Deep Earthquakes: A Fault Too Big?

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Because deep Earth processes are inaccessible to direct observation, ideas about them reflect inferences from seismology and other remote sensing, laboratory experiments, analogies to near-surface processes and materials, and personal views of how the Earth works. Geophysical arguments thus often follow Sherlock Holmes' approach: When you have eliminated the impossible, whatever remains, however improbable, must be the truth. Often, however, nature seems so complicated that when taken at face value, no possible explanation remains. Recent results for the mysterious deep earthquakes that occur to depths greater than 600 km, such as those reported in this issue by Silver *et al.* (*1*), come close to this situation. The problem is that large deep earthquakes (*1–3*) seem to have occurred on faults larger than expected from the competing models of the process causing deep earthquakes.

Deep earthquakes, which occur at depths below 325 km, have long been a subject of great geophysical interest (*4*). They occur in a tectonic setting very different from that of a vast majority of earthquakes, which occur at shallower depths (less than 50 km). Shallow earthquakes usually occur at the boundaries of plates and reflect relative motion between them. In contrast, deep and intermediate depth (50 to 325 km) earthquakes occur in the cold interiors of slabs of oceanic lithosphere subducting into the hotter mantle. Because seismicity as a function of depth reaches a minimum at about 350 km and then increases, deep earthquakes may result from physical processes different from those that cause both intermediate and shallow earthquakes.

Until last year, the fault dimensions for deep earthquakes were essentially unknown. Fault areas of shallow earthquakes are estimated from the positions of aftershocks on the fault surface and smaller subevents making up the main shock. For deep earthquakes, however, aftershocks are rare and seismological data could generally not resolve subevents. This situation changed when two large deep earthquakes were recorded on modern digital seismometers, including portable ones near the epicenters. A magnitude 7.6 earthquake 570 km beneath Tonga in March 1994 had an unusually large aftershock sequence, which defined a 50 km by 65 km fault zone (*3*). Only a few months later, the largest deep earthquake ever instrumentally recorded occurred in June, 630 km beneath Bolivia. Analyses of data for this magnitude 8.3 earthquake, such as the report of Silver *et al.* (*1, 2*), indicate a fault area 30 to 50 km on a side.

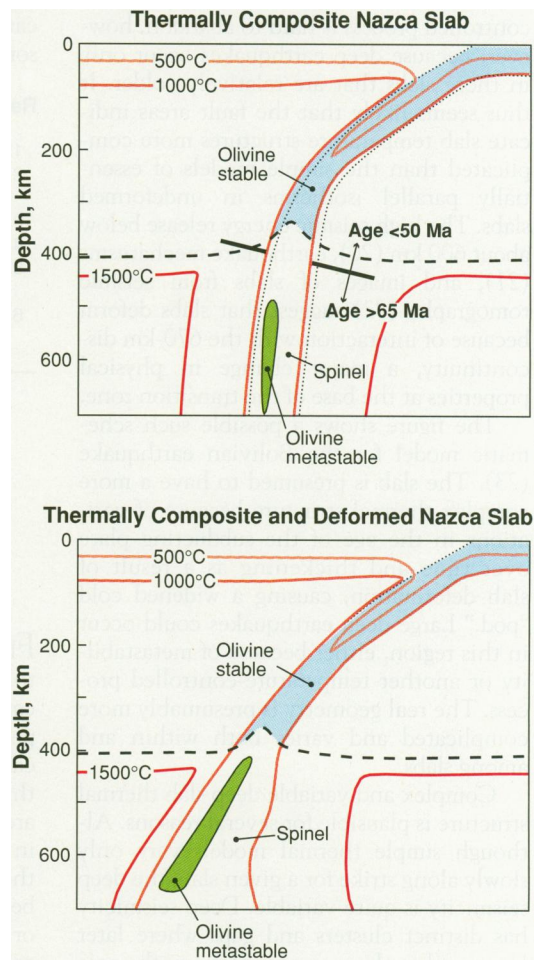
These results bear on the question of how earthquakes occur at depths where temperatures may exceed 1600°C and pressures exceed 24 GPa (about 240,000 atm). With the formulation of the theory of plate tectonics in the late 1960s, it was recognized that deep earthquakes occur in subducting slabs, where temperatures may be up to 1000°C colder than the surrounding mantle. Temperature seems to be a crucial factor because deep earthquakes generally occur in relatively colder slabs of fast-subducting old lithosphere but not warmer slow-subducting slabs of young lithosphere (*5–7*).

Ideas about temperatures within slabs come from simple models of cold slabs subducting into a hotter mantle (*8, 9*). Although the precise temperatures vary between models (*10*), the basic pattern (see figure) is that successively hotter isotherms reach greater depths. Although these models cannot be tested directly, they predict travel times for seismic waves similar to those observed (*9, 11*), suggesting that they are reasonable approximations.

For deep earthquakes, the important prediction of the thermal models is that, at depths greater than 600 km, the portion of the slab colder than 600° to 800°C should be a wedge narrowing to a width less than about 10 km. The two major models offered to date for the mechanics of deep earthquakes presume that faulting should be restricted to material in this temperature range.

In one model, faulting occurs by the brittle fracture process that causes shallow earthquakes. Although high pressures would normally suppress fracture, it may occur once slabs become hot enough to decompose hydrous minerals; the water released would reduce the effective stress on fossil faults formed before subduction (*1, 12*). Because shallow earthquakes in oceanic lithosphere, including the large normal fault earthquakes near trenches, only occur where the temperature is less than about 800°C (*13*), similar temperature control would be expected in the slab. Although the limiting temperature might be higher at high pressures (*14*), the variation in earthquake depths between slabs is inconsistent with such a pressure effect (*5, 15*). It is also unclear whether the hydrated minerals could survive to these depths (*16*). Hence, although dehydration effects may be important for intermediate depth earthquakes, they seem less likely for deep earthquakes.

In another model receiving much recent attention, deep earthquakes result from solid-state phase changes, primarily that in which the mineral olivine transforms to a denser spinel structure (*6, 7, 17, 18*). Thus, deep seismicity occurs only in the depth



Deep trouble. A possible solution to the "fault too big problem," drawn for the region of the Bolivian earthquake (*23*). The slab is presumed to have a more complex thermal structure because of variations in the age of the subducting plate over time (**top**) and to have been deformed and thickened (**bottom**), causing a widened cold region. Large deep earthquakes could occur by temperature-controlled processes such as transformational faulting in metastable olivine (shown) or brittle faulting as a result of mineral dehydration. The dashed line shows the equilibrium phase boundary between olivine and spinel. If such a model applies, the real geometry is presumably more complicated and varies both within and among slabs.

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range of the mantle transition zone, where phase changes should occur in downgoing slabs. Modeling shows that in fast-subducting cold slabs, the transformation cannot keep pace with the descent, so metastable olivine should persist well below the equilibrium phase boundary in wedge-shaped regions bounded approximately by the 600°C isotherm (*7*, *19*). Deep earthquakes are assumed to occur by a shear instability, known as transformational faulting, observed in the laboratory for metastable materials under stress. This model is consistent with the variation in earthquake depths between and along subduction zones.

The recent earthquake observations (*1*–*3*) pose a problem for both models, in that the large fault zones appear to cut across the predicted narrow wedge of material below 600° to 800°C. The idea of a temperature-controlled process is hard to abandon, however, because deep earthquakes occur only in those slabs that are relatively colder. It thus seems likely that the fault areas indicate slab temperature structures more complicated than the simple models of essentially parallel isotherms in undeformed slabs. The high seismic energy release below about 600 km (*20*), earthquake mechanisms (*21*), and images of slabs from seismic tomography (*22*) suggest that slabs deform because of interaction with the 670-km discontinuity, a major change in physical properties at the base of the transition zone.

The figure shows a possible such schematic model for the Bolivian earthquake (*23*). The slab is presumed to have a more complex thermal structure because of variations in the age of the subducting plate over time and thickening as a result of slab deformation, causing a widened cold "pod." Large deep earthquakes could occur in this region, either because of metastability or another temperature-controlled process. The real geometry is presumably more complicated and varies both within and among slabs.

Complex and variable deep slab thermal structure is plausible for several reasons. Although simple thermal models vary only slowly along strike for a given slab, the deep seismicity is quite variable. Deep seismicity has distinct clusters and gaps where later large earthquakes can occur (as was the case for the Bolivian earthquake) (*23*). Tomographic images of deep slabs also vary along strike and show more complexity (*22*) than simple thermal models predict (*11*). In addition to mechanical perturbations to the slab, some of this variability may reflect metastability because latent heat release would perturb thermal structure (*7*, *24*). These variations in both temperature and metastability would cause complex density variations and would thus affect slab stresses and driving forces (*7*). If the wedges were large enough and continuous, the resulting buoyancy might contribute to deflecting the slab to a near-horizontal attitude (*1*), as observed in some cases (*22*), although not for the Bolivian earthquake region.

To date, ideas about subduction have evolved as seismological data have improved. Deep earthquakes showed that subducting slabs exist, indicated that they were colder than their surroundings, suggested that stresses in slabs result largely from the higher density, and now imply that slabs are complicated and variable. Simple slab models will need to be revised to reflect this complexity and then tested against observations from recent and future deep earthquakes. The fact that large deep earthquakes are rare (the last one comparable to the Bolivian earthquake occurred in 1970) will help ensure that the issue of what causes deep seismicity remains open for some time.

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Springs for Wings

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Flying insects beat their wings very fast, up to 1000 cycles per second in the extreme case of a tiny midge. It has long been suspected that their beating is sustained elastically like the vibrations of a tuning fork, that kinetic energy lost by the wings as they are halted at the end of one stroke is stored in springs that recoil elastically to provide the kinetic energy for the next (*1*). It has been frustratingly difficult to demonstrate or disprove this, but in this issue Dickinson and Lighton (*2*) present clear evidence that elastic mechanisms are important for flying fruit flies.

Elucidation of this mechanism is important for understanding insect flight, because it makes a big difference in how we calculate the amounts of work that the wing muscles must do. They must perform aerodynamic work in each wing stroke to overcome the aerodynamic drag on the moving wings. In addition, they must do inertial work to give kinetic energy to the wings as they accelerate at the start of each stroke. If the wings are halted by muscles acting as brakes, their kinetic energy would be degraded to heat and be lost. If, on the other hand, the wings are halted by springs, their kinetic energy can be stored for reuse in the next stroke. If we can calculate these work requirements and also determine the metabolic energy cost of flight, we can estimate the efficiency of the muscles. If there is perfect elastic storage in springs well-matched to their task, the muscles have only to do aerodynamic work, and

$$\text{efficiency} = \frac{\text{aerodynamic work}}{\text{metabolic energy consumption}}$$

If, on the other hand, there is no elastic storage

$$\text{efficiency} = \frac{\text{(aerodynamic + inertial) work}}{\text{metabolic energy consumption}}$$

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