

Can Lower Mantle Slab-like Seismic Anomalies be Explained by Thermal Coupling Between the Upper and Lower Mantles?

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Abstract. Below subduction zones, high resolution seismic tomographic models resolve fast anomalies that often extend into the deep lower mantle. These anomalies are generally interpreted as slabs penetrating through the 660-km seismic discontinuity, evidence in support of whole-mantle convection. However, thermal coupling between two flow systems separated by an impermeable interface might provide an alternative explanation of the tomographic results. We have tested this hypothesis within the context of an axisymmetric model of mantle convection in which an impermeable boundary is imposed at a depth of 660 km. When an increase in viscosity alone is imposed across the impermeable interface, our results demonstrate the dominant role of mechanical coupling between shells, producing lower mantle upwellings (downwellings) below upper mantle downwellings (upwellings). However, we find that the effect of mechanical coupling can be significantly weakened if a narrow low viscosity zone exists beneath the 660-km discontinuity. In such a case, both thermally induced ‘slabs’ in the lower mantle and thermally activated plumes that rise from the upper/lower mantle boundary are observed even though mass transfer between the shells does not exist.

Introduction

Despite recent developments in seismic tomography and convection modelling, the impact of the boundary between the upper and lower mantles on the convective transfer of heat is not yet clear. While it has been argued that high resolution seismic tomographic models that resolve seismically fast, slab-like structures extending deep into the lower mantle support the concept of the whole mantle flow [Grand *et al.*, 1997; van der Hilst *et al.*, 1997; Bijwaard *et al.*, 1998], there exists other evidence that suggests an impermeable, or partially impermeable boundary between the upper and lower mantles [Hofmann, 1997]. Seismic anisotropy ob-

served near a depth of 660 km suggests horizontal alignment of crystals and, therefore, some degree of flow layering [Karato, 1998; Montagner, 1998; Čadek and van den Berg, 1997]. The dynamical interpretations of the geoid show that the model with an impermeable interface at 660 km or deeper can satisfy the data equally well as the whole-mantle model [Wen and Anderson, 1997; Čadek *et al.*, 1998] and some resistance to up- and downgoing flows can reduce the amplitudes of surface dynamic topography [Thoraval *et al.*, 1995]. Finally, flow-blocking of the circulation at a depth of 670 km has been shown to improve the prediction of the observed surface heat flux [Pari and Peltier, 1998].

The strongest indication that slabs extend into the lower mantle has been provided by seismic tomography. However, the images provided by this method do not necessarily yield direct dynamical information about the radial style of the circulation. If there is an impermeable interface at 660 km, cold subducted lithosphere that has accumulated above the boundary at 660 km can cool the underlying material and initiate a downwelling instability into the lower mantle. In such a case, it would be difficult on the basis of seismic tomography alone to discriminate between ‘thermal slabs’ (with no material exchange between the upper and lower mantles) and slabs penetrating into the lower mantle. Thermal coupling between partially or fully separated upper and lower mantle flow systems thus could be an alternative explanation of the tomographic results.

Slab-like downwelling structures have previously been simulated in convection models that include a phase transition boundary at 660 km and a high lower mantle viscosity but essentially imply whole-mantle flow [e.g. Bunge *et al.*, 1998]. In the present paper, we will test whether continuous slab-like structures across the boundary at 660 km can develop even if the exchange of mass across the discontinuity is inhibited. Simulating convective flow in a model with an impermeable boundary between the upper and lower mantles, we show that thermal coupling can indeed be important and that ‘thermal slabs’ can arise for certain viscosity profile.

This study should not be regarded as advocating purely two layer convection. Its only intention is to state that the concept of an impermeable or partially impermeable boundary between the upper and lower mantle should not be rejected on the basis of seismic tomographic images alone.

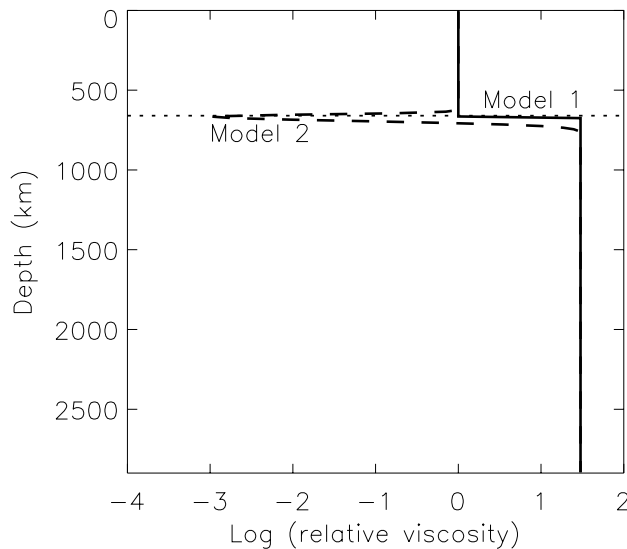


Figure 1. Viscosity models used in our study: model 1 (solid line) with the steep increase at a depth of 660 km and model 2 (dashed line) with a low viscosity zone beneath the upper/lower mantle boundary. The dotted line marks position of the impermeable boundary at a depth of 660 km.

Method

We consider incompressible Newtonian flow in an axisymmetric shell heated from below. An impermeable boundary (zero radial velocity and continuous tangential stress) is prescribed at a depth of 660 km. The boundary stays at the same depth and is not deformed. Free-slip stress conditions are imposed at the upper and lower boundaries of the shell. The Boussinesq approximation with constant parameters (except for viscosity) is adopted. The surface Rayleigh number is 10^7 . Two viscosity profiles are considered: a two layered profile with a steep increase by a factor of 30 at a depth of 660 km (model 1), and a profile with a thin low viscosity zone below the 660 km depth in addition to the lower mantle jump in viscosity (model 2), see Figure 1. The calculations have been carried out with a semi-spectral code developed by Čížková [1996]. The resolution of the model is 10 km in radius and about 2 degrees in latitude.

Results

Simulations were initially carried out for the viscosity model 1 shown in Fig. 1 characterized by a steep increase in viscosity at a depth of 660 km. Figure 2 (left column) shows two snapshots of the temperature distribution after a statistically steady state has been reached. The flow pattern is rather stable with a small number of convection cells. The cells in the upper and lower mantles are mostly coupled mechanically. This viscous coupling is much stronger than that due to the thermal effect of material lying above or below the boundary, and it forces the development of lower mantle downwellings below the upwellings in the upper mantle and vice versa. But even in this case, a downwelling in the lower mantle can occasionally develop below an upper mantle subducted cold slab, suggesting a continuous slab across 660-km (see Fig. 2, top left panel, the equatorial area). This particular feature may be rather stable and last for several hundred million years. However, the typical flow pattern

is mainly characterized by the mechanical coupling (Fig. 2, bottom left panel).

The existence of strong mechanical coupling controlling the interaction between upper and lower mantle circulations is in agreement with the results of previous studies of fully layered convection. *Richter and McKenzie* [1981] have shown that in the isoviscous case mechanical coupling at an impermeable interface dominates thermal coupling. Antisymmetric structures with upwellings below downwellings (and vice versa) are also characteristic of a model with temperature dependent viscosity [*Christensen and Yuen*, 1984; *Matyska*, results to be published]. However, a thermally induced downwelling can occasionally develop in the lower layer. *Cserepes et al.* [1988] have studied the effect of a viscosity contrast between the lower and upper layer on the type of coupling at the impermeable boundary. They have concluded that viscous coupling prevails if the viscosity contrast of the layers is small. A high viscosity contrast is required to reduce it significantly and to enhance the effect of thermal coupling. Temperature and stress dependence of viscosity should also decrease stress coupling across the boundary and, thus, increase the appearance of thermal coupling.

Here we suggest another possible mechanism that can weaken shear coupling between upper and lower mantle shells, namely, the presence of a low viscosity zone located below the impermeable interface. The existence of such a low viscosity zone located either above or below the 660-km discontinuity has recently been suggested by several authors dealing with inferences of viscosity from the geoid [*Forté et al.*, 1993; *Pari and Peltier*, 1996; *Panasjuk and Hager*, 1998; *Čadek et al.*, 1998]. Motivated by the above studies, we have tested the effect of such a low viscosity zone on mantle circulation within the context of a layered convection model. We locate the low viscosity zone in a narrow depth interval below the 660-km discontinuity (see model 2 in Fig. 1). We have found that a viscosity contrast of three orders of magnitude with respect to the upper mantle value is sufficient to suppress mechanical coupling between the upper and lower flow systems. The thermal effect of masses stored above or below the boundary then becomes important and both thermally induced ‘slabs’ in the lower mantle and ‘thermal plumes’ in the upper mantle are observed as characteristic features of the temperature field (Fig. 2, right column). In contrast to the broad low viscosity zone studied by *Cserepes and Yuen* [1997], the narrow low viscosity layer decreases the shear stress at the boundary without allowing the development of vigorous small-scale circulation. Both the plumes in the lower mantle and the downwellings in the upper mantle are quite stable. The latter cool the lower mantle material, giving rise to downwellings in the lower mantle (‘thermal slabs’). These slabs are stable for about 100 million years before they are swept by lateral flow in the lower mantle and detached from their upper mantle extensions. The upwellings behave in a similar way. The heads of the lower mantle plumes, flattened below the 660-km boundary, initiate the development of very narrow upwellings in the upper mantle which migrate towards the center of the plume head. Note that the presence of the low viscosity zone below the impermeable interface makes heat transport through the boundary more efficient than in model 1 which results in a smaller temperature jump over the mid-mantle thermal boundary layer (Fig. 3). However, even in model 2

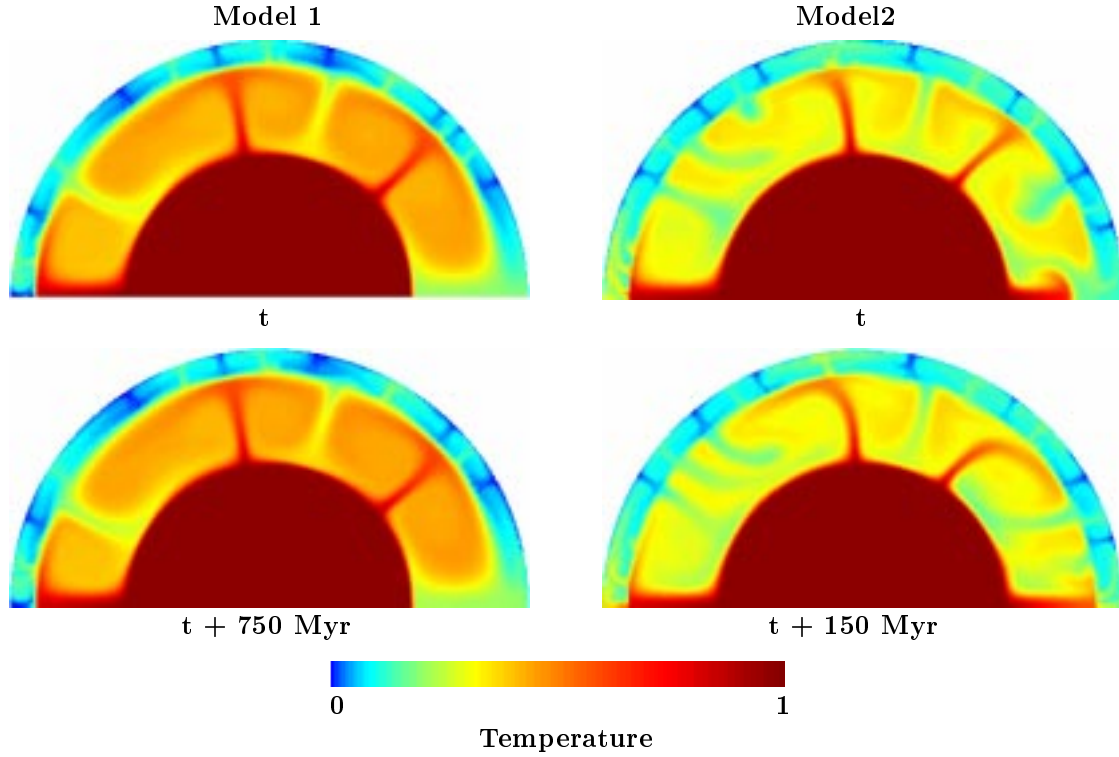


Figure 2. Left column: Two snapshots of temperature field obtained for model 1. Time difference between the upper and lower panel is 750 Myr. Right column: The same but for model 2. Time difference between the upper and lower panel is 150 Myr.

the temperature jump is about 800 K which is rather high. Including internal heating or increase of thermal conductivity with depth [Hofmeister, 1998] would probably bring the average geotherm closer to reality, without disturbing the effects of thermal coupling discussed above.

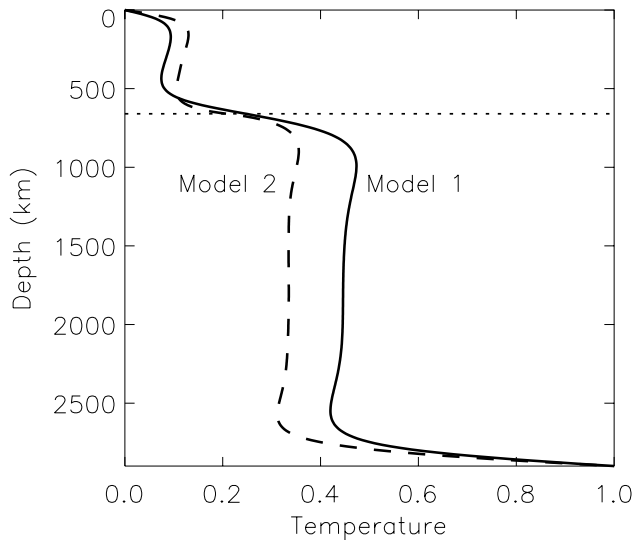


Figure 3. Average temperature profiles obtained for model 1 (solid line) and 2 (dashed line). The dotted line marks position of the impermeable boundary at 660 km.

Figure 4 shows details of several slab-like structures developed in model 2. ‘Slabs’ apparently penetrating the whole mantle (panels a and c), a thick blob reaching mid-lower mantle depth (b) as well as downwelling structures offset from the slabs in the upper mantle (d) can be observed.

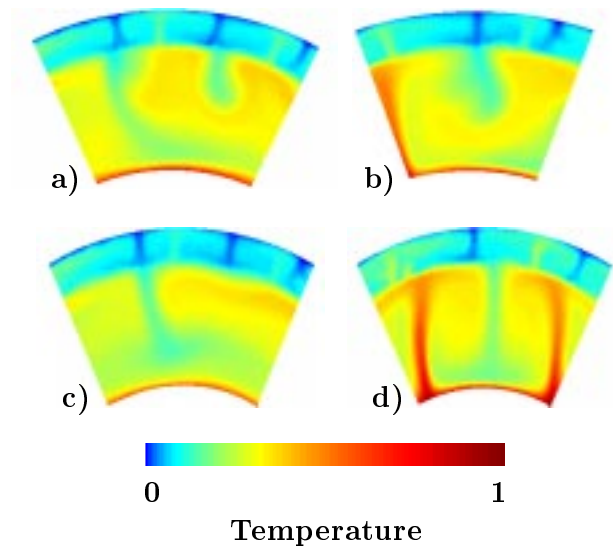


Figure 4. Details of several slab-like structures developed in model 2.

We suggest that these temperature patterns are remindful of features imaged by seismic tomography [van der Hilst, 1997; Grand et al., 1997; Bijwaard et al., 1998].

Conclusions

The results of our study suggest that the concept of a fully impermeable boundary between the upper and lower mantle is not necessarily in contradiction with seismic tomographic images of mantle heterogeneity. The slab-like structures in the lower mantle are observed under several conditions, but they directly underlie the upper mantle slabs only if the viscous coupling is decreased. Then, thermally induced continuous slab-like structures become characteristic features of the flow.

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References

- Bijwaard, H., W. Spakman, and E. Engdahl, Closing the gap between regional and global travel time tomography, *J. Geophys. Res.*, **103**, 30055-30078, 1998.
- Bunge, H., M. Richards, C. Lithgow-Bertelloni, J. Baumgardner, S. Grand, and B. Romanowicz, Time scales and heterogeneous structure in geodynamic Earth models, *Science*, **280**, 91-95, 1998.
- Christensen, U., and D.A. Yuen, The interaction of a subducting lithospheric slab with a chemical or phase boundary, *J. Geophys. Res.*, **89**, 4389-4402, 1984.
- Cserepes L., M. Rabinowicz, and C. Rosemberg-Borot, Three-dimensional infinite Prandtl number convection in one and two layers with implications for the Earth's gravity field, *J. Geophys. Res.*, **93**, 12009-12025, 1988.
- Cserepes, L., and D.A. Yuen, Dynamical consequences of mid-mantle viscosity stratification on mantle flows with an endothermic phase transition, *Geophys. Res. Lett.*, **24**, 181-184, 1997.
- Čadek, O., and A.P. van den Berg, Layered mantle convection with a composite Newtonian and non-Newtonian rheology: consequences for seismic anisotropy, *EOS, abstract supplement AGU 78(46)*, F660, 1997.
- Čadek, O., D.A. Yuen, and H. Čížková, Mantle viscosity inferred from geoid and seismic tomography by genetic algorithms: Results for layered mantle flow, *Phys. Chem. Earth*, **23** (9-10), 865-872, 1998.
- Čížková, H., Modeling the dynamical processes in the Earth mantle, PhD thesis, Charles University, Prague 1996.
- Forte, A.M., A.M. Dziewonski, and R.L. Woodward, Aspherical structure of the mantle, tectonic plate motions, nonhydrostatic geoid, and topography of the core-mantle boundary, in *Dynamics of the Earth's Deep Interior and Earth Rotation*, J.-L. Le Mouél, D.E. Smylie and T. Herring (eds.), pp 135-166, Geophys. Monograph No. 72, AGU, Washington, D.C., 1993.
- Grand, S.P., R.D. van der Hilst, and S. Widiyantoro, Global seismic tomography: A snapshot of convection in the Earth, *GSA Today*, **7(4)**, 1-7, 1997.
- Hofmann, A.W., Mantle geochemistry: the message from oceanic volcanism, *Nature*, **385**, 219-229, 1997.
- Hofmeister, A., Mantle values of thermal conductivity and the geotherm from phonon lifetime, *Science*, **283**, 1699-1706, 1999.
- Karato, S., Seismic anisotropy in the deep mantle, boundary layers and the geometry of mantle convection, *Pure appl. geophys.*, **151**, 565-587, 1998.
- Montagner, J.-P., Where can seismic anisotropy be detected in the Earth's mantle? In boundary layers..., *Pure. appl. geophys.*, **151**, 223-256, 1998.
- Panasjuk, S.V., and B.H. Hager, A model of transformational superplasticity in the upper mantle, *Geophys. J. Int.*, **133**, 741-755, 1998.
- Pari, G., and W.R. Peltier, The free-air gravity constraint on subcontinental mantle dynamics, *J. Geophys. Res.*, **101**, 28105-28132, 1996.
- Pari, G., and W.R. Peltier, Global surface heat flux anomalies from seismic tomography-based models of mantle flow: Implications for mantle convection, *J. Geophys. Res.*, **103**, 23743-23780, 1998.
- Richter, F., and D. McKenzie, On some consequences and possible causes of layered mantle convection, *J. Geophys. Res.*, **86**, 6133-6142, 1981.
- Thoraval, C., Ph. Machetel, and A. Cazenave, Locally layered convection inferred from dynamic models of the Earth's mantle, *Nature*, **375**, 777-780, 1995.
- van der Hilst, R.D., S. Widiyantoro, and E.R. Engdahl, Evidence for deep mantle circulation from global tomography, *Nature*, **386**, 578-584, 1997.
- Wen, L., and D.L. Anderson, Layered mantle convection: A model for geoid and topography, *Earth Planet. Sci. Lett.*, **146**, 367-377, 1997.

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