# 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 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-

HARRY W. GREEN II is a professor at the University of California, Riverside, where he directs the Institute of Geophysics and Planetary Physics. In 1968 he received a Ph.D. in geology and geophysics from the University of California, Los Angeles. Currently he investigates the rheology of geologic materials and how stress affects polymorphic phase transformations. He is a fellow of the Mineralogical Society of America and a member of many other professional organizations. He has published more than 70 papers and offers counsel to the National Science Foundation, the Department of Energy and other such agencies.