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GEOPHYSICS:

Enhanced: Deep Earthquakes in Real Slabs

Seth A. Stein [HN13] and David C. Rubie [HN14] *

How can earthquakes occur deep in Earth where rocks flow rather than fracture [HN1]? In most of the planet, earthquakes do not occur deeper than about 50 km, because once temperatures increase with depth beyond 500º to 700ºC, 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.

Participants at a recent meeting on subduction [HN2] 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 [HN3] (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 [HN4]. 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 [HN5]. These reactions, thought to give rise to seismic discontinuities [HN6] 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 [HN7] 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 [HN8]. 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.

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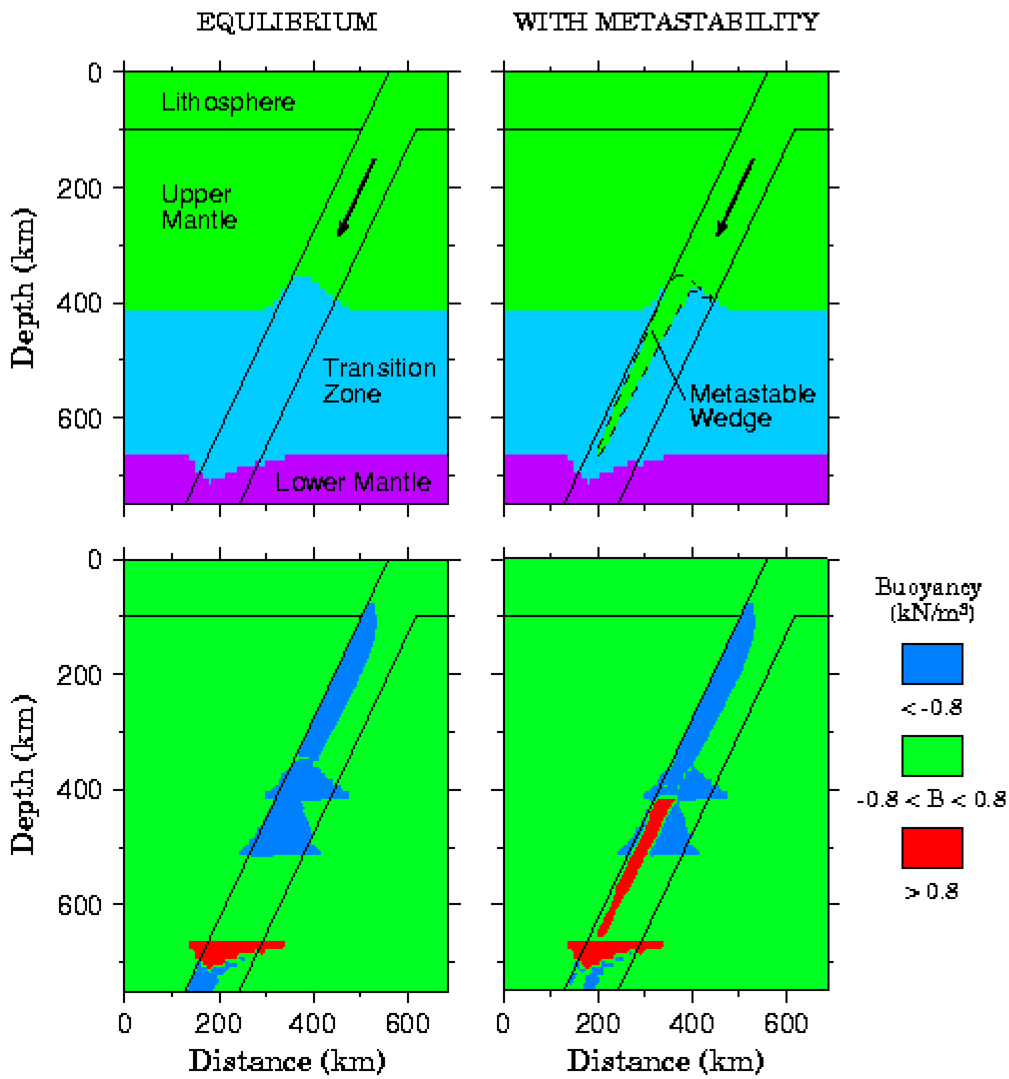
However, other presentations explored difficulties with the model. First, several large deep earthquakes occur on fault planes that appear to extend well beyond the boundaries of the expected metastable wedge [HN9] (8). Participants discussed the possibility that slabs may deform at depth, giving wider 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-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 [HN10] (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 [HN11] (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 [HN12] 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.

References and Notes

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HyperNotes

Related Resources on the World Wide Web

General Hypernotes

A glossary of geologic terms is made available by the Department of Geological and Atmospheric Sciences, Iowa State University. An earthquake glossary is offered by the Earthquake Studies Office Project at the Montana Bureau of Mines and Geology.

Visualizing Earth, an educational project funded by the National Science Foundation, provides illustrated introductions to geological processes.

The Earth science section of explorezone.com offers an introduction to earthquakes with links to news and other earthquake Internet resources

Surfing the Internet for Earthquake Data is a collection of Internet links maintained by S. Malone, Geophysics Program, University of Washington.

This Dynamic Earth: The Story of Plate Tectonics and *Earthquakes* are publications made available online by the U.S. Geological Survey (USGS). The USGS National Earthquake Information Center collects and disseminates earthquake information; it offers a glossary and a page of general earthquake information. SeismoLinks is a topical collection of links to seismology Web resources provided by the USGS Pasadena, CA, office.

P. Gore, Department of Geology, Georgia Perimeter College, Clarkston, presents an Earthquake Information Page of links to earthquake resources on the Web.

J. Louie, Seismological Laboratory, University of Nevada, provides an About Earthquakes page with links to his lecture notes and other Web resources.

J. Butler, Department of Geosciences, University of Houston, presents lecture notes on earthquakes for a physical geology course. He also maintains Geophysics on the Internet, which offers annotated lists of geophysics resources on the Web.

J. Revenaugh, Department of Earth Sciences, University of California, Santa Cruz, provides lecture notes on plate tectonics, earthquakes, and Earth's interior for a course on geologic principles.

T. Lay, Department of Earth Sciences, University of California, Santa Cruz, includes presentations on plate tectonics and earthquakes in the lecture notes for a course on Earth catastrophes. The university issued a news release about Lay's research on deep earthquakes.

J. Smyth, Department of Geological Sciences, University of Colorado, provides introductions to earthquakes and Earth's interior in lecture notes for a physical geology course. A glossary is provided.

C. Ammon, Department of Earth and Atmospheric Sciences, St. Louis University, offers lecture notes for a course on earthquakes.

R. Phinney, Department of Geosciences, Princeton University, provides lecture notes on earthquakes for a course on earthquakes, volcanoes, and other hazards.

S. Nelson, Department of Geology, Tulane University, offers lecture notes on earthquakes and Earth's interior for a physical geology course.

The *U.S. National Report to IUGG, 1991-1994*, published in 1995 by the American Geophysical Union, included chapters on the dynamics of the solid Earth, such as the contribution by S. Kirby titled "Intraslab earthquakes and phase changes in subducting lithosphere."

The International Association of Seismology and Physics of the Earth's Interior provides an overview of its research interests.

The American Geophysical Union makes available an article from *Eos* by J. Wakefield titled "Scientists get a closer look at mechanism of deep Bolivian quake."

The March-April 1995 issue of *American Scientist* had an article by M. Wysession titled "The inner workings of the Earth."

The Geodynamics Program at the Pacific Geoscience Centre of the Geological Survey of Canada makes available a review article by R. Hyndman *et al.* titled "Seismology: Giant megathrust earthquakes" about deep earthquakes in the Cascadia subduction zone region.

The 6 February 1998 issue of *Science* had an Enhanced Perspective by D. Wiens titled "Sliding skis and slipping faults" about different models of faulting for deep earthquakes.

Numbered Hypernotes

1. L. Moresi of the CSIRO Geoscience and Geoengineering Research Group, Australia, provides information on the structure and layering of Earth in his Past and Future of the Planet Earth Web site. A presentation by R. Hamilton on Earth's interior and plate tectonics is part of C. Hamilton's Views of the Solar System. J. Louie offers lecture notes on the composition of Earth and lithospheric deformation. The *U.S. National Report to IUGG, 1991-1994* had a chapter by T. Duffy and R. Hemley titled "Some like it hot: The temperature structure of the Earth" and a chapter titled "Rock deformation: Ductile and brittle" by S. Karato and T. Wong. The National Earthquake Information Center offers an introduction to determining the depth of earthquakes. S. Kirby reviewed intermediate and deep faulting processes in his contribution to the *U.S. National Report to IUGG, 1991-1994*.

2. The Alfred Wegener Conference on the Processes and Consequences of Deep Subduction was an interdisciplinary workshop held from 5 to 11 September 1999 in Verbania, Italy. W. Leeman, Department of Geology and Geophysics, Rice University, offers a presentation on subduction zone studies, as well as lecture notes on global seismicity and earthquakes for a geology course on geologic hazards. T. Dunn, Department of Geology, University of New Brunswick, provides lecture notes on subduction and convergent margins for a geology course. Windows to the Universe offers a presentation on subduction.

3. R. Phinney provides lecture notes on seismic waves and their use as a tool for studying Earth's interior. V. Cormier, Geology and Geophysics Department, University of Connecticut, provides lecture notes on Earth structure from seismology for a course on Earth structure. For a course on reflection seismology taught by J. Lorenzo, Department of Geology and Geophysics, Louisiana State University, J. Curry and E. Ferry prepared a presentation on seismic tomography. S. Kirby included a section on seismological observations of slabs in his contribution to the *U.S. National Report to IUGG, 1991-1994*.

4. A presentation on high-pressure minerals by L. Finger is made available by the Geophysical Laboratory of the Carnegie Institution of Washington. The *U.S. National Report to IUGG, 1991-1994* included a chapter by S. Kirby titled "Intraslab earthquakes and phase changes in subducting lithosphere," and a chapter by L. Stixrude titled "Mineral physics of the mantle"; in a chapter section on plastic deformation in the deep interior of Earth, S. Karoto and T. Wong discussed instability associated with phase transformations.

5. Mineral Web, presented by the Department of Earth Sciences, University of Manchester, UK, provides information on olivine. D. Barthelmy's Mineralogy Database has entries for olivine, wadsleyite, and ringwoodite, as well as links to other Web resources about the minerals. D. Sherman, Department of Earth Sciences, University of Bristol, UK, provides lecture notes on olivine and related structures for a mineralogy course. J. Banfield, Department of Geology and Geophysics, University of Wisconsin, provides lecture notes on olivine for a course on gems and minerals. J. Smyth includes an entry for olivines in his Mineral Structures Data Base, as well as information on wadsleyite on his Web page. The 1998 Annual Report of the Bayerisches Geoinstitut, Universität Bayreuth, Germany, describes ongoing research to determine of the relative strengths of olivine polymorphs in the section about projects on phase transformations, deformation, and properties of mantle minerals. The Mineral Physics Laboratory, Department of Geological Sciences, Cornell University, provides a presentation about their research on the kinetics of olivine phase transition at high pressure.

6. The *U.S. National Report to IUGG, 1991-1994* included a contribution by P. Shearer titled "Seismic studies of the upper mantle and transition zone" with a section on the 410- and 660-km discontinuities. The Harvard Seismology group offers presentations on the topography of the 410 and 660 discontinuities.

7. S. Stein offers a brief illustrated introduction to his research interest in the transformational faulting model.

8. In his Mineral Structures Data Base, J. Smyth discusses the perovskite group. The 11 June 1999 issue of *Science* had an Enhanced Perspective by A. Navrotsky titled "A Lesson from Ceramics" that discussed perovskite structures.

9. D. Wiens, Department of Earth and Planetary Sciences, Washington University, St. Louis, makes available articles and abstracts describing his research on deep earthquakes where aftershocks occur outside the presumed metastable wedge.

10. Creep is defined in the glossary offered by the Montana Bureau of Mines and Geology. R. Phinney discuses creep in lecture notes on earthquake physics.

11. The 30 August 1997 issue of *New Scientist* had an article by L. Bergeron titled "Deep waters" about water in the mantle and its possible connection to deep seismicity.

12. The Web site for the text book *Earth Structures: An Introduction to Structural Geology and Tectonics* by B. van der Pluijm and S. Marshak offers a brief introduction to rheology.

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