Single or double convection layers within the mantle? An alternative point of view

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The geochemists and geophysicians have a long controversy on the convection mode of the mantle. The former insists there should exist two separate convection layers divided by some discontinuity, while the latter suggests a big undivided thorough convection layer. These two groups have different proofs standing for their own hypotheses, but can there be a unified perspective within?

The two main sites of the upwelling in the earth mantle are the mid-ocean ridges and the intraplate hotspots, or oceanic islands. Due to different geochemical composition of the basalt in these two sites, we use two different abbreviated terms to describe the lava from these two environments: the **MORB** (Mid-Ocean Ridge Basalt) and the **OIB** (Ocean-Island Basalt). In general, geochemists believe that the MORBs come from the upwelling of the shallow convection cell within the upper reservoir, while the OIBs come from the upwelling of the deep-seated upwelling plumes from the lower reservoir.

The main proof by which geochemists stand for their idea is: the MORBs are depleted in incompatible elements, such as uranium and thorium, while OIBs are relatively enriched in these elements. This gives a reasonable interpretation for different sources of these two basalts. Besides, the terrestrial heat flow studies also support this idea. The approximately 36 TW of mantle heat output could not be possibly achieved only by the MORB source material, for too few radioactive heat sources; the remainders are thought to be contributed by the deeper materials which are not sampled by the mid-ocean ridge, but instead, by the deep-seated plumes[1].

Therefore, what would be the boundary of the upper and lower convection cells? Several possibilities are provided by geochemists. The 660-km discontinuity is believed to be the most promising boundary between these two reservoirs, for clear olivine phase change from spinel to perovskite and magnesowüstite (*pv+mw*)[2]. Recently, a **1600-km barrier** was proposed by Kellogg et al[3]. Numerical modeling of the thermochemical convection implies an intrinsically dense layer in the lower mantle, enriched in heat producing elements. The top of this layer ranges from ~1600 km to near CMB, often deflected by downwelling slabs, with plumes developing around local high spots (**Fig. 1**).

Till now, the viewpoints of the geochemists seem clear. However, accompanied with the progress of computer hardware, geophysicians developed the technique of **tomography** in order to do the "body scanning" inside the earth's depth. During the past two decades, plenty of interesting results have been published, within most of them are against the double layer convection hypothesis.

Application of tomography

Seismic tomography, named in analogy to medical imaging, is a technique involving analysis of seismic waves that travel through the Earth and are affected in various ways by what they pass through *en route* from source to sensor[4]. High-velocity anomalies, where seismic waves speed up, are comparatively common and correspond to regions where cold lithospheric plates have sunk in to the mantle at the convergent margins of tectonic plates (subduction zones), whereas low-velocity anomalies may imply the lower down of seismic waves, and tentatively, the hot material brought up by plumes.

The first breakthrough of global tomography came in 1994, done by Grand[5], in which he used the shear wave to image the

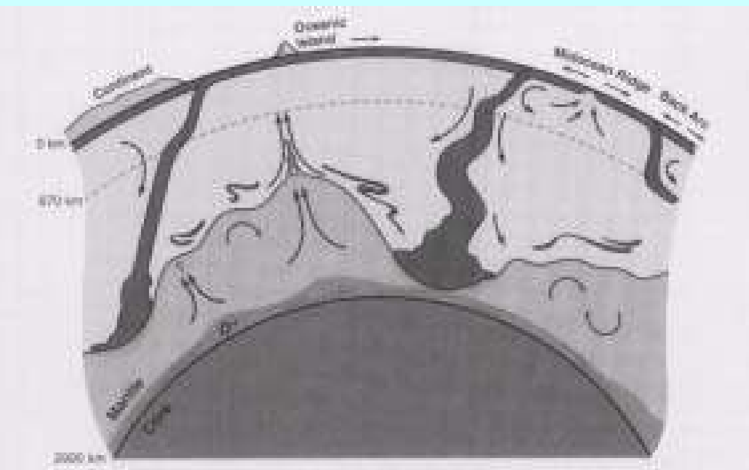

Fig. 1 Diagram illustrating the possible dynamics of an intrinsically dense layer in the lower mantle. Depth to the top of the layer ranges from ~1600 km to near the CMB, where it is deflected by the downwelling slabs. Internal circulation within the layer is driven by internal heating and by heat flow across the CMB. A thermal boundary layer develops at the interface, and plumes arise from local high spots, carrying recycled slab and some primordial material. (Kellogg et al., 1999)[3]

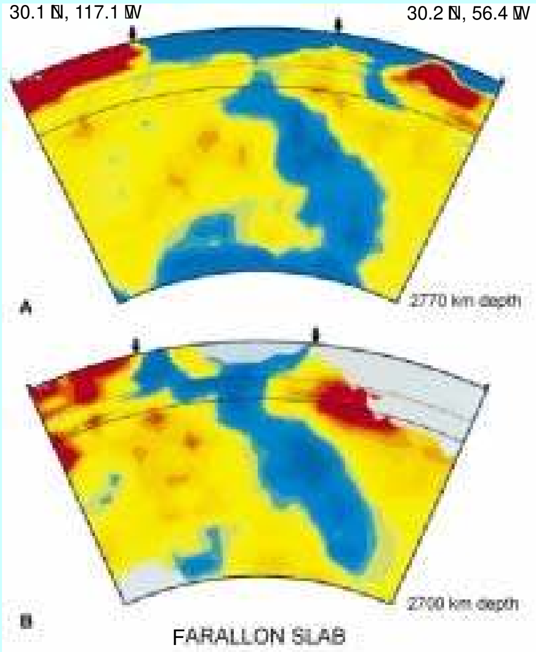

Fig. 2 Cross sections of mantle P-wave (A) and S-wave (B) velocity along a section through the southern United States. The images show variations in seismic velocity relative to the global mean at depths from the surface to the CMB. Blues: faster than average; reds: slower than average. The large tabular feature is possibly the Farallon slab. (Grand et al., 1997)[6]

Farallon Slab (United States). Later in 1997, Grand et al. publish a paper using both compression wave and shear wave to image the **Farallon slab**[6] (**Fig. 2**). The importance of Grand's study lied in the identical structural features via very different data coverage in the P and S datasets. It confirms the stability of seismic tomography as well as the lower-mantle-impinging of the Farallon slab.

Another similarly well-known case is the study of the **Mongol-Okhotsk slab** by Van der Voo et al. in 1999[7] (**Fig. 3**). The subduction of this slab began at late-Jurassic, causing Monglo-Okhotsk ocean to close and the giant Eurasia Plate to form. At probably 150 Myr, the subduction ceased and the younger Pacific subduction zone took place later to the east. Through tomographic imaging, it is interesting to see the injection of the Mongol-Okhotsk slab west of the Pacific subduction zone, and a "graveyard" of slabs near the CMB. Combined with paleogeomagnetic studies, Van der Voo et al. even estimated the approximate sinking velocity to be 1 cm/yr, and possible surficial convergence rate of 4 cm/yr.

In this trend of the latest-rising "**seismoslabology**", many slabs were found to have penetrated deeper than 2000 km, such as the Farallon slab, Mongol-Okhotsk slab and the Indonesia-Europe high-velocity structure[6]. In contrast to the double convection cell model, the tomographic imaging shows neither signs of any possible barrier at the depth of 1600 km, nor slab stagnancy at any velocity discontinuities (660 km or 1600 km) except near the CMB.

As for the absence of the 1600-km barrier in the seismic imaging, Kellog argued this is due to the large undulations of the interface (**Fig. 1**), causing an effectively broad, diffuse and

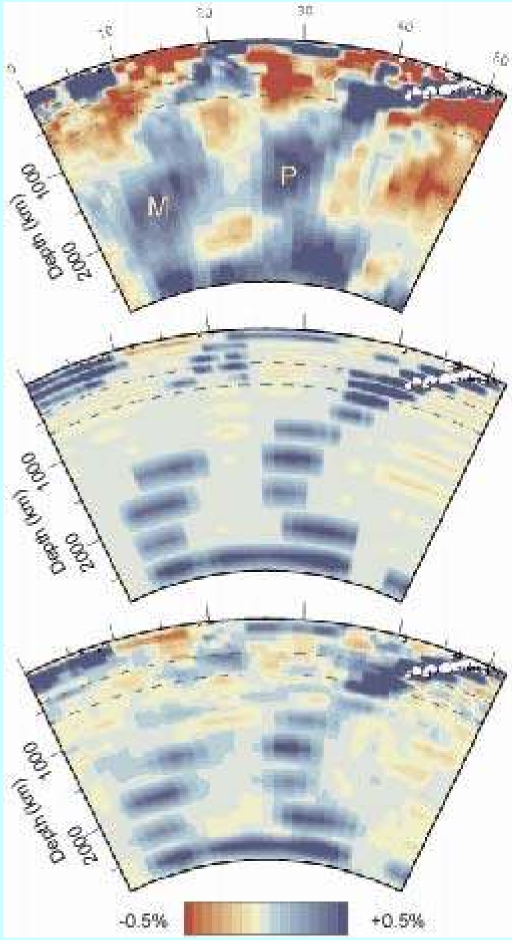

Fig. 3 Cross-section through tomographic model. Top: tomographic results, showing the Pacific Subduction zone (P) under Japan and the Mongol-Okhotsk slab (M) side-by-side. White dots show location of W-B zone. Middle: a simulated input of a whole-mantle layer cake model for this same cross-section, which is resoled and reproduced in our inversion analysis (bottom). (Van der Voo et al., 1999)[7]

hence undetectable boundary. Nevertheless, if we take the down going of the slab as the main driving force of the mantle convection, the heat flux of the layered-convection model could hardly reconcile with the slab-dominated convection circulation[8]. Therefore, an important issue will be how we can develop a model and take the geochemical and geophysical points of view into account at the same time.

An alternative explanation: the transition-zone water filter

In 2003, Bercovici and Karato raised a hypothetical mechanism of "**transition-zone water filter**"[1] (**Fig. 4**) to avoid the distinct chemical reservoir and mantle layering. According to this model, the mantle transition zone (410-660 km) materials have unusual properties relative to upper-mantle materials, such as **water solubility** and diffusivity of various atomic and electronic species. If upper and lower mantle are near chemically equilibrium with the transition zone, and given the water solubility of the transition zone is about 10-30 times higher than the upper and lower mantle, then the water content will end up with 10-30 times higher than the upper and lower mantle, which is a relatively wet condition.

In this case, the direct consequence of this heterogeneous water solubility is the dramatic redistribution of both water and trace elements through partial melting during any vertical motion across the transition zone. When the primary ascending ambient mantle is forced upward by the injection of the subducting slabs and, upon crossing the transition zone, it transforms to olivine-dominated assembly with significantly lower water solubility. This saturation to super-saturation phenomenon will soon lead to the partial melting, after which the solid phase will continue to rise. The solid phase will be relatively dry and largely filtered of incompatible elements, filling the upper mantle and later sampled by the mid-ocean ridge. The water- and incompatible-element-enriched melt residue is likely to be denser than the solid phase in the upper mantle and lighter than the transition zone material, so that it keeps accumulating above the transition zone.

This melt zone will not unlimitedly thicken and spread. Once encountering the cold subducting slab, it will be entrained back into the deeper mantle. The incompatible-element will also be returned to the lower mantle as well. Nonetheless, water will mostly be deposited in the transition zone instead of brought down by descending slabs. This is due to the lower saturation value under the 660-km discontinuity, which will cause the slab mineral to be supersaturated and exsolve water.

In contrast to upwelling ambient mantle, the water-filter effect would be largely suppressed in mantle plumes, thus allowing them to deliver moderately enriched mantle material of OIB chemistry to the surface. The plume will also absorb less water than would ambient upwelling mantle. There are two reasons for this. First, the plume moves in a higher velocity than the ambient upwelling mantle. The water entrainment zone has an inverse ratio to square root of the upwelling speed. Here, the zone width of the plume is likely between 30 m to 10 km, which implies that most of the plume remains relatively dry. Second, some studies point out that water solubility will decrease with temperature in transition-zone minerals. Therefore, hot plume with high temperature passing through the transition zone would have little capacity for water.

This "transition-zone water filter" seems fit most of the known phenomena in the mantle. However, some further testing is required. Some mineral physics remain uncertain, and whether we can observe these physical properties through seismic studies need to be examined.

Conclusion

We reviewed several papers about the convection mode of the mantle. Due to the different chemical properties of MORBs and OIBs, geochemists support the double-convection model. Many kinds of layer models are hence proposed and several discontinuities are considered to be the possible boundary between the upper and lower reservoir. In contrast, geophisicians stand for single convection model based on the imaging from seismic tomography. Here we introduce one more alternative—"transition-zone water filter". This model stands for ONE reservoir but different chemical properties in the TWO upwelling systems. The controlling mechanism lies in the high water solubility within the transition zone (410-660 km).

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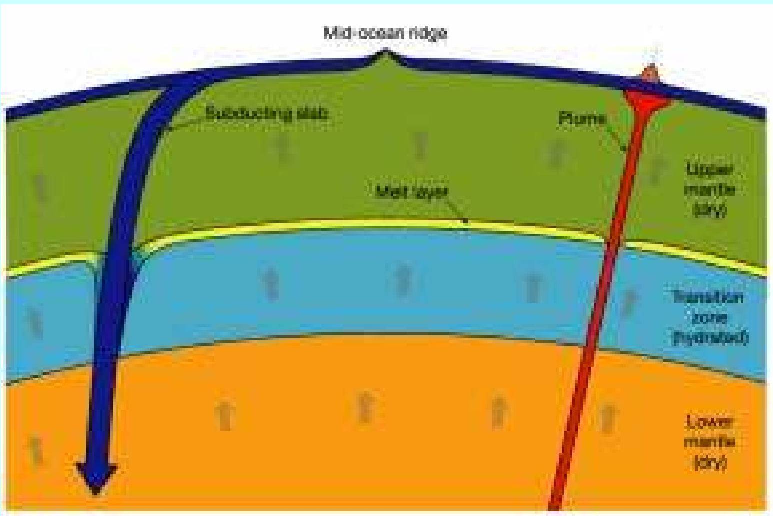

Fig. 4 Sketch of the "transition-zone water-filter" model. Cold slab (dark blue) subducting forces up the ambient mantle upwelling (arrows) that, upon passing through the high-water-solubility transition zone (light blue), gets hydrated. When leaving the transition zone at 410 km, this ambient mantle becomes low-water solubility divine and is thus super-saturated and partially melted. The wet, incompatible-element enriched melt is likely to be heavy and gathers into the high-melt fraction layer trapped above the 410-km discontinuity (yellow). The residual solid portion of upwelling ambient mantle is buoyant but very dry and depleted of incompatible elements; it provides the MORB source region (green). The water-filtering mechanism is suppressed in mantle plumes (red) due to high plume velocity and temperature. Plumes arrive at the surface still relatively wet and enriched in incompatible elements, providing the source for OIBs. Slabs efficiently entrain the melted material, returning water to the transition zone and incompatible elements to the deeper mantle. (Bercovici & Karato, 2003) [1]