Phase Boundaries and Mantle Convection

J. E. Vidale and T. Lay

The Earth has a vigorous thermal engine, continuously running as the planet cools. The heat, created long ago by the release of gravitational energy during planetary accretion and core-mantle separation, as well as by the continuing decay of radioactive isotopes, is carried upward to the base of the Earth's tectonic plates by convection. The heat escapes to space by conduction across these plates, followed by radiation from the Earth's surface.

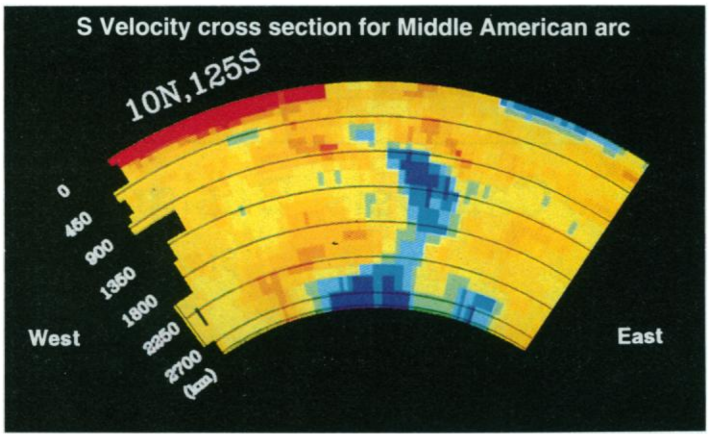

Fig. 1. Slab in the lower mantle. Cross section through a seismic tomography image of the shear (S) velocity structure beneath Central America. The blue regions correspond to fast velocity, presumably cold and downwelling material, probably associated with the current subduction beneath the Middle American Trench. The velocity perturbations shallower than 400-km depth are de-emphasized. [Adapted from (*2*) with permission, copyright American Geophysical Union]

Just as in a pot of soup on the stove, convection in the Earth involves the upwelling of hot buoyant material and downwelling of cold dense material. The motion is on the order of centimeters per year, and the upwellings are a few hundred kelvin hotter than the downwellings. Because mantle rock is stiffer when cold, downwellings are concentrated in slabs of subducting lithosphere, whereas softer hot upwellings take the form of cylindrical thermal plumes. Geophysicists are now striving to resolve questions about the configuration of the Earth's internal thermal system (*1*). For example, is the entire mantle homogeneously mixed by convection or are there several regions with distinct geochemical signatures?

Seismologists can study the deep thermal structure because cold material transmits elastic waves faster than hot material. Seismic tomography provides three-dimensional images of fast- and slow-velocity regions in the Earth's interior, which can be related to the convective regime. The lithospheric plates sinking beneath most of the Pacific margin can be mapped by the seismic imaging of tabular regions of higher than average seismic velocity. But how deep and effortlessly do these slabs sink? The abrupt increase of 5 to 10% in seismic velocities and density that occurs globally near a depth of 660 km marks the most likely level for disruption of vertical flow. Fast seismic velocity anomalies can be traced deep into the lower mantle beneath some subduction zones, as seen below Central America (Fig. 1) (*2*). Other subduction-related anomalies appear to deflect laterally above the 660-km discontinuity, as seen beneath the Izu-Bonin trench (Fig. 2) (*3*) where Wicks and Richards studied the 660-km boundary, as reported in this issue (*4*).

The seismic discontinuity near a depth of 660 km plays a key role in the mantle-flow regime, and the precise depth of the boundary is a sensitive temperature indicator. It is probably the result of a mineralogical phase transition of $(Mg,Fe)_2SiO_4$ in the spinel phase to spinel-structured $MgSiO_3$ + (Mg,Fe)O, although not all details have been explained (*5*). This phase transition is sensitive to the pressure and temperature of the material. Thus, the boundary should vary in depth between regions of cold and hot mantle. Wicks and Richards' determination of depth variations of the olivine-perovskite phase boundary in the Izu-Bonin region is the highest resolution mapping of this boundary near a subducting slab (*4*). Their study analyzes seismic waves that convert from the shear to the compressional mode at the 660-km boundary and arrive a few seconds after the direct P waves at distant stations. Australian array recordings of 73 deep earthquakes in the Izu slab are used to map the depth of the conversion point along and transverse to the subduction zone. Small variations in arrival time of the converted phase allow the measurement of subtle but telling depth variations of the boundary. The phase boundary is depressed by as much as 50 km over a 300-km-wide zone directly beneath the deep earthquakes in the Izu slab.

High-pressure and -temperature experiments indicate that colder spinel transforms to perovskite at higher pressures than does warmer spinel. Downward deflection of the boundary below a cold downwelling can thus be used to estimate the temperature anomaly of material going through the transition. The observed 50-km depression of the boundary requires temperatures from a 600 to 900 K cooler (*6*), which is compatible with thermal models of sinking lithosphere. Such low temperatures persist over the 10 million years required for the slab to sink to a 660-km depth because the conductive warming by the surrounding mantle only slowly overcomes the typically 100 million years or so of cooling that occurs while the plate is at the surface. The high-resolution mapping of such a downwelling thermal anomaly is a major step in delineating the internal thermal structure of the convective regime.

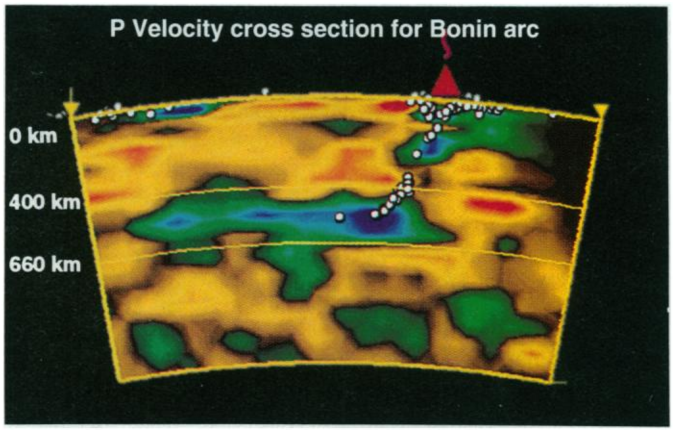

Fig. 2. Slab turning near 660-km depth. Cross section through a seismic tomography image of the compressional (P) velocity structure beneath the Izu-Bonin island arc. The blue-green region corresponds to fast velocity material, which appears to be deflected above the 660-km discontinuity. The white circles show earthquake locations. [Courtesy of R. D. van der Hilst]

The 10% increase in density across the

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perovskite phase transition is expected to have an important mechanical effect on the downwelling flow. Because cold material must sink to depths greater than 660 km before it undergoes the transition, material less dense than that lying on either side is found in the region above the depressed boundary, which creates a buoyant force resisting the downward flow. This resistance may cause the sinking slab to deflect horizontally or to buckle and then pile up instead of penetrating into the lower mantle. The compositional buoyancy of the chemically differentiated rock in the slab and any viscosity increase or additional density increase due to possible differences between upper mantle and lower mantle bulk chemistry also produce resistance to the sinking slab. Thus, determination of the depth to which the subducting material sinks requires careful analysis.

Three-dimensional flow models with high Rayleigh numbers (7) suggest that downwelling material piles up above the 660-km boundary and then overturns catastrophically with large-scale downwellings. This unsteady behavior may be responsible for the variable character of the downwellings imaged by seismology (Figs. 1 and 2). Partly stratified convection may also help to explain long-term plate tectonic motion periodicities and geological cycles (8). However, the effects of strong temperature dependence of viscosity, which must be present to produce realistic slab-like behavior, are not yet fully known.

Another approach is to use global seismic velocity models in conjunction with phase-boundary undulations to develop mantle flow models. Morgan and Shearer (9) recently completed such an exercise. The density contrasts, caused by lateral temperature differences, drive the convective flow, whereas the viscosity and 660-km boundary deformation oppose the flow. They find little evidence for the inhibition of the vertical flow by phase boundary deformation and thus favor simple whole-mantle convection. A similar conclusion is reached by Jordan and co-workers (10), who argue that the seismic velocity anomalies above and below the 660-km depth are too well correlated to allow strongly stratified mantle convection.

Major questions remain unresolved. Seismologists are striving to sharpen images of deep velocity anomalies and discontinuity topography. Mineral physicists are obtaining better experimental data for phase transitions and elastic properties of mantle materials for the evaluation of differences in chemistry between the upper and lower mantle. Geodynamicists are investigating the viscosity structure, effects of phase transitions, and the role of plates in mantle convection. Multidisciplinary efforts drawing on the latest results from each of these fields are likely to be fruitful, as we try to find out how Mother Earth keeps her cool.

References and Notes

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Catalysis: Design Versus Selection

Steven A. Benner

There are two fundamentally different ways to create biological macromolecules that catalyze chemical reactions. The first involves rational (or at least rationalized) design of a biomolecule that folds in solution and presents an array of catalytic functional groups to a substrate. The second requires a system for selecting from a large pool of randomly generated biomolecules a few that present an effective array of catalytic functional groups to a substrate.

Each approach has its merits. Creation by design requires a detailed understanding of and control over biomolecular conformation and reactivity. Thus, examples are few (1, 2) and are even fewer in cases where the microscopic rate constant of the catalytic system is at least partly understood (3). Nevertheless, the process of design forces the biochemist to address and solve problems fundamental to biological catalysts generally: What is the rate-limiting microscopic transformation in the reaction sequence? Where must functional groups be placed in space to catalyze the transformation? What biomolecules will fold correctly to deliver this functionality?

Selection strategies avoid these questions and may be viewed as technologically useful alternatives to true design. At present, the immune system is the best known tool for selecting catalytically active proteins from a random pool (4). As technology, catalytic antibodies can be viewed either as exciting (rate enhancements are typically two to six orders of magnitude) or not (rate enhancements are *only* two to six orders of magnitude). However, this and other selection technologies allow the discovery of fundamentals of catalysis that might later support rational design (5). Further, they raise scientific questions of their own. What can selection experiments in the laboratory reveal about the probability of a random biostructure having catalytic activity? What do they tell us about how biocatalysts arose naturally on Earth? How should the catalytic power of a selected enzyme be evaluated?

Appearing today in *Science* is a landmark paper by Bartel and Szostak (6) that touches on these and other questions. Starting from a pool of some 10^{15} different RNA sequences, a small number of RNA molecules were selected that covalently attached (ligated) a short RNA segment to their own 5' ends. The additional segment contained a binding site for a primer that selectively allowed these RNA molecules to be amplified by the polymerase chain reaction. The pool of amplified molecules was then subjected to random variation and repeated selection. This process yielded RNA molecules capable of effecting a ligation with a rate constant of $0.06\ \text{min}^{-1}$. These RNA molecules are not, of course, true catalysts; they do not remain unchanged at the end of the reaction cycle. Nevertheless, they offer insight into scientific issues relevant to selection processes that might ultimately yield true RNA catalysts, perhaps including those that created the first forms of life on Earth over 3 billion years ago.

The last point relates to the hypothesis that the first form of life on Earth was an RNA molecule catalyzing the template-directed polymerization of RNA, that is, it made copies of itself (7). Evidence for the existence of an "RNA world," in which a complex metabolism was sustained in life forms having RNA as the sole genetically encoded catalysis, can be found throughout contemporary biochemistry (8). Yet the problem remains: Is it plausible that the

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