Deep Earthquakes

They have posed a fruitful puzzle since their discovery 60 years ago. How can rock fail at the temperatures and pressures that prevail hundreds of kilometers down?

by Cliff Frohlich

In most earthquakes the earth's crust cracks like porcelain. Stress builds up until a fracture forms at a depth of a few kilometers and slip relieves the stress. Some earthquakes, however, take place where the earth cannot fracture. They occur hundreds of kilometers down in the earth's mantle, where high pressure is thought to prevent rock from cracking even at stresses high enough to deform it like putty. How can there be earthquakes at such depths?

These mysterious deep events are common enough. Since 1964 the International Seismological Centre (ISC) in London has catalogued more than 60,000 earthquakes at depths greater than 70 kilometers—22 percent of all the earthquakes located during the period. A few of them have even been destructive. Although almost all catastrophic earthquakes are shallow, occurring at a depth of 50 kilometers or less, a tremor centered at a depth of 100 kilometers devastated Bucharest, Romania, on March 4, 1977.

For the most part, however, deep events have had their greatest impact in geophysics. Their geographic pattern provided evidence for the great unifying theory of modern geophysics, plate tectonics. They have also proved to be good energy sources for seismic studies of the earth's deep interior, which attempt to decipher structure from the behavior of earthquake waves traveling through the earth. Now deep earthquakes themselves may be yielding their secrets. Seismological observations together with laboratory studies of rock behavior at high pressures have led to plausible accounts of how they may occur.

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The depths of all earthquakes had been controversial in the decades before 1927, when the Japanese seismologist Kiyoo Wadati convincingly demonstrated the existence of deep events. Noting that in some cases intense shaking is confined to a small area, certain workers had argued that earthquake sources must lie within a few kilometers of the surface. Other workers arrived at much greater focal depths, down to 1,200 kilometers, when they tried to determine earthquake directions from the deflections their waves produced on the simple seismographs of the day.

The controversy sharpened as more was learned about seismic waves and how they travel. Investigators studying seismograms learned to recognize several kinds of body waves (earthquake waves that travel through the earth, in contrast to surface waves, which follow the surface). First to arrive are *P* waves, or primary waves. Also called compressional waves, they are waves of sound in the earth, propagating as alternating zones of high and low pressure. They are followed by *S* waves—secondary or shear waves—which propagate through the earth as a side-to-side shaking. Comparisons of times at which *P* and *S* waves from a given earthquake arrived at different stations showed that their travel time depends on both distance and the internal structure of the earth.

Given a model of the earth's structure and a set of arrival times recorded at a variety of locations, then, one could in theory determine the location of the event itself. In 1922 H. H. Turner, who directed the clearinghouse of seismological data that later became the ISC, applied this method in a stimulating and controversial paper. Based on an analysis of data from stations around the world, Turner proposed that earthquakes occur in three depth ranges. "High focus" events have sources near the surface, but normal earthquakes, the most plentiful kind, take place roughly 150 kilometers down. "Deep focus" events have focuses at depths of as much as 650 kilometers.

Turner's approach was sound, but his data were sketchy by modern standards, existing knowledge of the earth's deep structure was incomplete and the inaccurate clocks of the day made the timing of wave arrivals inaccurate by seconds or even minutes. Turner's argument convinced few of his contemporaries. S. K. Banerji of the Bombay Observatory pointed out that if the bulk of earthquakes have focuses at a depth of 150 kilometers or more, few events should produce strong surface waves, and yet Turner's own catalogue reported surface waves in abundance. Harold Jeffreys of the University of Cambridge put forward a more fundamental objection: he argued that earthquakes simply could not take place at such depths.

Below a depth of about 50 kilometers, Jeffreys contended, heat and pressure change the mantle rock from a brittle material, capable of fracturing, to a ductile one. In support of his argument Jeffreys pointed out that since the end of the most recent ice age, coastlines in Canada and northern Europe, relieved of the glaciers' weight, have risen as if the underlying mantle was capable of flowing under stress, like an extremely viscous liquid. He also cited laboratory work confirming that at high temperatures and pressures rock deforms gradually in response to stress instead of fracturing suddenly.

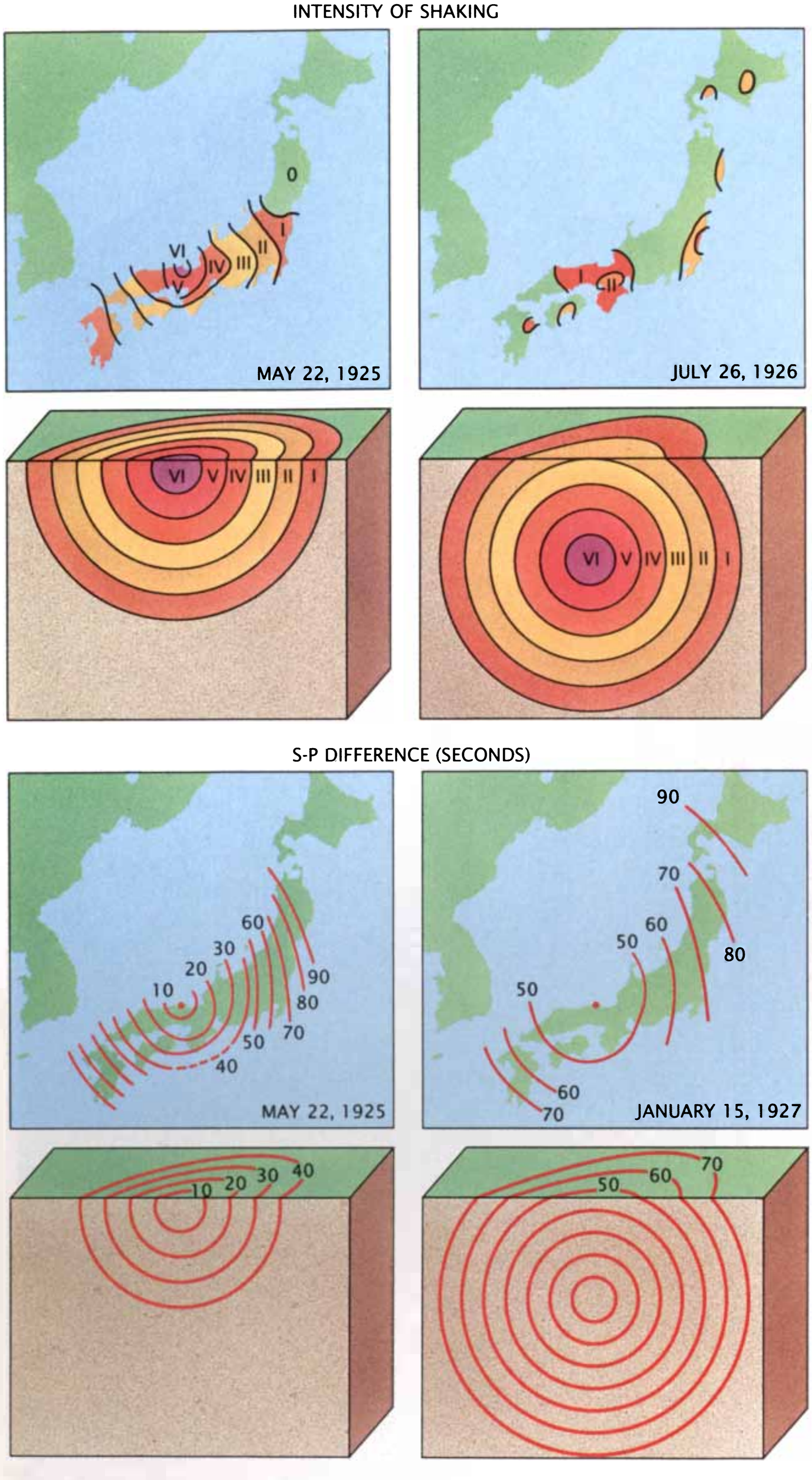
Kiyoo Wadati, a 25-year-old employee of the Japan Meteorological Agency, did not refute Jeffrey's argument; he simply presented convincing evidence that some earthquakes are very deep. The frequency and destructiveness of earthquakes in Japan had led the Japanese government to establish what was then the world's best network of seismographic stations. Hence Wadati had abundant data, and he applied new methods of determining earthquake depths. Instead of comparing absolute arrival times at different seismographic stations, as Turner had done, he relied on a time difference that could easily be measured at individual stations even if clocks were inaccurate: the interval between the arrival of *P* waves and the arrival of the slower *S* waves. Because each kind of wave travels at a fairly constant speed, the interval increases in proportion to the station's distance from the earthquake focus.

For most earthquakes, Wadati discovered, the interval was quite small near the epicenter, the point of strongest shaking. For a few events, however, the delay was long even at the epicenter. Wadati saw a similar pattern when he analyzed data on the intensity of shaking. Most earthquakes had a small area of intense shaking, which weakened rapidly with increasing distance from the epicenter, but others were characterized by a lower peak intensity, felt over a broader area. Both the *P-S* intervals and the intensity patterns suggested two kinds of earthquakes: shallow events, in which the focus lay just under the epicenter, and deep events, with a focus several hundred kilometers down.

Other workers applied Wadati's techniques to data from earthquakes in other geographic areas and confirmed his results: "normal" earthquakes had a focal depth of 50 kilometers or less, and yet a few events had much deeper origins—as deep as 600 kilometers or more. Turner had been wrong about the depth of normal earthquakes, but deep events did exist. Banerji too had been right: the seismograms of confirmed deep events showed that they produced only weak surface waves.

What of Jeffreys' assertion that mantle rock at a depth of more than 50 kilometers is too ductile to store the stress needed for an earthquake? An observation Wadati made foreshadowed part of the answer: deep earthquakes do not take place in ordinary mantle rock. In 1935 Wadati published a map showing the sites of earthquakes near Japan and their focal depths. He had

DESTRUCTIVE DEEP EARTHQUAKE is a rare event. The only severe one in recent decades took place on March 4, 1977, 150 kilometers under Bucharest. Columns on the ground floor of this building failed, allowing the corner to slump by one floor. Similar destruction throughout the city killed 1,500 people. The photograph was made by Neculai Mandrescu of the Institute for Physics of the Earth in Bucharest.



SURFACE MANIFESTATIONS distinguish shallow and deep events. The maps compare data on the intensity of shaking and the delay between the arrival of *P* (compressional) and *S* (shear) waves for several earthquakes between 1925 and 1927. The data were collected by the Japanese seismologist Kiyoo Wadati. Shaking was very intense near the epicenter of a 1925 event but fell off rapidly with distance (*top left*); a 1926 earthquake produced less intense shaking that fell off more slowly (*top right*). The *S-P* difference at the epicenter of the first event was less than 10 seconds, but the delay increased rapidly with distance (*bottom left*); the minimum *S-P* difference for a 1927 event was longer—about 40 seconds—but it increased more slowly (*bottom right*). From the data Wadati concluded that the 1925 earthquake had a focus near the surface and the later events had focuses some 400 kilometers down (*cutaway views*).

found that the focuses lay along approximately parallel contour lines, and that the depths of the contours increased steadily from the east coast of Japan westward. He commented: "The possibility of drawing contour lines of the focal depth suggests that there exists in the crust something like a *weak surface*... where the earthquake outburst is liable to occur. This surface extends slopewise in the crust near the Japanese Islands."

Earthquake depths in other parts of the world, Wadati continued, define similar sloping surfaces: "Deep-focus earthquakes are apt to take place on one side nearer to the continent and shallow-focus ones on the other side, [which] is in most cases bordered [by] a very deep sea. This tendency seems to be observable in many volcanic regions in the world."

Almost all deep earthquakes conform to the pattern Wadati described. Wherever they are common—generally at the edge of a deep ocean—they define an inclined zone extending from near the surface to a depth of 600 kilometers or more. Now known as Wadati-Benioff zones, after Wadati and the seismologist Hugo Benioff, who mapped such zones in the 1940's and 1950's, the earthquake patterns provided crucial evidence for the new geophysical paradigm that emerged in the 1960's.

This new view of the earth accounts for many of the earth's major surface features and much of geologic history in terms of a set of moving plates covering the earth's surface. The plates spread apart from mid-ocean ridges; where they collide, generally at the edge of ocean basins, they thrust up mountains and sculpt the margins of continents. This process of plate tectonics is the surface expression of convection, or heat-driven circulation, in the earth's mantle. Hot material rises from within the mantle and circulates horizontally near the earth's surface. The top 50 kilometers or so of the horizontal flow cools to form the rigid plates, which include the earth's crust and some of the underlying mantle.

The cold, downgoing limb of the circulation is found where plates converge. There one plate is subducted: it bends under the other plate and sinks back into the mantle. Deep earthquakes helped to establish the reality of subduction when it was realized that they take place in a descending slab and that the Wadati-Benioff zone traces its shape. The deep trench that is generally found just seaward of the Wadati-Benioff zone—the "deep sea" of Wadati's description—marks the downward bend of the subducted plate; the line of volcanoes that often forms nearby is fed by molten material rising from the slab. Wadati had been prescient: in his 1935 paper he had speculated that the earthquakes and volcanoes near Japan might be the result of continental drift (a forerunner of plate tectonics), which had been proposed some 20 years earlier by Alfred Wegener.

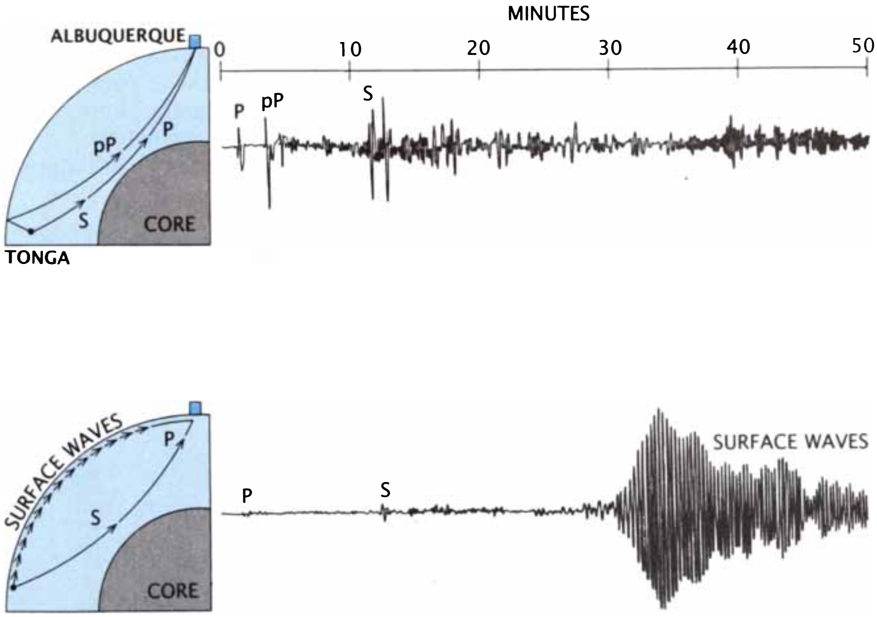
That geophysical scheme supplies part of the answer to Jeffreys' objection. The deep earthquakes in a Wadati-Benioff zone take place in rock that is hundreds of degrees colder than the surrounding mantle and hence is less ductile and better able to store elastic energy. Yet other factors also seem to affect the distribution of deep earthquakes. Their focuses, for example, are not scattered evenly along the Wadati-Benioff zone. Instead changes in earthquake frequency seem to coincide with depths where the crystal structure of mantle rocks changes to a denser phase as a result of increasing pressure.

At about 400 kilometers, for example, seismographic studies show a sudden increase in seismic-wave velocity, indicating an increase in rock density. There olivine—a silicate compound with various admixtures of iron and magnesium that is the main constituent of the mantle and the subducted plate—changes to a denser crystal phase known as spinel. At about this depth the number of deep earthquakes falls to a minimum.

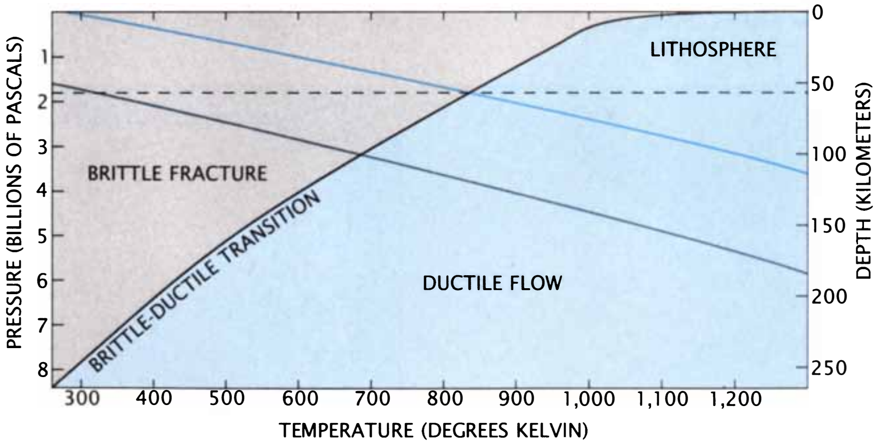
Some subduction zones stay quiet below this first transition. Zones that do have earthquakes at these depths, however, show their highest level of activity from below the transition down to another, more mysterious boundary at a depth of about 650 kilometers. Again a sharp increase in seismic-wave velocity marks the boundary, but workers disagree about whether the increase in density it indicates represents a second phase change or a change in composition. In any event earthquake activity drops abruptly to zero near this second boundary.

In an effort to determine the maximum depth of deep events Philip B. Stark, then at the University of Texas at Austin, and I applied several means of analysis. Among other things, we examined the intervals between ordinary *P* waves and *pP* waves (pressure waves that travel upward to the surface and are reflected back through the earth to a distant seismographic station). We found that the deepest recorded events took place at a depth of between 680 and 690 kilometers. Beth A. Rees and Emile A. Okal of Northwestern University did a similar analysis, with comparable results.

The cutoff of earthquake activity is too abrupt to result from a gradual softening of the slab as it is heated by the surrounding mantle. It may mean that subducted slabs cannot penetrate the 650-kilometer boundary. In that case convection may be confined to



SEISMOGRAMS of deep and shallow earthquakes in Tonga were recorded in Albuquerque, N.Mex., nearly a fourth of the way around the world. The deep event (*top*) produced strong *P* and *S* waves, which passed through the earth at different speeds. Some of the *P* waves took the form of *pP* waves, having traveled upward from the focus to the earth's surface and then been reflected back through the earth. Because of its depth—about 625 kilometers—the event produced only a few surface waves. Both the *P* and the *S* waves from the shallow event (*bottom*) were relatively feeble; most of the energy was observed as surface waves, the last form of signal to arrive.

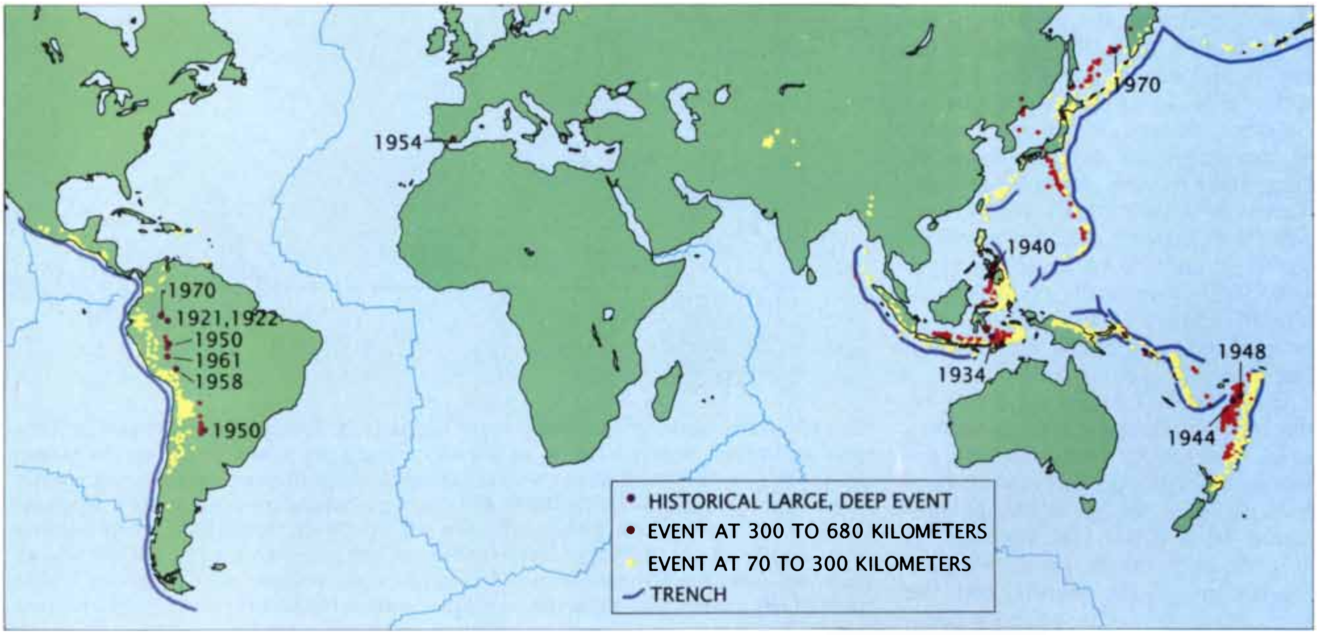


PUZZLE OF DEEP EARTHQUAKES is shown in a chart of the conditions of pressure and temperature under which rock changes from a brittle substance that can fracture when it is stressed, causing an earthquake, to a ductile medium that responds to stress by deforming gradually. Pressure and temperature increase with depth, so that rock ordinarily becomes ductile at a depth of about 60 kilometers (*blue curve*). Rock in deep-earthquake zones is anomalously cool, but even if it is 500 degrees cooler than "normal" mantle, the rock should still be ductile by about 100 kilometers (*gray curve*). Yet deep earthquakes have been recorded at nearly 700 kilometers.

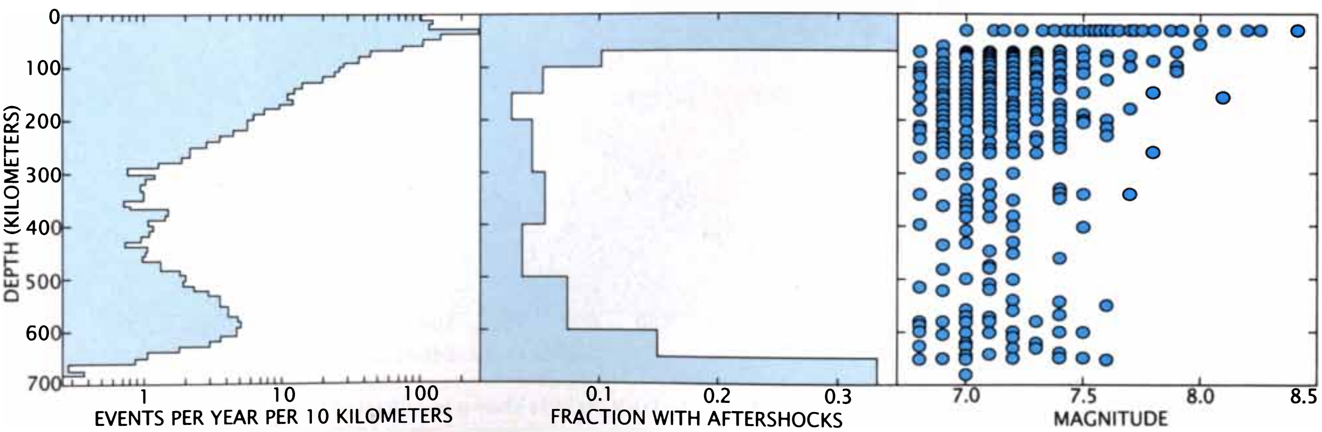
the upper mantle, above the boundary, and material from the upper and lower mantle may never mix. The change in seismic-wave velocity at 650 kilometers would then be likely to mark a change in the composition of the mantle. Alternatively (and this is one of the most hotly debated controversies in solid-earth geophysics), the subducted slab may penetrate the lower mantle. Convection would then involve the entire mantle, and the 650-kilometer boundary would mark a phase change in a compositionally uniform medium. A concomitant change in the rock's mechanical properties would be responsible for the cutoff of earthquake activity.

The descent of a subducted plate provides several possible sources of the stress released in deep earthquakes. A descending plate is variously bent, stretched and compressed; heating and phase changes could also generate stresses by changing rock volume. How is such stress released? What actually happens at the focus of a deep earthquake?

Deep earthquakes can be as large as all but the very largest shallow earthquakes; the most destructive deep earthquake of recent years, the 1977 Romanian event, had a magnitude of 7.2, and an earthquake with a magnitude of 7.6 took place 650 kilometers under Colombia in 1970. And yet the mechanism by which the energy is released must differ from the brittle fracture that triggers shallow earthquakes. Even though the material in which deep earthquakes occur is much cooler—hence stronger—than Jeffreys had thought, it still should not fracture as rocks do at low pres-



MAP SHOWS DEEP EVENTS recorded over the past 25 years, distinguished by depth; it also shows historical very large earthquakes (those that have a magnitude of more than 7) at extreme depths (more than 630 kilometers) and gives their year. Nearly all deep earthquakes occur near a deep-sea trench, where one of the rigid plates of lithosphere—the crust and uppermost mantle—that make up the surface of the earth is being drawn into the mantle through the process of subduction.



EARTHQUAKE STATISTICS change with depth. The number of earthquakes with a magnitude of 5 or more in each 10-kilometer interval of depth (*left*) reaches a minimum at about 400 kilometers but then increases again before abruptly falling to zero at about 650 kilometers. Aftershocks are rare for most deep events of moderate size but become commoner at the greatest depths (*middle*). The strongest earthquakes are generally recorded at shallow depths, but at greater depths the size of the largest events remains quite constant until seismic activity stops altogether (*right*). The data suggest that changes in the crystal phase of mantle rocks, thought to occur at depths of 400 and 650 kilometers, may affect deep earthquakes.

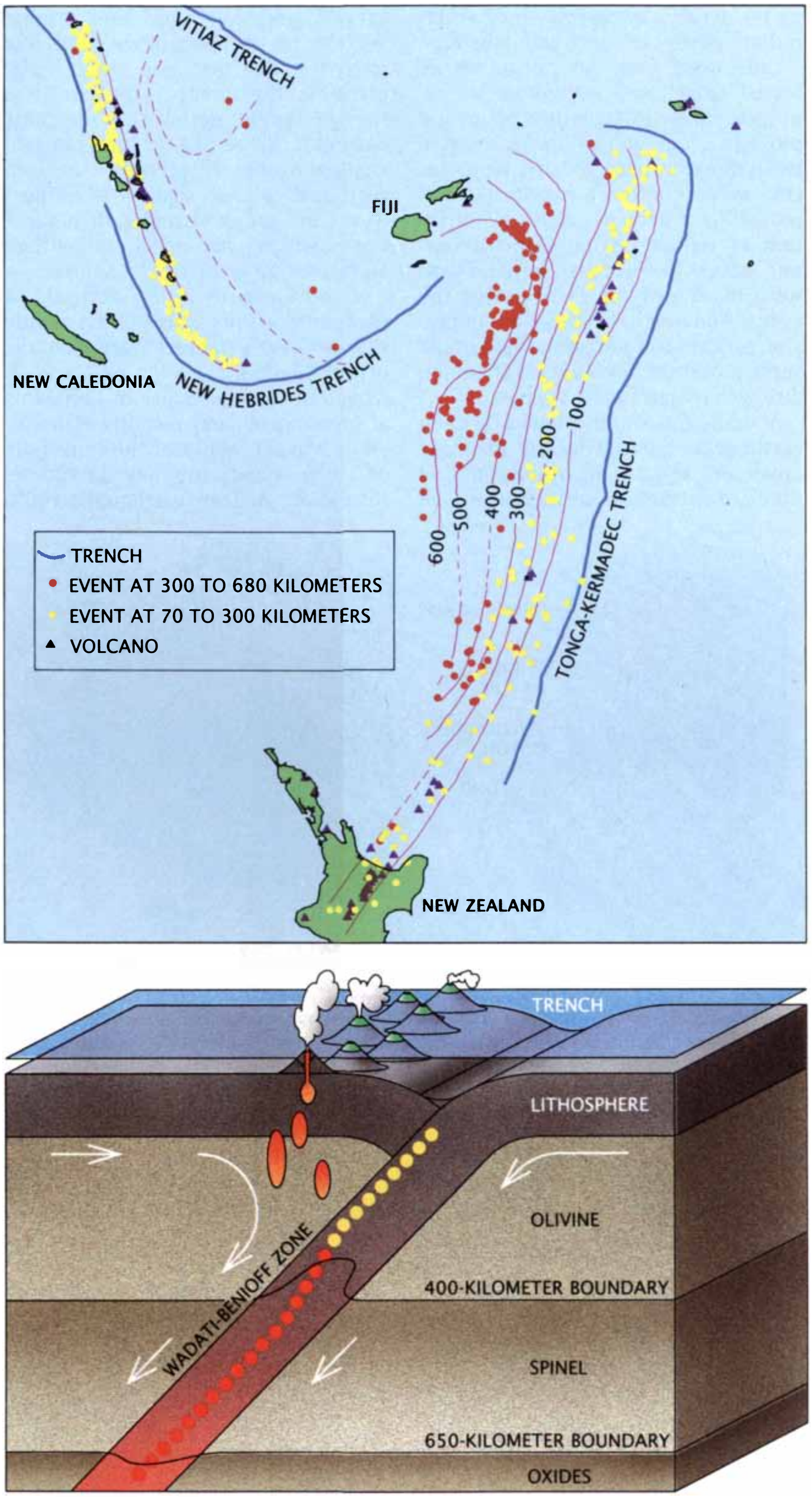
sures. If stress were to open a crack in the slab, the weight of all the rock above it would simply close it again. If the rock deforms at all, it should deform plastically. Jeffreys' objection still holds: conventional earthquakes, in which rock fractures and slips, should not happen in the mantle.

Recent seismographic studies of deep earthquakes support the case against a conventional mechanism. Nearly all large shallow events are accompanied by many smaller tremors known as aftershocks. Aftershocks often occur along the same plane as the initial slip, apparently releasing residual stress along the fracture. Aftershocks are much rarer for deep events. The 1970 deep earthquake under Colombia, which was probably the largest really deep event of the past 25 years, had no aftershocks whatever. Deep earthquakes that do have aftershocks—and they are commonest among the deepest events—generally have only one or a few at most.

The aftershocks that do occur define a spatial pattern quite different from those of shallow earthquakes. Recently Raymond J. Willemann, then at the Los Alamos National Laboratory, and I studied the spatial relations between the initial shocks and the aftershocks of deep earthquakes. Small shallow earthquakes often have aftershocks centered relatively near the main event, which is consistent with the idea that the aftershocks represent continued slip along the same fracture that produced the main tremor. We found, however, that some small deep earthquakes—ones with a magnitude of 5.5 or less—have aftershocks at a distance of 30 kilometers or more from the initial shock. A rupture zone responsible for such a small earthquake is not likely to be 30 kilometers long.

Deep aftershocks, moreover, do not fall along a plane, as shallow ones often do. The existing data suggest, on the contrary, that they are more or less randomly distributed in three-dimensional space around the initial event. Again the pattern suggests that deep earthquakes and shallow ones have fundamentally different mechanisms.

One attractive but incorrect way of accounting for deep earthquakes was proposed almost as soon as they were discovered. It holds that they are the direct result of the transformation of subducted material to a denser phase. Such transformations must take place in the subducted rock, and if they happened fast enough—if the rock in effect imploded



SUBDUCTION ZONE is the setting for nearly all deep earthquakes. The focal depths of earthquakes along the Tonga-Kermadec Trench, a deep-sea trench in the southwestern Pacific bordered by seismic activity and volcanic islands, fall along a series of parallel contour lines of increasing depth—a pattern known as a Wadati-Benioff zone (*top*). The Wadati-Benioff zone traces the subduction of a lithospheric plate (*bottom*): the earthquakes take place within the descending slab. The downward bend of the subducting plate is responsible for the trench, and molten material rising from the plate feeds the line of volcanoes. The process is driven by the convective circulation of the mantle; the descending plate is the cold, downgoing limb of the circulation.

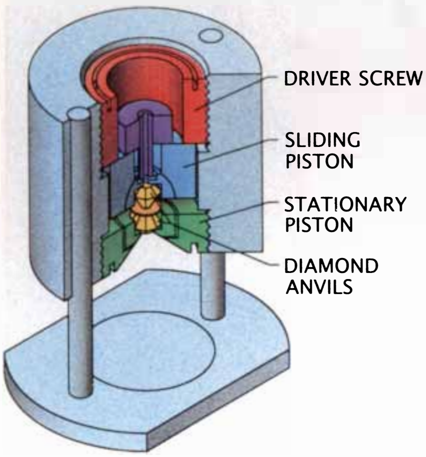
as its density increased—they could radiate energy as earthquake waves.

Unfortunately the seismic waves detected from deep earthquakes look nothing like the signature of an implosion. In an implosion nearby material moves inward, toward the focus. One would therefore expect all seismographs (which register the direction as well as the amplitude of seismic waves) to record an initial downward motion of the earth during the event. Moreover, because an implosion produces radial rather than transverse motion, it would generate much stronger *P* waves than *S* waves.

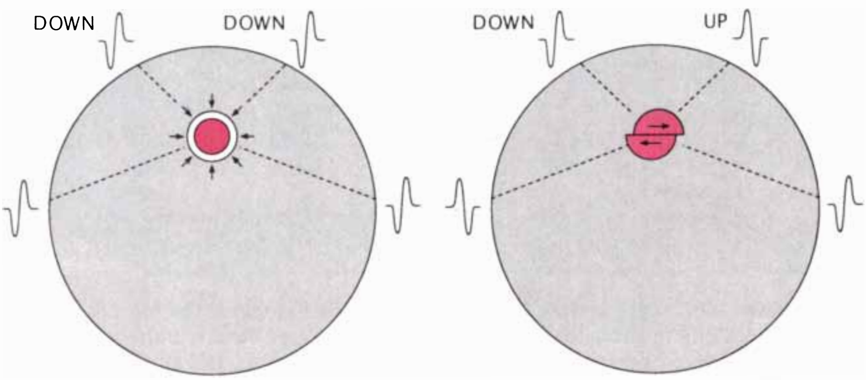
Actually the first motions of a deep earthquake are downward in some areas and upward in others, just as they are in shallow earthquakes. The upward and downward motions are segregated, as if part of the earth had moved in one direction along a slip plane and the other part had moved in the opposite direction; it is the same pattern observed in seismograms of shallow events. Furthermore, in deep earthquakes as in shallow ones the *S* waves are much stronger than the *P* waves, which points to slip rather than an implosion as being the source.

So how can rock slip abruptly, if the enormous pressures of the mantle rule out brittle fracture? One scenario, proposed in the 1960's by David T. Griggs of the University of California at Los Angeles and recently elaborated by Masaki Ogawa of the University of Tokyo, posits runaway ductile deformation. A deep earthquake could take place when rock deforming under shear stress begins to produce frictional heat faster than the surrounding rock can carry it away. The heat softens the rock and even melts some of it, accelerating the deformation. This feedback process could cause both the temperature and the slip rate to increase explosively and produce an earthquake.

The plausibility of the mechanism depends strongly on the composition and structure of the rock in a Wadati-Benioff zone. It is most strongly favored if rock structure—an existing weak layer, for example—tends to concentrate ductile slip along a plane. It is by no means certain that the layering in subducted material has the right orientation to foster slip in the directions most often observed in deep earthquakes.



PHASE CHANGES in mantle rock, which may have a role in deep earthquakes, can be simulated in a device called the diamond-anvil cell, which compresses rock samples between two diamonds (*left*). The diamonds' transparency allows the samples to be heated with a laser and photographed. In a sample of olivine (a primary mantle constituent) that has been compressed and heated to as much as 300,000 atmospheres and 1,500 degrees Celsius, distinct phases form concentric rings (*right*). A pale outer ring of unaltered olivine gives way to yellower spinel in a transition thought to occur at a depth of 400 kilometers; at the center, where pressure and temperature are highest, is the dark oxide phase into which spinel may change at 650 kilometers. The photograph was provided by William A. Bassett of Cornell University.

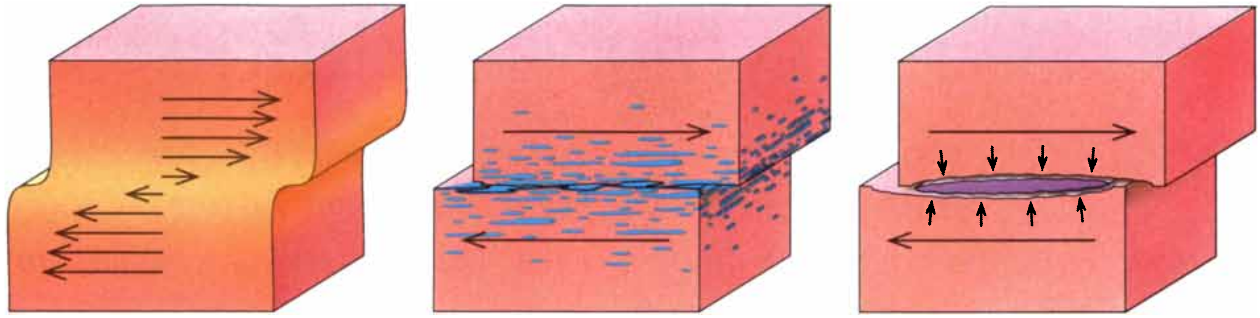


IMPLOSION due to the sudden transformation of subducted rock to a denser phase can be ruled out as a cause of deep earthquakes. An implosion should show itself on seismographs around the world as an initial downward motion (*left*). Instead deep earthquakes generate an initial upward motion at some points and a downward motion at other points (*right*), suggesting their source is lateral slip in deeply buried rock.

A different scenario attributes slip in deep-earthquake zones to the effect of trapped fluids. Laboratory work has shown that at pressures equivalent to shallower depths, fluids trapped in rock pores can counteract the forces binding a potential fracture, allowing it to fail at a lower shear stress than before. In at least one case, at the Rocky Mountain Arsenal near Denver, a sequence of shallow earthquakes occurred after fluid wastes were injected into the earth, apparently lowering confining stresses enough for rock layers to slip.

In 1966 C. B. Raleigh and Mervyn S. Paterson of the Australian National University suggested that pore fluids in deep-earthquake zones might have the same effect, allowing subducted material to fracture like rock at lower pressures. The source of the fluids, Raleigh and Paterson proposed, might be the dehydration of minerals such as serpentine (a form of magnesium silicate) in the subducted material: the release of water incorporated in their crystal structure as they are heated by the surrounding mantle to temperatures above 500 degrees Celsius. Raleigh and Paterson also proposed other sources of fluid: water trapped in sediments in deep-sea trenches and carried down with the crust, and partially molten mantle rock.

To affect the bulk properties of rock, such as its tendency to fracture, a fluid must be able to migrate through it, and it is not certain that mantle rock is porous enough. Moreover, the dehydration of minerals would be expected to occur at specific temperatures and pressures, corresponding to specific depths. If pore fluids do trigger deep earthquakes, those depths might



PROPOSED MECHANISMS OF SLIP acknowledge that at great depths the earth cannot simply fracture. In one scenario slow rock deformation accelerates abruptly as the frictional heat it creates builds up, softening the rock and speeding the deformation in a runaway process (*left*). A second mechanism attributes slip to the influence of fluids (*middle*). Below a certain depth high pressure might release water bound in the crystal structure of subducted minerals; the water might counteract forces binding potential faults and allow them to fail. A third proposal holds that shear stress could induce a phase change in a layer parallel to the stress (*right*). The sudden change in crystal structure would weaken the rock, allowing it to slip.

show intense concentrations of seismicity. Yet the frequency of earthquakes shows only a moderate variation with depth.

What variation there is (the falloff in earthquake activity at the 400-kilometer olivine-spinel boundary and its revival at greater depths) seems to bear some relation to the depths of phase changes. Stephen H. Kirby of the U.S. Geological Survey has proposed a deep-earthquake mechanism that depends on phase transitions but, in contrast to earlier proposals, results in slip rather than implosions. As a surrogate for actual mantle rock Kirby and his colleagues studied ice and tremolite, a calcium magnesium silicate, both of which change to a denser phase at pressures that can readily be produced in the laboratory.

When the workers compressed each material to a pressure slightly below that of the normal phase transition and subjected it to shear stress, they found that the phase transition was triggered along a thin layer parallel to the stress. The sudden rearrangement of crystal structure along the layer apparently weakened the material, allowing it to slip. Kirby and his colleagues noticed that in the process their samples emitted cracking or snapping noises—laboratory analogues of earthquakes.

Kirby proposes that such premature phase changes also take place in subducted rock as it is stressed, and that the resulting slip accounts for at least some earthquakes in Wadati-Benioff zones. The proposal would not conflict with the occurrence of deep earthquakes over a broad range of depths below the 400-kilometer boundary: several investigators, including William A. Bassett of Cornell University, have found that phase transitions in subducted material can occur at a variety of depths depending on its precise composition and the speed at which it is descending. Kirby's mechanism would, however, account for the abrupt disappearance of deep earthquakes at depths greater than 680 kilometers. At that depth all the known phase transitions in the mantle have already taken place.

No one has yet shown that shear stress has the same effect on phase transitions in actual mantle rock that it has on transitions in ice and tremolite. But even if Kirby's hypothesis is wrong, phase transitions may play some role in deep earthquakes. Perhaps they simply generate stresses that are abruptly released elsewhere, by some unknown failure mode.

It may soon be possible to choose among the various hypotheses with greater confidence. Raymond Jeanloz and Charles Meade of the University of California at Berkeley are re-creating mantle conditions in the laboratory in order to study proposed deep-earthquake mechanisms. A fist-size press called a diamond-anvil cell generates the needed pressures by squeezing a minute rock sample between the points of two diamonds. The sample can be heated by shining a laser through one diamond; phase transitions and other changes in the rock can be seen through the other diamond, while acoustic sensors detect any "earthquakes." The studies are still quite preliminary, but so far they suggest that at high pressures olivine fails only when it also contains serpentine—a result favoring Raleigh and Paterson's dehydration mechanism.

By respectively demonstrating the reality of deep earthquakes and their "impossibility," Wadati and Jeffreys posed a puzzle that geophysicists are still struggling to solve. (As it happens, both men are still alive more than 60 years later.) In the context of plate tectonics and mantle convection, which deep earthquakes themselves helped to establish, these events have led to new puzzles.

One concerns the earthquake cutoff at a depth of 680 kilometers: does it mark the lower limit of mantle convection or just a change in the mechanical properties of a mantle that is convecting throughout its depth? The occasional deep earthquakes that occur in regions lacking known subduction zones embody another puzzle. Deep earthquakes in Romania and the Hindu Kush, two such regions, may reflect the presence of an old subduction zone obscured by later tectonic activity. That explanation is less plausible for the tremors sometimes recorded under northern Africa and Spain. There the riddle of deep earthquakes is wrapped in a further mystery: the possibility that some deep earthquakes can occur in the complete absence of subduction.

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