

ture area measuring about $40 \times 40 \text{ km}^2$ and oriented in a plane cutting across the slab. This area was much larger than could be accommodated easily by either of the most detailed theories of deep seismicity—dehydration or transformational faulting. According to both of these theories, deep-focus earthquakes occur as a result of runaway processes in a thin wedge of either hydrated minerals or metastable low-pressure minerals, with the wedge being preserved in a metastable state in the middle of the slab by its cold temperature. Recently, Hiroo Kanamori, Don Anderson and Thomas Heaton (Caltech) suggested² a possible explanation for the large rupture zone of the Bolivian and similar quakes: Regardless of how a quake starts, once it has begun, large scale melting within the rupture zone could facilitate propagation of the rupture zone outside its original boundaries.

Hidden energy

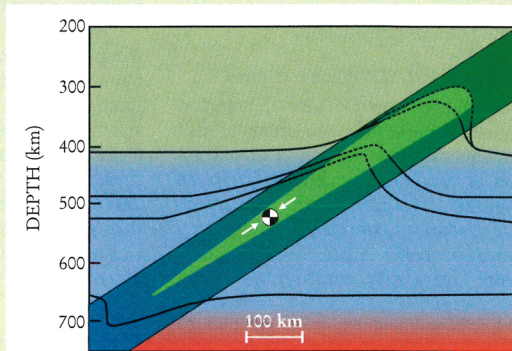
The idea that melting could have been a factor in the Bolivian quake was discussed informally within a year of the quake's occurrence. However, a detailed treatment of the role of melting did not seem of central importance, particularly given the many other opportunities the event presented for research into Earth's structure and the mechanisms of deep seismicity. Thus, it was not until three years after the event that Kanamori, Anderson and Heaton fully realized just how important a role melting could have played in the Bolivian earthquake. They pointed out that the rupture characteristics of the Bolivian quake suggested that the total seismic energy— 5.2×10^{16} joules—radiated by the event constituted, at most, only about 3.8% of its total energy. The slow speed of the rupture—only about 20% of the local shear-wave speed—also suggested the quake's rupture mechanism was highly dissipative. The remaining energy, the Caltech researchers argued, would have gone into heating a layer around the rupture zone.

In the view of the researchers, the Bolivian event would have proceeded according to the following scenario: As the slab descended into the mantle, stresses would mount within it until some unspecified process initiated rupture between two blocks of material in the slab. Initially, frictional stress between the two moving blocks would have been quite high and would have generated sufficient heat to melt a layer—perhaps up to 31 cm thick—at the interface between the blocks, lubricating subsequent motion along the rupture. Because the stress associated with motion would have been low for

Deep Earthquakes: Old Faults or New?

Although deep-focus earthquakes occur deep in the mantle, where high temperatures and pressures should make impossible brittle failure (the mechanism of shallow quakes), seismically, deep quakes look very much like their shallow counterparts. For this reason, researchers have sought mechanisms that resemble shallow faulting, but that involve processes occurring in regions prone to deep earthquakes—that is, in slabs of oceanic plates descending into the mantle. The figure below depicts a cross section of such a slab (dark green and dark blue) as it descends into the mantle (light green and light blue). According to one theory, the dehydration of magnesium/iron silicates, occurs from 100 to 125 km beneath the surface and liberates water that could weaken and reactivate a preexisting fault plane. This dehydration mechanism^{1,5} probably accounts for earthquakes occurring at depths below 75 km down to 300 km, and possibly down to 670 km.

Another theory, called transformational faulting,⁶ was introduced by Stephen Kirby (US Geological Survey, Menlo Park, California), Harry Green (University of California, Riverside) and Pamela Burnley (now at Georgia State University) to account for the increase in seismicity below 410 km. In this theory, rupture occurs as a result of the exothermic transformation of iron/magnesium silicates (green) such as olivine to denser phases (blue) such as spinel. Although this change ought to occur at pressures found at depths of about 410 km, it can be inhibited by the low temperature of the slab, preserving a wedge of metastable olivine in the middle of the slab, perhaps to depths as low as 670 km or below. High-pressure experiments with related minerals suggest that fault-like structures—called anticracks—and seismic activity can occur along these growing regions of microcrystalline spinel. Compression and shear (indicated by arrows) along these anticracks could lead to faulting (indicated by the circular symbol) within the olivine wedge, giving rise to earthquakes.



Transformational faulting is appealing because it offers a comprehensive framework for interpretation of observations of earthquakes below 410 km. It explains why such earthquakes occur at depths between 410 and 670 km (where the endothermic transformation to lower-mantle minerals, such as perovskite, puts an end to anticrack formation) and in slabs that are descending rapidly and so are more likely to remain colder than the surrounding mantle. The fact that transformational faulting would occur as a runaway reaction with thermal feedback could also explain why deep-focus earthquakes have far fewer aftershocks than their shallow counterparts.

Although transformational faulting is currently the most comprehensive theory of earthquakes below 410 km, it is not universally accepted. According to Paul Silver (Carnegie Institution of Washington), "Since stable hydrous phases are expected to exist for the pressure-temperature conditions of a descending slab throughout the upper mantle, a dehydration mechanism could account for all deep seismicity." Silver and his colleagues at Carnegie plan to conduct high-pressure tests to determine whether fault reactivation (by dehydration or other means) may prove to be a viable mechanism for deep seismicity. As Kirby and his colleagues have pointed out,⁷ the debate may have implications well beyond explaining the mechanism of deep-focus earthquakes. Olivine is about 10% less dense than spinel, and a substantial wedge of this lighter material in a descending slab could slow its descent (as well as the motion of the oceanic plate to which the slab is attached) and perhaps delay mixing of the slab's material into the lower mantle. (Figure adapted from ref. 7.)

the melt-assisted portion of the event, very high stresses would have built up at the edge of the rupture zone, allowing for propagation of the rupture outside the initially affected area.

The probable importance of melt-assisted rupture during the Bolivian

earthquake raises the question of whether melting is important in other deep-focus events. Kanamori and his collaborators point out that all deep-focus earthquakes appear to radiate only a small proportion of their energy seismically. However, so far, the only