PERSPECTIVES: GEOPHYSICS

Deep Earthquakes in Real Slabs

Seth A. Stein and David C. Rubie

How can earthquakes occur deep in Earth where rocks flow rather than fracture? In most of the planet, earthquakes do not occur deeper than about 50 km, because once temperatures increase with depth beyond 500° to 700°C, rock deforms plastically rather than behaving as a brittle solid. Great slabs of subducting oceanic crust at trenches, however, are colder than the surrounding upper mantle into which they descend, so rocks within them are somehow able to fail catastrophically to cause earthquakes.

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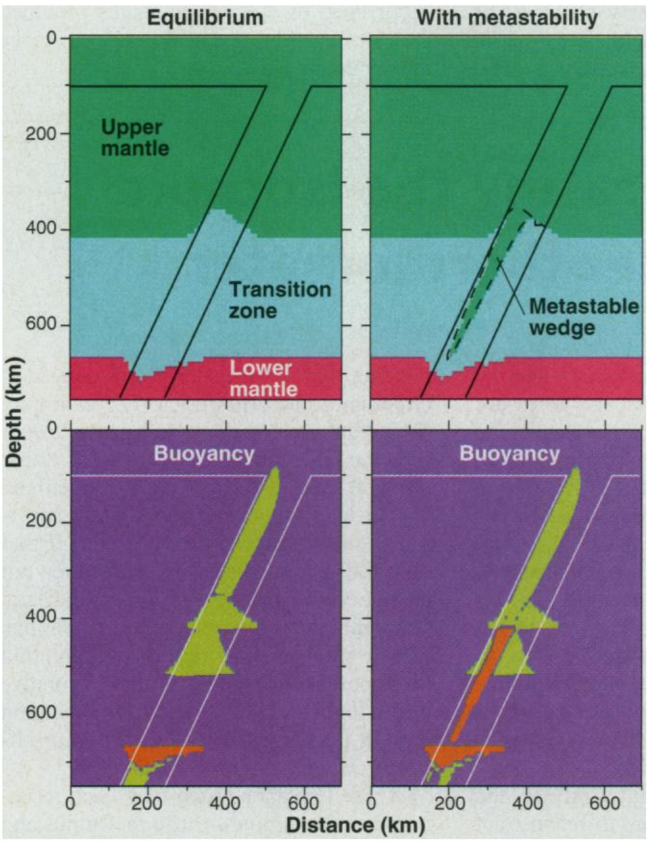
Participants at a recent meeting on subduction explored this unusual seismic activity and other related topics (*1*, *2*). A consensus emerged that the deep earthquakes reflect the complexity of processes within slabs. Many features of slabs, such as the way they show up clearly in seismic images (*3*), can be crudely explained if we think of the slabs as downgoing material distinguished from the surrounding mantle largely by being colder. Deep earthquakes, on the other hand, appear to depend on complex mineral reactions that take place as slabs descend toward higher pressure and warm up.

Conference speakers discussed several possible causes for deep earthquakes, citing experimental and theoretical studies about mineral transformation behavior at high temperatures and pressures. An important feature of high-pressure mineral transformations in subducting slabs is that they may not occur at equilibrium. Instead, mineral phases may persist outside their equilibrium stability fields in temperature-pressure space. Such metastability is expected because the relatively colder temperatures in slabs should inhibit reaction rates. This is much like the behavior of diamonds, which are unstable at the low pressures of Earth's surface and survive metastably rather than transform to graphite.

In one model, deep earthquakes result from the transformation of the mineral olivine, the dominant mineral in slabs, to its denser wadsleyite and ringwoodite polymorphs. These reactions, thought to give rise to seismic discontinuities outside slabs (at 410-km depth, for example), would occur at different depths within slabs. Although under equilibrium conditions these reactions would occur at shallower depths within cold slabs, kinetic studies of mineral nucleation and growth suggest that in some slabs the phase transformation cannot keep pace with the rate of subduction, causing a wedge of olivine in the cold slab core to persist metastably to greater depths (*4*). Under these conditions, laboratory experiments suggest that the transformation should occur by means of a shear instability on planar surfaces known as transformational faults, causing earthquakes (*5*).

Several participants explored how this transformational faulting model explains a variety of features of deep seismicity (*6*), including the observation that deep earthquakes first appear at about 325-km depth, where the phase change might first be expected, and cease at about 700-km depth, where ringwoodite would transform to the denser perovskite structure. It predicts the observed variation in earthquake depths between subduction zones, because younger and slower-subducting slabs should be hotter and less prone to metastability than older and faster-subducting slabs. It also explains how isolated deep earthquakes can occur in what appear to be detached fragments of slabs, where metastable olivine survives. Moreover, it suggests that metastable olivine may help regulate subduction rates. Because the primary force driving subduction should be the negative buoyancy of the cold slab, faster subduction would cause a larger wedge of low-density metastable olivine, reducing the driving force (see figure) and slowing the slab (*7*).



Model slabs. Predicted mineral phase boundaries (**top**) and resulting buoyancy forces (**bottom**) in a downgoing slab with equilibrium mineralogy (**left**) and for a non-equilibrium metastable olivine wedge (**right**). Assuming equilibrium mineralogy, the slab has significant negative thermal buoyancy (yellow) due to both its colder temperature and the elevated 410-km discontinuity, and significant positive compositional buoyancy (orange) associated with the depressed 660-km discontinuity. If a metastable wedge is present, it adds positive buoyancy (orange) and, hence, decreases the net negative buoyancy force driving subduction.

However, other presentations explored difficulties with the model. First, several large deep earthquakes occur on fault planes that appear to extend well beyond the boundaries of the expected metastable wedge (*8*). Participants discussed the possibility that slabs may deform at depth, giving wider than expected metastable regions. Another possibility is that earthquakes may nucleate by transformational faulting but then propagate outside the metastable wedge by means of another failure mechanism.

A second difficulty with the metastability model is that seismological studies reported at the meeting show no evidence for a metastable wedge (*9*). Although the low–seismic velocity wedge within the complex geometry of the high-velocity slab is likely to be an elusive target (only after years of study have trapped seismic waves been observed for the analogous case of low-

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velocity fault interiors), the seismological results are most simply explained by the absence of a wedge. Similarly, although the idea that deep earthquakes in detached slabs reflect metastability is attractive, calculations suggest that such metastability would not persist long enough (*10*), although it is not excluded given the poorly known age of slab detachment.

Given these difficulties, many participants concluded that the kinetics of the phase changes and slab thermal structure are sufficiently poorly known that although metastability is likely, it is not definitely required. As a result, two other possible mechanisms for deep earthquakes were explored. In one, deep earthquakes reflect a plastic instability where faulting occurs by means of rapid creep (*11*). In another, deep earthquakes occur by brittle fracture, which can occur at these high pressures because of the release of water from mineral structures (*12*). Although both these ideas have long histories, they are being revived because of the difficulties with the metastability model and because of new data on the rheology of slabs (*13*) and on the issue of whether water could be carried to great depth in mineral structures and released as the slab heats up (*2*). Neither model appears ideal: For example, the brittle fracture model does not directly address the observation that the depth range of deep earthquakes coincides with that of the olivine phase changes, and this process would be temperature controlled, giving rise to the same problems of fault dimensions that are too large as faced by the metastability model (*14*).

Although simple models based on idealized slabs explain some gross features of deep earthquakes, it appears that more sophisticated explanations must reflect the complex thermal structure, mineralogy, rheology, and geometry of real slabs. It seems likely that features of the simple models will need to be combined; for example, earthquakes may nucleate by one mechanism but propagate by a different type of shear instability. Although this situation is frustrating, it offers the exciting prospect of learning more about the complexities of real slabs from the details of deep earthquakes, in the same way that the occurrence of deep earthquakes provided the classic evidence for the very existence of subducting slabs.

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PERSPECTIVES: GEOSCIENCE

Calibrating the Isotopic Paleothermometer

Jean Jouzel

Paleoclimatologists who study the tiny air bubbles trapped in ice cores are very lucky. They can observe the composition of Earth's past atmosphere over hundreds of thousands of years and place greenhouse gas changes due to human activities in perspective (*1*). Now, two studies in this issue on pages 930 and 934 (*2*, *3*) fully confirm that isotopic analysis ($^{15}N/^{14}N$ and $^{40}Ar/^{36}Ar$ ratios) can reveal the temperature shifts associated with abrupt climate changes. Even more important, this analysis provides precise information about the timing of these changes between high and low latitudes.

Glaciologists traditionally rely on the isotopic composition of ice to reconstruct continuous past temperature records. Fractionation produces a linear relation between annual oxygen-18 ($\delta^{18}O$) of mid- and high-latitude precipitation and mean annual temperature that is particularly well obeyed in Greenland and Antarctica. For example, $\delta^{18}O$ regularly decreases by 1 per mil every time the temperature drops by 1.5°C when going from coastal to Central Greenland (*4*). In using this relation as a paleothermometer, researchers have assumed that the present-day spatial relation does not change with time; that is, the spatial and temporal slopes are assumed to be similar. Simple models show that this assumption holds only if such factors as the evaporative origin and the seasonality of precipitation remain unchanged between different climates, which is not at all guaranteed.

These limitations have long been recognized and examined through simple and complex isotopic models (*5*). Central Greenland borehole temperature profiles effectively reveal that the Last Glacial Maximum (LGM) cooling at 20,000 years ago was about twice $\Delta T^{18}O$, the temperature changed predicted from the isotopic change on the basis of the spatial slope (*6*). Because of heat diffusion, however, this method cannot retain information about the numerous abrupt climatic changes documented in the isotopic record. The isotopic analysis of air bubbles can provide estimates of abrupt temperature changes on short time scales (a few decades or less) (see the figure).

Because of compaction, the density of snow increases with depth. Air is trapped when the firn (the consolidated snow) reaches a density of ~0.82 kg dm^{-3} and closes off bubbles of trapped gas. The entrapped air is thus younger than the ice matrix, with the age difference, Δ_{age}, depending on both accumulation and temperature (in Central Greenland, Δ_{age} varies between 200 and 900 years). Air composition is slightly modified by physical processes, such as gravitational and thermal fractionation. The latter depends on the thermal diffusion sensitivity and on the temperature difference between the surface and the close-off depth (*2*). Gases diffuse about 10 times as fast as heat, and in the case of a rapid change, this temperature difference is temporarily modified, which causes a detectable anomaly in the isotopic composition of nitrogen and argon. Both the depth of this anomaly, which allows estimate of Δ_{age} by comparison with the ice $\delta^{18}O$ record, and its strength provide estimates of rapid changes.

This approach was pioneered by Severinghaus, who first showed that thermal diffusion, a process familiar in the laboratory, can be observed in sand dunes (*7*). At the

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