a Theory

FROM THESE THREE characteristics, we formulated a theory of transformation-induced faulting that is analogous

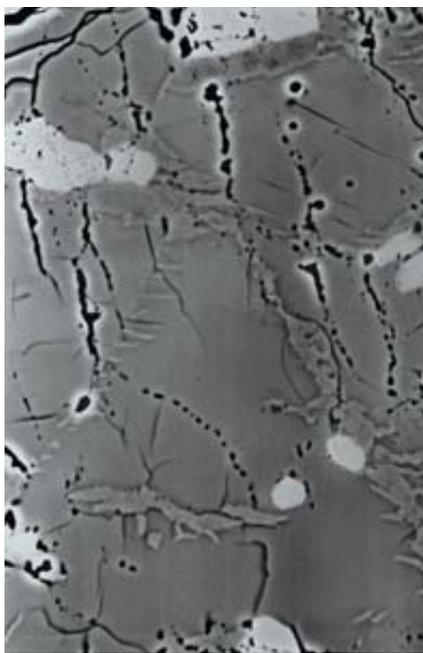


FREQUENCY of earthquakes corresponds closely to the depths at which olivine undergoes phase transformations (left). A minimum number of events occur at roughly 400 kilometers, the depth at which olivine transforms into a denser spinel (or cubic) phase. No earthquakes occur below a depth of 700 kilometers, which is where spinel decomposes.

Pressure and temperature govern these reactions (right). In germanate olivine that is subject to 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.”

LAURIE GRACE

to brittle shear fracture but 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. 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.



**MICROSCOPIC LENSES** of dense spinel phase (light gray) in olivine weakened germanate olivine specimens. These “anticracks” weaken olivine and lead to failure. The rocks were deformed at temperatures at which spinel crystals nucleate sluggishly. At lower temperatures, high stress can induce a shearing transformation from olivine to the spinel phase. Likewise, at higher temperatures, spinel crystals nucleate easily and quickly.

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 the maximum compressive stress. The spinel phase is denser 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. But since the displacement of their boundaries is reversed, concentrations of compressive stresses develop at their tips rather than tensile stresses. It is the tensile stresses at the tips of opening cracks in brittle materials that cause them to orient themselves parallel to the maximum compressive stress; similarly, the compressive stresses at the tips of the lenses in our specimens cause them to orient themselves perpendicular to the maximum compressive stress.

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 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 specimens 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 fault zones, 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 ex-

hibit 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 dilatant movements occur (as in the granular flow of sand), so pressure has little inhibitory effect. Thus, we postulated that the fine-grained spinel within the anticracks is much weaker than the host olivine and has this “superplastic” flow capacity.

From these observations we formulated the following hypothesis: during loading, under conditions for which the spinel phase grows with difficulty, olivine transforms to spinel primarily as new crystals that form by repeated nucleation adjacent to one another at concentrations of stress. In a nonhydrostatic stress field, the developing packets of spinel tend to grow perpendicular to maximum compressive stress. This preference leads to their lens-shaped morphology and general orientation. These Mode I microanticracks initially develop randomly 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 an-

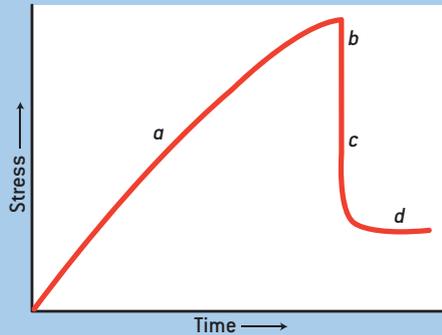
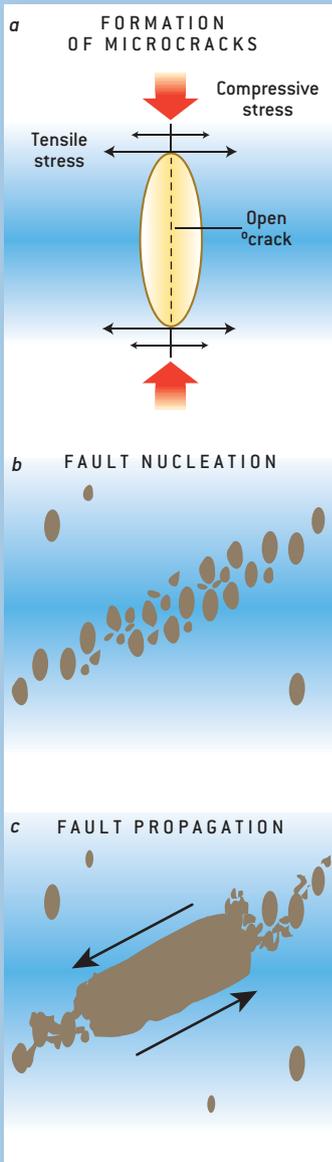
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HARRY W. GREEN II

# BRITTLE VERSUS ANTICRACK FAILURE

## BRITTLE FAILURE



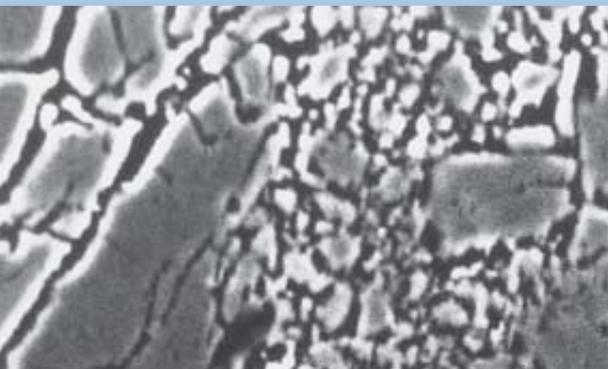
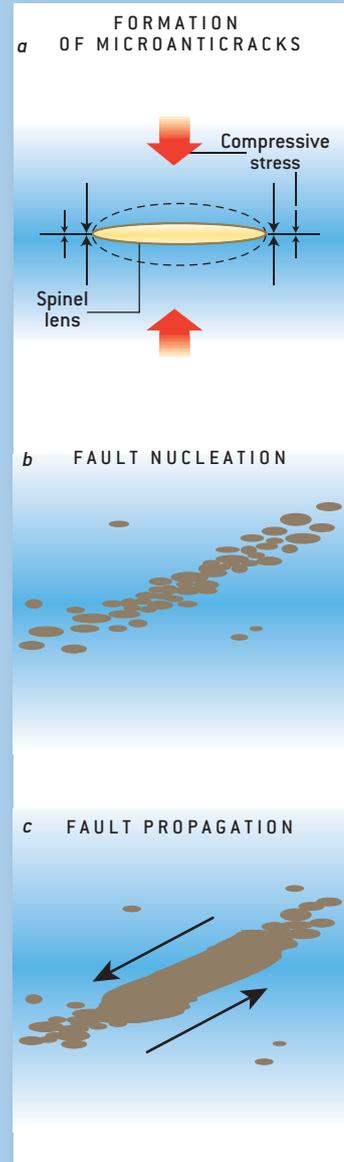
Brittle failure and anticrack failure, the mechanisms that account for shallow and deep earthquakes, respectively, share many characteristics. Both processes involve the development of microscopic features (a) that cooperatively form a fault and allow for movement on it.

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 containing broken rock fragments. 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).

## ANTICRACK FAILURE



IAN WORPOLE; HARRY W. GREEN II (bottom, left and right)

ticracks accelerates. Preexisting micro-anticracks 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, and so forth, leading to catastrophic failure.

## Putting Theory to the Test

BURNLEY AND I published the essence of this model in *Nature* magazine 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 a result of 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.

Therefore, I established a collaboration with Christopher H. Scholz of the Lamont-Doherty Earth Observatory of Columbia University, who investigates brittle fracture. 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 (now deceased) 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.

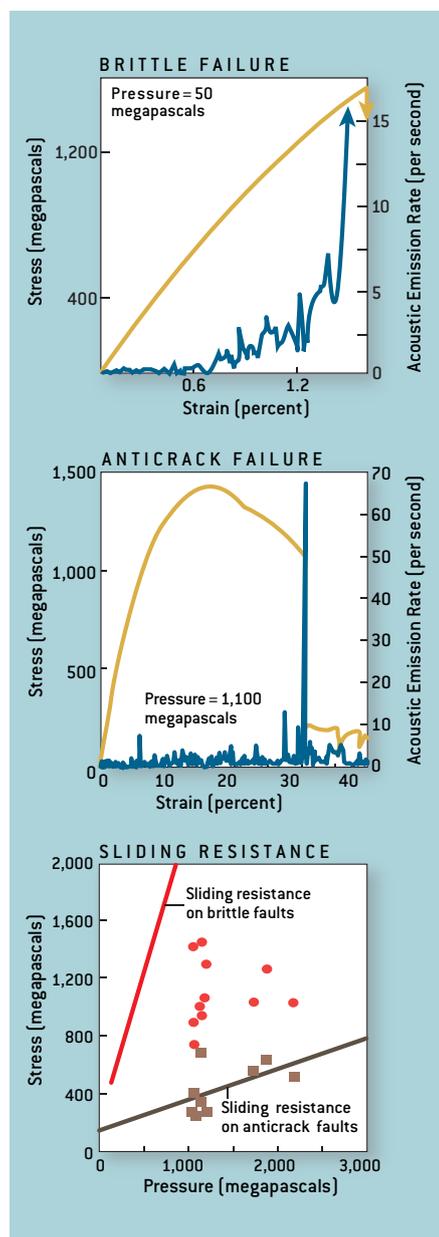
Tingle and I investigated the flow strength of  $Mg_2GeO_4$  spinel when the

crystals are comparable in size to the olivine crystals of the starting material. We then compared that strength with 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 of these experiments on germanate olivine, not the silicate olivine found in the mantle. Of course, as mentioned above, none of this work could have been done on silicate olivine; at that time it was impossible to measure stresses at the high pressures needed to reach the spinel stability field in the silicate system.

David Walker, also at Lamont-Doherty, then suggested that we attempt crude deformation experiments on mantle olivine in his multianvil apparatus, a machine that can attain the requisite pressures. Such a device had never before been used for deforming mineral specimens, but we decided to give it a try. 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 faulting would develop in the silicate. The approach worked beyond our wildest dreams; after only four trials, we produced faulting and characteristic anticrack microstructures at a pressure of 14 gigapascals.

Despite the attractive properties of the anticrack faulting mechanism, it can operate only if olivine is carried deep into the upper mantle, where the spinel crystal structure is stable. In particular,



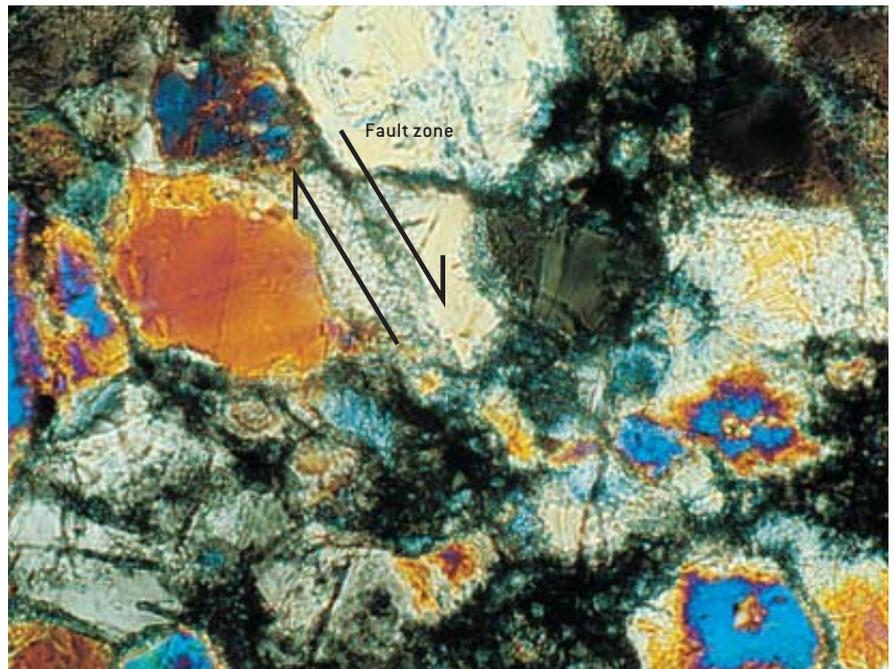
ACOUSTIC EMISSIONS (blue) occur when a fault suddenly slips, radiating energy that relieves stress (yellow). Brittle failure, the mechanism responsible for shallow earthquakes, emits noise before and during movement on a fault (top). In contrast, anticrack failure, the mechanism behind deep earthquakes, 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 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 experiments have neatly provided the explanation for intermediate-focus earthquakes.

Barry Raleigh, now at the University of Hawaii at Manoa, and Mervyn Paterson of the Australian National University in Canberra demonstrated in the 1960s that when the hydrous mineral serpentine breaks down to olivine plus water under stress at somewhat elevated pressure, it enables brittle shear failure under conditions where the rock otherwise would flow. 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. Little additional experimental work was produced on this system for the following 40 years until Haemyeong Jung, Larissa Dobrzhinetskaya and I showed in 2004 that this faulting mechanism is viable to at least six gigapascals of pressure, despite the fact that the volume change during serpentine dehydration changes from expansion to contraction.

We know from a variety of geophysical and geological 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 minerals 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 this 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



**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.

why earthquakes extend to great depth. But can this mechanism also explain why they suddenly stop? As mentioned above, 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, in 1996 Yi Zhou and I published a set of experiments on  $\text{CdTiO}_3$ , 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; we observed neither anticracks nor faulting. If olivine should be carried all the way to 700 kilometers or more, however, its direct breakdown in the lower mantle would be exothermic. Therefore, Gayle Gleason (now at the State University of New York

College at Cortland) and I performed a series of experiments on the mineral jadeite ( $\text{NaAlSi}_3\text{O}_8$ ) that breaks down to two dense phases in a strongly exothermic reaction. Once again, no faulting was produced. These two sets of experiments demonstrated that anticrack faulting requires both an exothermic reaction and a single product phase. Thus, earthquakes triggered by this mechanism are not possible in the lower mantle.

In summary, the depth distribution of earthquakes and the experimental results lead naturally to the following model. Normal brittle fracture and frictional sliding accounts for shallow earthquakes. Because pressure inhibits this mechanism, earthquakes in most parts of the world cease by 20 to 30 kilometers below Earth's surface. In subduction zones, however, partially hydrated oceanic crust and mantle sink downward and become slowly heated. The water-bearing minerals begin to dehydrate and, in the process, make fluid-assisted faulting possible. The exponential decrease in earthquake frequency down to 300 kilometers reflects the progressive heating and dewatering of the subducting slab.

The interior of the slab remains suf-

ficiently 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 deep. At the margins of this cold interior region, the temperature slowly increases. The metastable olivine heats to the critical temperature at which anticrack faulting occurs. In the coldest subduction zones, the wedge of metastable olivine extends down about 700 kilometers, generating earthquakes all the way. Earthquakes, however, stop there whether or not the slab enters the lower mantle; olivine decomposition into the two very dense phases of the lower mantle would be silent.

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 to produce the denser polymorphs. In 1992 Takashi Iidaka and Deisuke Suetsugu of the University of Tokyo modeled both possibilities for the descending slab beneath Japan and found the telltale slow velocity of the metastable olivine wedge. This result has remained controversial, but recent results by Wang-Ping Chen and Michael Brudzinski of the University of Illinois have shown that a peculiar extended subhorizontal group of deep earthquakes west of the Tonga subduction zone in the southwest Pacific Ocean occur in rocks whose seismic velocity is much too slow to be normal for rocks at that depth; they conclude that the only interpretation consistent with all the observations is that these earthquakes are occurring in a fossil subducted slab that is floating at 400 to 600 kilometers, its buoyancy and earthquake activity caused by extensive retention of metastable olivine.

If, as we propose, a critical temperature controls the anticrack faulting instability, the faulting in descending slabs 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 seismolo-

gists, one led by Douglas Wiens of Washington University and the other by Iidaka, discovered such double zones in 1994. Iidaka's team found the double zone in the slab in which they previously reported a metastable olivine wedge.

Additional indirect seismic evidence of the mechanism of deep earthquakes comes from remotely triggered deep earthquakes, also beneath Fiji, reported in 2003 by Rigobert Tibi of Washington University, Wiens and Hiroshi Inoue of the National Research Institute for Earth Science and Disaster Prevention in Japan. They showed that the seismic waves from a large earthquake, magnitude 7.6, triggered two other earthquakes (one of magnitude 7.7) in an area 300 kilometers away and 60 kilometers deeper within seven minutes of the first earthquake in a region of no previous recorded earthquake activity. By the time the earthquake waves of the first large earthquake had traveled 300 kilometers, the stresses and strains associated with those waves would have become very small, yet they were sufficient to set the earthquake process in motion at that great distance—implying that the regions where the triggered earthquakes occurred were ripe for failure and needed only the smallest of assistance to be set off; but even so, a few minutes were needed for local organization of the process. These same authors then showed equally compelling evidence that another pair of large earthquakes in 1986, separated in time by 26 minutes and in distance by hundreds of kilometers, must also have been a triggering/triggered pair.

In a discussion of this paper, I point-

ed out that of the three mechanisms previously proposed to explain deep earthquakes (dehydration embrittlement, transformation-induced faulting and runaway shear heating), the first two are known from experiments to be potentially activated within a few minutes and hence cannot be ruled out by these observations. Even under optimal conditions, however, runaway shear heating would require a minimum of several years and more probably thousands of years to develop, making it highly unlikely that two locations in a region never before found to generate earthquakes would have just happened to be on the verge of failure.

In conclusion, the laboratory results explain how earthquakes can be initiated at very high pressures. The composite model advanced here, in which intermediate-depth earthquakes are triggered by fluid-assisted faulting and deep events by anticrack faulting, is highly consistent with our current understanding of subduction zones. But any earthquake could develop a component of shear heating during its propagation, thereby perhaps contributing significantly to the very large, very deep earthquakes, as suggested by Hiroo Kanamori, Don Anderson and Thomas Heaton of the California Institute of Technology for the great Bolivian earthquake of 1994. Modern seismological techniques are now illuminating this problem by providing methods to detect the presence of metastable olivine or other mineralogical anomalies that may be involved in generation of deep earthquakes. Thus, questions remain, but the paradox behind deep earthquakes has been resolved. SA

#### MORE TO EXPLORE

**A New Self-Organizing Mechanism for Deep-Focus Earthquakes.** Harry W. Green II and Pamela C. Burnley in *Nature*, Vol. 341, pages 733–737; October 26, 1989.

**Anticrack-Associated Faulting at Very High Pressure in Natural Olivine.** Harry W. Green II, Thomas E. Young, David Walker and Christopher H. Scholz in *Nature*, Vol. 348, pages 720–722; December 20–27, 1990.

**The Mechanics of Deep Earthquakes.** Harry W. Green II and Heidi Houston in *Annual Reviews of Earth and Planetary Sciences*, Vol. 23, pages 169–213; 1995.

**Evidence for a Large-Scale Remnant of Subducted Lithosphere Beneath Fiji.** Wang-Ping Chen and Michael R. Brudzinski in *Science*, Vol. 292, pages 2475–2479; June 29, 2001.

**Instability of Deformation.** Harry W. Green II and Chris Marone in *Plastic Deformation of Minerals and Rocks*. Edited by Hans-Rudolph Wenk and Shun-Ichiro Karato. *Reviews in Mineralogy and Geochemistry*, Vol. 51, 2002.