Mantle Dynamics and the D″ Layer: Impacts of the Post Perovskite Phase

W.R. Peltier

Department of Physics, University of Toronto, Toronto, Ontario, Canada

The D″ layer at the base of the planetary mantle is a feature of the structure of the deep Earth that is intimately connected to the dynamical process of convective mixing that is responsible for surface plate tectonic processes. Although the existence of this distinct layer was first recognized by *Damn* [1934] and later given its present name by *Bullen* [1950], its understanding has since remained enigmatic and a significant focus of geophysical investigation. The recent discovery of the post-Perovskite phase transformation at a pressure near 125 GPa and a temperature near 2500°K may have finally resolved the reason for the existence of this deepest mantle layer but in doing so the discovery has raised numerous new questions that have yet to be answered.

1. INTRODUCTION

The D″ layer was first introduced into geophysical nomenclature by the New Zealand seismologist Keith Edward Bullen who, in 1942, as a consequence of his work with Sir Harold Jefferies on the Jefferies-Bullen travel time tables, had proposed a spherically symmetric "shell model" of Earth's interior in which the individual shells were labeled by the letters A through G, shell A corresponding to the crust and shell G to the inner core. As we were recently reminded in an EOS article on D″ by *Chao* [2000], Bullen's lower mantle in the original shell model was denoted by the letter D. By 1950, however, Bullen had recognized that the lowermost region of the lower mantle, a layer of thickness 200-300 km, had properties that made it distinct from the overlying and much thicker portion of this region. He was therefore compelled by the evidence to split the D layer into two parts which he labeled D′ and D″. The former of these regions we now refer to simply as the lower mantle, but the latter has retained the name originally given it by Bullen. Chao suggested on this basis that this layer might more reasonably be referred to as the Bullen layer, a suggestion that elicited a great deal of interesting historical comment in which it was pointed out that the discovery of a seismically distinctive layer immediately above the cmb was made much earlier by *Cornelius Damn* in 1934 in his doctoral dissertation at St. Louis University [*Kisslinger*, 2000].

From a geodynamic perspective, this layer is profoundly important as it forms a "boundary layer" above the core-mantle boundary that is presumably actively involved in the process of mantle convective mixing, although to a degree that remains to be understood. The physical nature of this boundary layer also persists as an issue of active debate and my purpose in this brief article is to comment upon the evolution of our understanding of this feature as a means of highlighting the impact that the discovery of the post-Perovskite phase transformation is having on the subject. The important paper of *Murakami et al.* [2004], in which high P-T experiments were shown to reveal the existence of a new phase transformation, a "last phase transformation", at a pressure of ~125 GPa corresponding approximately to the depth to the top of Bullen's D″ layer, and at a temperature of ~2500°K, suggests that the existence of this phase transformation may play a more important role in understanding the properties of this layer than the chemical heterogeneity that has often been invoked to explain many of its most important attributes (e.g. seismic anisotropy, see

Post-Perovskite: The Last Mantle Phase Transition
Geophysical Monograph Series 174

10.1029/174GM15

Oganov and Shigeaki, 2004). The issue of the extent of the chemical heterogeneity in the lowermost mantle (e.g. as recently discussed in *Trampert et al.*, 2004) is clearly of fundamental interest insofar as the physical nature of the convective circulation is concerned. Recent analyses of the azimuthal anisotropy in D" and the recognition that this onsets at the "top" of the layer [*Garnero et al.*, 2004] suggest that its interpretation as being defined primarily by chemical heterogeneity [e.g. *Lay et al.*, 2004] may be misleading. The success of a chemically homogeneous interpretation of D" data from the central Pacific [*Lay et al.*, 2006] is rather convincing although the authors believe that there remains the necessity to include chemical heterogeneity at the base of the mantle in the surrounding region in which down going slabs may be leading to the accumulation of "piles" of chemically distinct material. In *Mao et al.* [2006], on the other hand, the authors suggest that Fe enrichment of the post Perovskite phase due to the influence of direct chemical interaction with core would lead to the association of the Fe enriched post Perovskite phase with regions of upwelling which they would be expected to underplate. These issues will be further discussed in what follows.

The dynamical implications of the post-Perovskite interpretation of the D" layer are perhaps even more important than the implications insofar as the interpretation of seismic observations are concerned. From a dynamical perspective, a critical property of any pressure induced phase transition concerns its Clapeyron slope. In this regard it is interesting to note the contribution of *Sidorin et al.* [1999] on the "Evidence for an ubiquitous seismic discontinuity at the base of the mantle" in which it was suggested that the inferred discontinuity might be most easily explained by the presence of a phase transition having a Clapeyron slope of approximately 6 MPa/°K. *Tsuchiya et al.* [2004] have confirmed, using first principles high P-T theoretical computation, that a structural phase transition is expected in silicate Perovskite under the same conditions as those in the experiments of *Murakami et al.* [2004] and have computed the Clapeyron slope of the transition to be 7.5 ± 0.3 MPa/°K. A range of estimates for this Clapeyron slope is now available that includes those by *Hirose et al.* [2006] who have obtained slopes in the range 4.7 MPa/°K - 11.5 Mpa/°K by using, respectively, the Au and MgO pressure standards, and *Ono and Oganov* [2005] that may extend the upper bound of this range to the very high value of 13 MPa/°K. According to the results of past analyses of the influence of such a phase transformation upon high Rayleigh number thermal convection, a phase transformation with a positive Clapeyron slope will enhance the vigour of the circulation if this is entirely thermally driven [e.g. *Peltier and Solheim*, 1994]. This mechanism for the enhancement of instability in D" could be important to understanding the origin of mantle plumes.

There is therefore a confluence of evidence suggesting that the explanation of Bullen's D" layer may be primarily that its existence is due to the Perovskite to post Perovskite phase transformation. Given the possible importance of this discovery for our understanding of mantle dynamics, it may serve as a useful contribution to this collection of papers on the Pv-pPv phase transformation, "the last phase transition", to consider how our understanding of the D" layer above the cmb has evolved over the past few decades.

2. INTERNAL EARTH STRUCTURE AND MANTLE DYNAMICS

Plate 1, modified from that in *Jeanloz* [1989], depicts the well known primary divisions of Earth's interior as they were described by *Bullen* [1950] but with the addition of an envisioned layer of the post Perovskite phase. Although the discontinuities in the internal elastic properties at the interfaces that bracket the transition zone are now known to be primarily due to the phase transitions from Olivine to Spinel at 410 km depth [*Ringwood and Major*, 1970] and from Spinel via a disproportionation reaction to a mixture of Perovskite ((Mg, Fe) SiO_3; Pv) and magnesiowustite ((Mg, Fe)O) at 660 km depth [*Ito et al.*, 1989], there has been a tendency in some quarters to continue to connect the deeper of these discontinuities to a change in mean atomic weight [e.g. *Anderson*, 1989]. A similar tension currently exists in connection with the interpretation of the D" layer as mentioned above. Because of the extremely large density discontinuity at the cmb, denoted by the arrows on Plate 1, there is clearly a very good reason to imagine that the interface between the outer core and the mantle could be a boundary at which chemically distinct phases with density intermediate between the core and the lower mantle might concentrate, just as is the case at the Earth's surface where buoyant continental crust is created by irreversible chemical differentiation from the mantle through partial melting. Plate 2 presents a cartoon of the D" layer, modified from *Lay et al.* [1989], which emphasizes an emerging interpretation in which not only chemical heterogeneity may exist but also extensive pockets of the new pPv phase. However, the true extent of such chemical heterogeneity, associated say with the degree of iron enrichment and the extent to which this may be a pervasive property of the lower half or so of the lower mantle [e.g. *Trampert et al.*, 2004], must be considered to remain an open question. Since the interpretation of the D" layer in terms of chemical heterogeneity was originally invoked to explain properties of this layer that appear to be well (in some cases better) explained by the Pv-pPv transition, it is interesting to speculate as to whether the currently prevalent mantle convection models that include significant chemical heterogeneity in the bottom half of the lower mantle will survive if the interpretation of

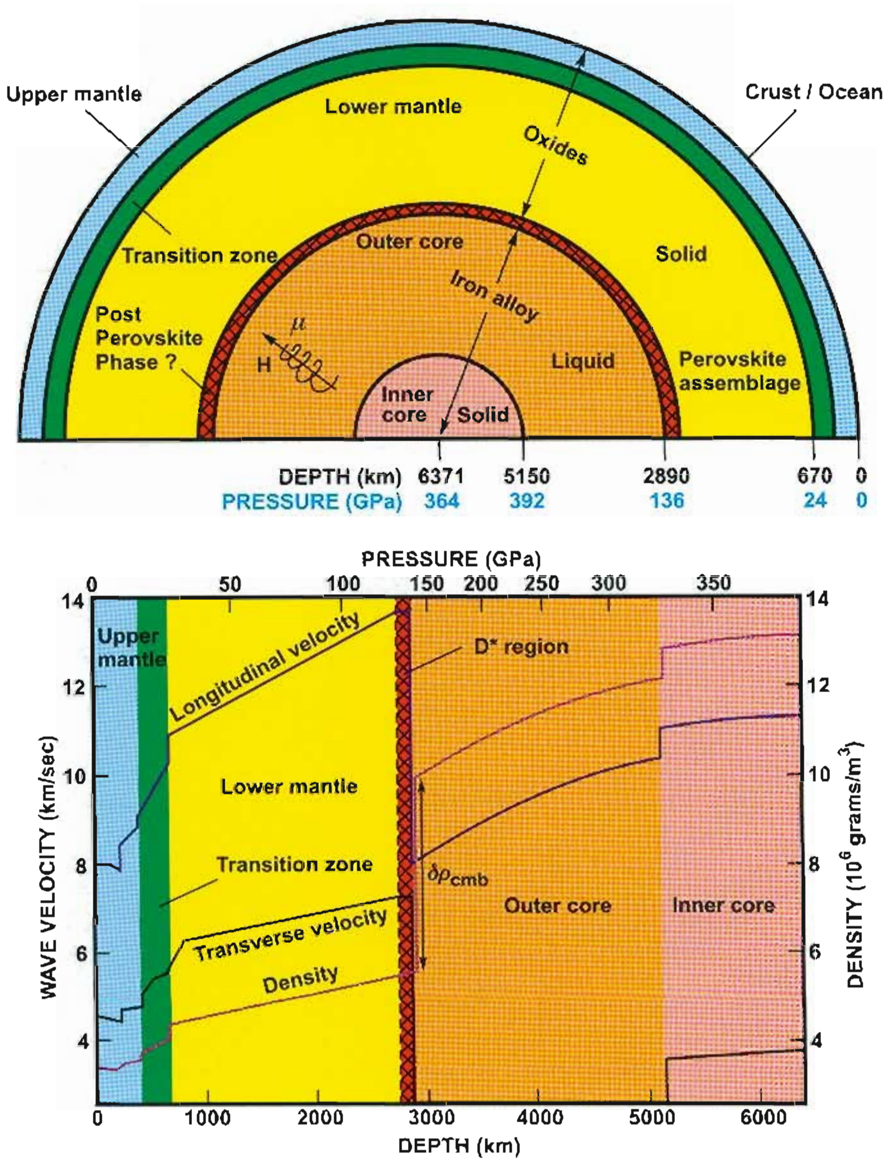

Plate 1. (a) Schematic cross-section of the Earth illustrating the distinction between the overlying crust and hydrosphere, and the solid mantle comprised of oxides. as well as the predominantly iron core. The upper mantle, transition zone, lower mantle and D" region are shown as distinct color-coded regions with D" indicated as perhaps being comprised of the newly discovered post Perovskite phase. The cyclonic motions denoted by the vector $\underline{u}$ in the liquid outer core are responsible through a dynamo mechanism for the generation of the planetary magnetic field, **H** (b). The structure in (a) is inferred on the basis of seismological observations of the longitudinal (V_p) and transverse velocity (V_t) of elastic waves and the density as a function of depth. This part of the Figure, which is color coded as in (a), is based upon the preliminary reference Earth model (PREM) of *Dziewonski and Anderson* [1981]. Especially notable is the large density difference between the outer core and the lower mantle across the core-mantle boundary (cmb). This Figure is modified after Figures 4.1 and 4.2 of *Jeanloz* [1989].

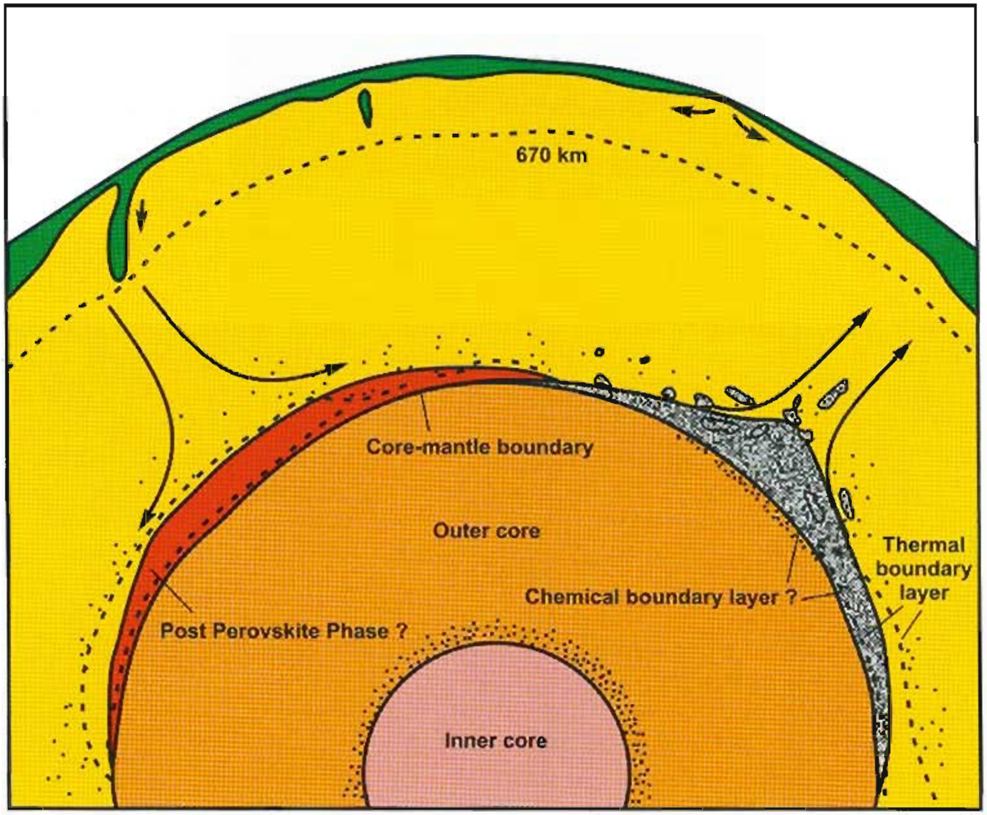

Plate 2. A mantle dynamics cartoon which attempts to depict the possible inter-relations between the dynamical process of mantle convection and the perhaps chemically heterogeneous and post Perovskite phase dominated thermal boundary layer that is D". This Figure is modified after a paper by T. Lay (Trans. Am. Geophysics. Union, 70, 49, 1989; © American Geophysical Union).

the D″ layer as primarily a (final) phase change interface is supported by further research.

It is therefore useful as a means of reviewing the plausibility of chemically homogeneous models of the mantle convection process to consider what such models say about the interpretation of D″ when the pPv transition is taken into account. For some time, all such models have included the influence of both the Olivine-Spinel and the Spinel-post Spinel transitions in the transition zone, the former having a weakly destabilizing influence and the latter a significantly stabilizing influence depending upon the magnitude of the negative Clapeyron slope that characterizes the strength of its influence. *Solheim and Peltier* [1994a, b] have presented detailed models of this kind in which the transition at 660 km depth has the effect of causing the circulation to undergo episodic transitions from a layered circulation to one of whole mantle style. Plate 3 from their paper illustrates a typical result from such an isochemical model of the convective mixing process. This model was axisymmetric in geometry and the graphic illustrates the radial velocity and temperature fields within the flow at an "instant" when the Spinel-post Spinel transition at 660 km depth has enforced a strongly layered style of mixing such that the mass flux across 660 km depth is significantly reduced. The inhibition of radial mixing due to the influence of this endothermic transition is in close accord with expectations based upon seismic tomographic images of transition zone heterogeneity in the vicinity of subduction zones [e.g. *van der Hilst et al.*, 1996; *Zhao*, 2004; *van der Hoeven*, 2004] which reveal clear evidence of anomalously cold down-going slabs being at least temporarily "trapped" between the two bounding phase transition interfaces.

Inspection of the temperature field in Plate 3, which is from an isochemical convective circulation operating at a Rayleigh number of 10^7 with no pPv transition, shows that the cmb region is the source of multiple intense thermal upwellings (thermal plumes), only some of which are sufficiently vigorous to traverse the entire depth of the lower mantle. Most have insufficient positive buoyancy to survive the thermal and viscous dissipation against which they must compete in order to ascend. In the isochemical interpretation of the mantle convection process, the D″ layer is simply interpreted as the lower thermal boundary layer of the convecting region across which heat is transported by thermal diffusion from the outer core into the base of the mantle.

Figure 1 illustrates this thermal boundary layer through the depth dependence of the azimuthally averaged temperature field in the mantle shell. Results are shown for models that both include and exclude the influence of the phase transitions that bracket the transition zone and which both exclude ($\mu = 0$) and include ($\mu = 10$) the influence of internal heating in the mantle due to the decay of the long lived radioactive isotopes of U, K and Th. For the $\mu = 10$ cases without and with the transition zone phase transitions present, the ratio of the internal heating to the total heating from within and below is .42 and .53 respectively. These profiles are adiabatic in the interior of the flow and away from the internal phase boundaries. Inspection of the Figure will show that this uniphase version of the D″ layer involves an intense lower thermal boundary layer across which there is an increase in

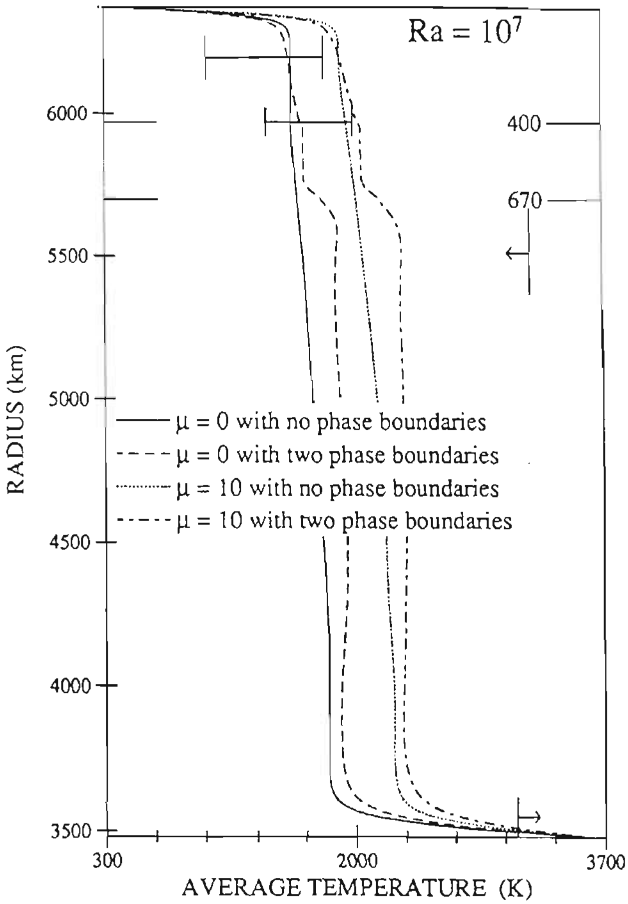

Figure 1. Illustrates the influence of internal heating on the temporally averaged geotherm in a sequence of mantle convection simulations that includes that from which the snap-shot shown in Plate 3 was taken. These 4 geotherms are from simulations in which there are either no phase boundaries, or which include both of the phase boundaries that bracket the transition zone with Clapeyron slopes as for the model with properties discussed in the caption to Plate 3. The 2 curves on the right come from simulations in which there is internal heating corresponding to $\mu = 10$ whereas those on the left have no internal heating. Inspection will show that the most obvious effect of adding internal heating is to raise the temperature characteristic of the geotherm by ~400°K in these cases. The error bars and vertical lines with attached arrows represent constraints on an "Earth-like" geotherm.

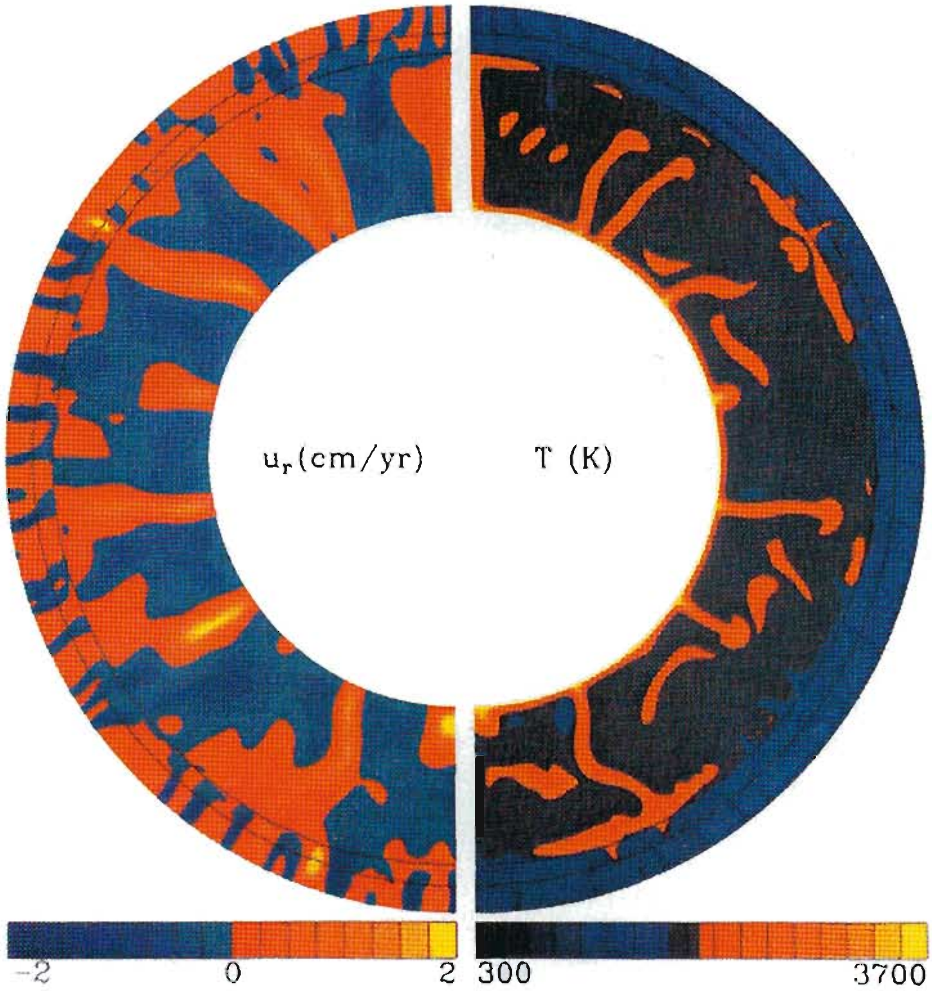

Plate 3. A "snap-shot" showing isotherms (right) and radial velocity contours (left) from a simulation of the mantle convection process in which the Rayleigh number Ra = 10^7 with no internal heating ($\mu = 0$) and the Clapeyron slopes of the Olivine-Spinel and Spinel-post Spinel transitions are taken to be +3.0 MPa/°K and −2.8 MPa/°K respectively. This is a reproduction of plate 2 from *Solheim and Peltier* [1994a].

temperature of approximately 1400°K. This calculation matches the constraint on cmb temperature (within the uncertainty) obtained by *Boehler* [1993. 1996] based upon an adiabatic extrapolation from the phase transformation in Fe at the inner-core, outer-core boundary upwards to the cmb. The thickness of this purely thermal boundary layer very well matches the observed thickness of the D″ layer of approximately 250 km. The surface and cmb heat flows for this model are also in reasonably close accord with observations and geochemically derived inferences respectively.

Now the isochemical and isoviscous model for which results are shown on Figures 3 and 4 obviously excludes a number of processes that are known to exert some, perhaps significant, influence on the flow even in the isochemical limit. Perhaps the foremost among these is the influence of the temperature and pressure dependence of viscosity. *Christiansen* [1989], however, has shown that the net effect of such variations of viscosity may be extremely modest in the sense that they can be represented simply by an appropriate re-scaling of the Rayleigh number. Of course the detailed form of the hot upwelling plumes that are triggered through convective destabilization of the boundary layer itself will be significantly modified by the impact of the viscosity variation that occurs as the plume ascends into the lower temperature environment above its D″ source.

It will be interesting here from the perspective of understanding the evolution of thinking concerning D″ as a primary plume source to re-visit the arguments presented in *Yuen and Peltier* [1980a, 1980b]. In those papers, the authors assumed a boundary layer temperature profile characteristic of constant viscosity high Rayleigh number convection in the form:

$$\overline{T}(y) = T_b + (T_m - T_b)\, erf(y/\delta) \qquad (1)$$

in which $\overline{T}(y)$ is the basic state temperature profile in an assumed sub-solidus boundary layer above the cmb, y is the height above the boundary, T_m is the asymptotic temperature of the mantle above the boundary layer, T_b is the temperature at the cmb and δ is a characteristic boundary layer thickness. They then computed the viscosity profile through this boundary layer as:

$$v(\overline{T}) = v_m\, exp\left[\frac{Q^*}{R}\left(\frac{1}{\overline{T}} - \frac{1}{T_m}\right)\right] \qquad (2)$$

in which v_m is the asymptotic viscosity of the lower mantle above the boundary layer where $\overline{T} = T_m$, R is the universal gas constant and Q^* is the activation enthalpy for creep.

Given the one-dimensional basic state described by (1) and (2) the stability of such states was analysed by solving a coupled set of linear stability equations in the stream function and temperature by assuming velocity (u) and temperature (θ) fluctuations of the form (u, θ) α exp (σt ilx) in which both the growth rate (σ) and horizontal wave number (l) were assumed to be real. The governing linear stability equations are as follows:

$$\frac{d^4\psi}{dy^4} + \frac{2}{v}\frac{dv}{dy}\frac{d^3\psi}{dy^3} + \left(\frac{\ell}{v}\frac{d^2v}{dy^2} - 2\ell^2\right)\frac{d^2\psi}{dy^2} - \frac{2\ell^2}{v}\frac{dv}{dy}\frac{d\psi}{dy}$$

$$-\left(\ell^4 + \frac{\ell^2}{\gamma}\frac{d^2v}{dy^2}\right)\psi - \frac{\ell Ra\theta}{v} = 0 \qquad (3a)$$

$$\frac{d^2\theta}{dy^2} - (\Omega + \ell^2)\theta - \ell\frac{d\overline{T}}{dy}\psi = 0 \qquad (3b)$$

This set of equations was solved using a "shooting" method subject to the boundary conditions:

$$\text{(i)} \quad \theta = \psi = \frac{d^2\psi}{dy^2} = 0 \text{ on } y = 0 \text{ (the cmb)} \qquad (3c)$$

$$\text{(ii)} \quad \theta = \psi = \frac{d\psi}{dy} = 0 \text{ as } y = \infty \text{ (in the interior)} \qquad (3d)$$

In these equations y is the vertical co-ordinate non-dimensionalized by the boundary layer thickness δ, $\overline{T}$ is the error function temperature profile non-dimensionalized by the temperature at the cmb T_b, ℓ is the non-dimensional wave number $\ell = 2\pi\, \delta/\lambda$ and Ra = $(T_b - T_m)\, \delta^3\, \alpha g\, \rho/\kappa v_m$ is the local Rayleigh number associated with a particular asymptotic mantle viscosity v_m. The parameter $\alpha = 1 \times 10^{-5}$°K^{-1} is the coefficient of thermal expansion, $\rho = 5.5$ gm cm^{-3} is the lower mantle density, $\kappa = 10^{-2}$ cm^2 s^{-1} is the thermal diffusivity and $g = 1030$ cm/s^2 is the gravitational acceleration at the cmb. In (3) the growth rate Ω has been non-dimensionalized with respect to a diffusion timescale δ^2/κ.

The results obtained on the basis of analyses using this theoretical structure are well illustrated by Figure 2 in which are plotted viscosity and temperature of the 1-D basic state as a function of distance y from the cmb. Also shown on the same graph are eddy heat flux correlations for two different examples, labeled A and B respectively on the Figure. For these examples, the assumed values of the parameters of the problem are $T_m = 3000$°K, $\Delta T = T_b - T_m = 1500$°K, and $v_m = 5 \times 10^{23}$ Poise (=5 × 10^{22} Pa s), a deep mantle viscosity that is somewhat higher than that inferred in Peltier 1996

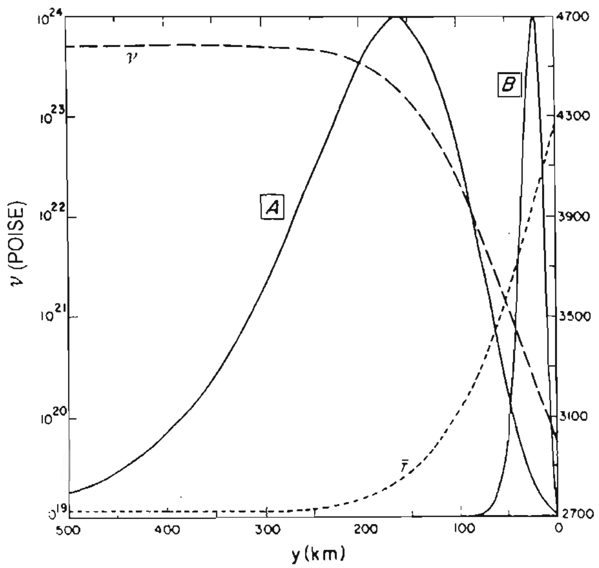

Figure 2. Basic state temperature $\bar{T}$ and viscosity ν profiles together with the "eddy" heat transport $\langle w\theta \rangle$ of the fastest growing mode of instability for (A) constant viscosity and (B) $Q^* = 160$ kcal/mode, $\nu_\infty = 5 \times 10^{23}$ Poise (5×10^{22} Pa s), $T_m = 3000°K$, $T_b - T_m = 1500°K$. The growth time for (A) is 411.2 Myr with horizontal wavelength $\lambda = 1675$ km. The growth time of (B) is 4.37 Myr with $\lambda = 132$ km. The absolute amplitudes of the vertical velocity (w) and temperature perturbation (θ) eigenfunctions are arbitrary in linear stability theory and the bracket < > represents the depth dependent correlation of the two eigenfunctions. This Figure is based upon Figure 1 of *Yuen and Peltier* [1980]a.

based upon the formal Bayesian inversion of data pertaining to the glacial isostatic adjustment process. Cases A and B, documented in the Figure by the depth dependence of the eddy heat flux correlations associated with their fastest growing modes of instability, then differ in that for A, $Q^* = 0$ whereas for B, $Q^* = 160$ kcal /mole. Thus A corresponds to a constant viscosity model. It is clear on the basis of this figure that in case A the region of significant eddy correlation extends well into the lower mantle above the D" layer whereas that for case B is strongly confined within the low viscosity region immediated adjacent to the cmb. Growth times (1/growth rates) for these two cases are respectively 411×10^6 years for the constant viscosity case A and 4.4×10^6 years for case B, demonstrating that the strong temperature dependence of viscosity within the lower thermal boundary layer will lead to a separation of timescales between that characteristic of the large scale overturning flow, and that on which intense small horizontal spatial scale plumes will form and subsequently be ejected into the mantle to serve as a "second scale" of the mantle convection circulation. It will be interesting in the next Section of this paper to comment briefly upon the impact that the discovery of the post Perovskite phase transition might be expected to have upon this purely thermal and chemically homogeneous view of Bullens D" layer.

3. DEEP MANTLE DYNAMICS IN THE POST - POST PEROVSKITE TRANSITION ERA

Prior to the discovery of the post Perovskite phase transition by *Murakami et al.* [2004], candidate characterizations of D" were those sketched in Figure 3 [from *Garnero*, 2000]. Part a of this sketch illustrates the thermal characterization of D" as a simple thermal boundary layer through which heat is transferred by diffusion from the hot outer core at the cmb into the lower mantle. Part b of the sketch displays alternative models that have been invoked to represent the radial variation of seismic velocities through the same region, models that have included both continuous and essentially discontinuous profiles. In part c of the sketch, partial melting, either in the form of a thin layer immediately adjacent to the cmb or in the form of thin lamellae or scatterers throughout D" have been suggested [*Kendall and Silver*, 1998; *Vidale and Hedlin*, 1998] in explanation of the apparent presence of ultra-low velocity zones [*Williams and Garnero*, 1996] within D". In part d of the sketch, the D" layer is shown as being perhaps characterized in an important way by the presence of chemical heterogeneity, either confined to D" itself or being present throughout the lower third of the entire lower mantle (e.g. *Kellogg et al.*, 1999).

It is clearly extremely important to the development of our understanding of deep mantle dynamics to appreciate the impact upon the most plausible characterization of D" that the discovery of the post Perovskite transition must have. In attempting to characterize this impact it will be useful to consider each of the elements of the above discussed cartoon in turn. First, in terms of the thermal characterization, the continuing existence of a thermal boundary layer at the base of the mantle is inevitable if the overlying mantle is as vigorously connecting as is required to drive surface plate tectonics. However, if the radiative contribution to the thermal conductivity were to be strongly enhanced in the post Perovskite phase, as suggested by the measurements described in *Badro et al.* [2004], then this boundary layer would tend to develop somewhat above the cmb rather than at the cmb itself.

Concerning the variations of seismic velocity from the lowermost mantle through D" to the cmb shown on part b of Figure 3, it will be clear that a (near) discontinuity in wave speeds should exist across the phase boundary on account of the change of elastic properties wherever the new phase

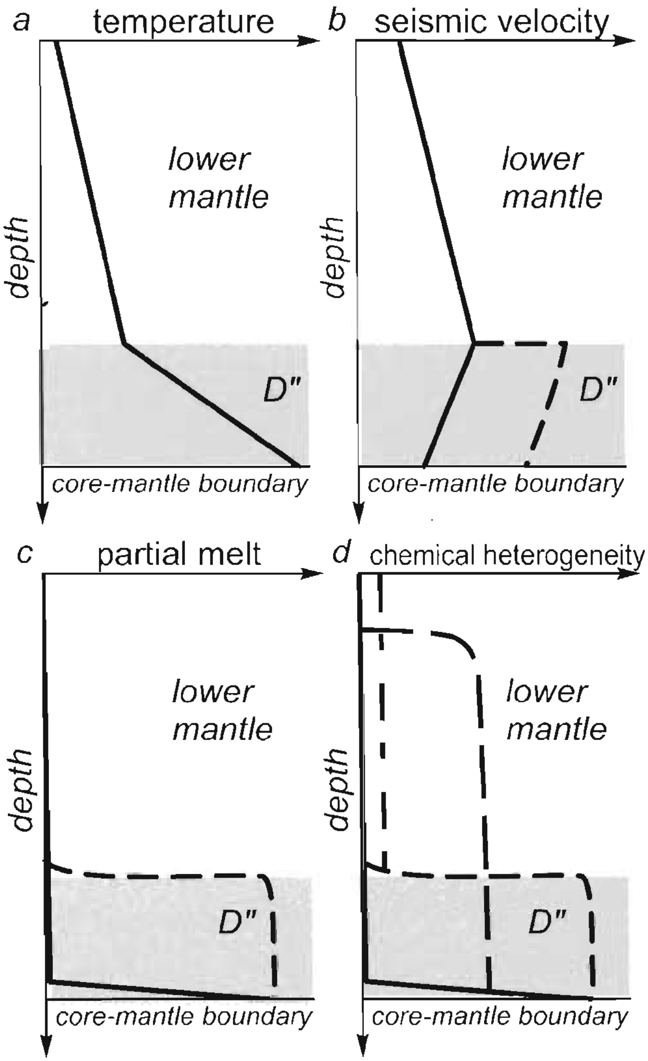

Figure 3. Depth dependent profiles of various physical properties in the lowermost mantle. The D" region is shown as shaded and represents the layer of thickness between 200 and 300 km that rests upon the core-mantle boundary at a depth of approximately 2890 km. In (a) D" is shown as being characterized as a thermal boundary layer, in (b) by the depth variation of seismic velocities throughout which have been inferred in various studies to be either continuous or discontinuous (dashed line). If D" were defined entirely as being comprised of the post Perovskite phase then the discontinuity would be ubiquitous as suggested in *Sidorin et al.* [1999]. In (c) D" is shown as perhaps incorporating ultra-low velocity zones (ULVZ's shown as the solid line). *Williams and Garnero* [1996] suggested that these could be associated with partial melting but the recent paper by *Mao et al.* [2006] demonstrates that such ULVZ's are most simply explained as resulting from Fe enrichment of the post Perovskite phase. In (d) the entire lower mantle has been suggested to be chemically heterogenous (*Kellogg et al.*, 1999, heavy dashed line), or entirely confined to D" itself. This Figure is based upon Figure 1 from *Garnero* [2000].

exists adjacent to the cmb in accord with the inference of *Sidorin et al.* [1999].

On the issue of partial melting and the origin of Ultra-Low Velocity Zones (ULVZ's) sketched in part c of Figure 3, the discovery of the pPv transition appears to have demonstrated that partial melting is not required to explain the high values of the Poisson ratio that is characteristic of the ULVZ's. *In Mao et al.* [2006], it has been convincingly demonstrated that the post Perovskite phase "can retain a large amount of Fe leading to a dramatic increase of density". This analysis demonstrates that Fe enrichment of this silicate is a highly likely consequence of contact of the post Perovskite phase with the liquid Fe alloy of the outer core. The authors argue that this Fe-rich post Perovskite silicate would be far "too heavy to rise in the mantle and would pile up beneath upwelling areas (as suggested in Plate 2) to form seismically observable ULVZ patches that could correlate with active hot spots and upwelling areas [*Helmberger et al.*, 1998; *Williams et al.*, 1998; *Ishi and Tromp*, 1999]. This work strongly suggests that partial melting may play no role at all in the existence of the ULVZ's that have been detected seismologically.

Concerning the final issue of chemical heterogeneity sketched in part d of Figure 3, namely that concerning the existence of chemical heterogeneity as a necessary attribute of the mantle mixing process, these results also have a strong bearing. If all of the chemical heterogeneity inferred to exist in D" were entirely due to the infiltration of Fe into the post Perovskite phase from the outer core, then there would appear to be no compelling need to invoke Fe enrichment in the mantle above D". This may be the most profound consequence of the evolving new paradigm for the interpretation of D" that is suggested by the discovery of the "last phase transition".

Concerning the direct dynamical impact of the new phase that is now expected to exist at the base of the mantle and which therefore may define this layer, some further commentary may be useful. Previous analyses of the way in which solid-solid phase transformations may directly impact the process of convective mixing demonstrate, as previously noted, that an exothermic transition such as that involving the transformation of Pv to pPv will strongly enhance the convective mixing process if the Rayleigh number of the system is sufficiently super-critical. Since the Rayleigh number that governs the mixing process in the mantle is $O(10^7)$, the degree of supercriticality guarantees that the deepest mantle phase transition would strongly enhance the boundary layer instabilities responsible for the plume formation process in the *Yuen and Peltier* [1980a,b] interpretation. Recent analyses of the mixing process that have included the influence of the phase change have indeed shown this to be the case [e.g. *Nakagawa and Tackley* 2005; *Yuen et al.*, 2007]. None of these analyses have however treated the influence of core-derived

Fe enrichment of the pPv phase upon the mixing process but have treated the influence of chemical heterogeneity on the basis of the assumption that it is a pervasive influence throughout the lowermost region of the lower mantle. As clearly noted in *Nakagawa and Tackley* [2005], however, "the density difference between subducted MORB and pyrolite in the deep mantle is quite uncertain", and this leads them to include a no deep chemical heterogeneity case in their sequence of analysis. It may well be that, in spite of the reduction of the coefficient of thermal expansion with depth, an influence fully incorporated in the analyses of *Solheim and Peltier* [1994a,b], thermal buoyancy may so overwhelm chemical buoyancy that the latter influence is as insignificant as originally suggested in *Forte and Mitrovica* [2001].

4. CONCLUSIONS

The discovery of the exothermic phase transformation of Perovskite to a post Perovskite phase under pressure and temperature conditions appropriate to the depth to the top of the D" layer has clearly impacted our understanding of this region of the Earth in an extremely important way that has shifted an important paradigm of mantle dynamics. It would appear to suggest that any chemical heterogeneity that is associated with D" may be entirely core-derived rather than deriving from an interpretation of D" as a "graveyard" for down going slabs. The dynamics community is clearly challenged by this discovery to more fully account for the complexity of its influence in the next generation of models of the mixing process.

REFERENCES

Anderson, Don L., Theory of the Earth. *Blackwell Sci. Pub.*. Boston, 366 pp., 1989.

Badro, J., J.-P. Rueff, G. Vanko, G. Moriaco, G. Fiquet, and F. Guyot, Electronic transitions in Perovskite: Possible nonconvecting layers in the lower mantle, *Science*. 305, 383-386, 2004.

Boehler, R., Temperature in the Earth's core from melting-point measurements of iron at high static pressures, *Nature*, 363, 534-536, 1993.

Boehler, R., Melting temperature of the Earth's mantle and core: Earth's thermal structure, *Annu. Rev. Earth Planet. Sci.*, 24, 15-40. 1996.

Bullen, K.E., The density variation of the Earth central core., *Bul. Seis. Soc. Amer.*, 30, 235-250, 1942.

Bullen, K.E., An Earth model based upon a compressibility-pressure hypothesis, *Mon. Not. R. Astron. Soc. Geophys. Suppl.* 6, 50-59, 1950.

Chao, Benjamin F, Renaming D double prime, *EOS* 81, p. 46, February 1. 2000.

Christiansen. Ulrich R.. Mantle rheology, Constitution, and Convection. Chapter 8 in *Mantle Convection: Plate Tectonics and Global Dynamics*, W.R. Peltier ed., pp. 595-655, Gordan and Breach Science Publishers, New York, 1989.

Dahm, C.G., A Study of Dilatational Wave Velocity in the Earth as a Function of Depth, Based on a Comparison of the P, P" and PcP Phases, Ph.D. dissertation, St. Louis University, St. Louis, MO, 1934.

Dziewonski, A.M., and D.L. Anderson. Preliminary reference Earth model, *Phys. Earth Planet. Inter.*, 25, 297-356, 1981.

Forte. A.M., and J.X. Mitrovica, Deep-mantle high-viscosity flow and thermo chemical structure inferred from seismic and geodynamic data, *Nature*, 410, 1049-1056.

Garnero, Ed, What on Earth is D", *EOS 81*, p. 501, October 24. 2000.

Garnero, Edward J., A new paradigm for Earth's core-mantle boundary. *Science*, 304, 834-836, 2004.

Garnero, Edward J., Valèrie Maupin, Thorne Lay and Matthew J. Fouch, Variable azimuthal anisotropy in Earth's lowermost mantle, *Science*. 306, 259-261, 2004.

Hirose, K., R. Sinmyo, N. Sata, and Y. Ohishi, Determination of post-perovskite phase transition boundary in Mg S_iO_3 using Au and MgO pressure standards, *Geophys. Res. Lett.*, 33, L01310, doi:10.1029/2005GL024468, 2006.

Helmberger, D.V., L. Wen, and X. Ding, Seismic evidence that the source of the Iceland hotspot lies at the core-mantle boundary, *Nature*, 396, 251-255, 1998.

Ishi, M., and J. Tromp, Normal mode and free-air gravity constraints on lateral variations in velocity and density in Earth's mantle, *Science*, 285, 1231-1236, 1999.

Ito, E., and E. Takahashi, Postspinel transformations in the system Mg_2 SiO_4 – Fe_2 SiO_4 and some geophysical implications, *J. Geophys. Res.*, 94, 10,637-10,646, 1989.

Jeanloz, Raymond, High pressure Chemistry of the Earth's mantle and core. Chapter 4 *in Mantle Conveciton: Plate Tectonics and Global Dynamics*, W.R. Peltier ed. pp. 203-259, Gordan and Breach Science Publishers, New York, 1989.

Kellog, K., B.H. Hager, and R.D. van der Hilst, Compositional stratification in the deep mantle, *Science*, 283, 1881-1884, 1999.

Kendall, M., and P.G. Silver, Investigating cases of D" anisotropy, *in The core-Mantle Boundary Region*, edited by M. Gurnis, M.E. Wysession, E. Knittle, and B.A. Buffett, pp. 97-118, American Geophysical Union, Washington, D.C., 1998.

Kisslinger, Carl, the "Dahm" Layer: Comments on renaming of D", *EOS* 81, p. 210, May 9, 2000.

Lay, T., *Trans. Am. Geophys. Union*, 70, 49, 1989.

Lay, Thorne, J. Hernlund, E.J. Garnero, and M.S. Thorne, A post Perovskite lens and D" heat flux beneath the Central Pacific, *Science*, 314, 1272-1276, 2006.

Mao, Wendy L., Ho-Kwang Mao, Wolfgang Sturhahn, Jiyong Zhao, Vitali B. Prakapenka, Yue Merg, Jinfu Shu, Yingwei Fei, and Russell J. Hemley, Iron-rich post Perovskite and the origin of Ultra low-velocity zones, *Science*, 312, 564-565, 2006.

Murakami, Motohiko, Kei Hirose, Katsuyuki Kawamura, Nagayoshi Sata, and Yasuo Ohishi, Post-Perovskite phase transition in $MgSiO_3$, *Science*, 304, 855-858, 2004.

Nakagawa, Takashi, and Paul J Tackley, The interaction between the post-perovskite phase change and a thermo-chemical boundary layer near the core-mantle boundary, *Earth Planet. Sci. Lett*, 238, 204-216, 2005.

Oganov, Artem R., and Shigeaki Ono, Theoretical and experimental evidence for a post-Perovskite phase of $MgSiD_3$ in Earth's D" layer, *Nature*, 430, 445-448, 2004.

Ono, Shigeaki, Taku Tsuchiya, Kei Hirose, and Yasuo Ohishi. High pressure form of pyrite-type germanium dioxide, *Phys. Rev. B*, 68, 014103, 2003.

Peltier, W.R., Mantle viscosity and ice-age ice-sheet topography, *Science*, 273, 1359-1364, 1996.

Peltier, W.R., and L.P. Solheim, Mantle phase transitions and layered chaotic convection, *Geophys. Res. Lett.*, 19, 321-324, 1992.

Ringwood, A.E., and A. Major, The system Mg_2 SiO_4 – Fe_2 SiO_4 at high pressures, *Phys. Earth Planet. Int.*, 3, 89-108, 1970.

Sidorin, I., M. Gurnis, and D.V. Helmberger, Evidence for a ubiquitous seismic discontinuity at the base of the mantle, *Science*, 286, 1326-1331, 1999.

Solheim, Larry P., and W.R. Peltier, Avalanche effects in phase transition modulated thermal convection: A model of the Earth's mantle, *J. Geophys. Res.*, 99, 6997-7018, 1994.

Solheim, Larry P., and W.R. Peltier, Phase boundary deflections at 660-km depth and episodically layered isochemical convection in the mantle, *J. Geophys. Res.*, 99, 15,861-15,875, 1994.

Trampert, Jeannot, Frèderic Deschamps, Resovsky, and David Yuen, Probabilistic tomography maps chemical homogeneities throughout the lower mantle, *Science*, 306, 853-856.

Tsuchiya, Taku, Jun Tsuchiya, Koichiro Umemoto, and Wentzcovitch, Phase transition in $MgSiO_3$ Perovskite in the earth's lower mantle, *Earth and Planet. Sci. Lett.*, 224, 241-248, 2004.

van der Hilst, R.D., S. Widiyantoro, and E.R. Engdahl, Evidence for deep mantle circulation from global tomography, *Nature*, 386, 578-584, 1997.

van der Hoeven. A., Gu Schmitt, G. Dinter. V. Mocanu, and W. Spakman, GPS probes the Vrancea seismogenic zone, *EOS*, 85, 185-186, 2004.

Vidale, J.E., and M.A.H. Hedlin, Evidence for partial melt at the core-mantle boundary north of Tonga from the strong scattering of seismic waves, *Nature*, 391, 682-684, 1998.

Williams, Q., and E.J. Garnero, Seismic evidence for partial melt at the base of the mantle, *Science*, 273, 1528-1530, 1996.

Williams, Q., J. Revenaugh, and E. Garnero, A correlation between ultra-low basal velocities in the mantle and hot spots *Science*. 281, 546-549, 1998.

Yuen, D.A., and W.R. Peltier, Mantle plumes and the thermal stability of the D" layer, *Geophys. Res. Lett.*, 7, 625-628, 1980a.

Yuen, D.A., and W.R. Peltier, Temperature dependent viscosity and local instabilities in mantle convection, *in Physics of the Earth's Interior*. Proceedings of the International School of Physics "Enrico Fermi", A.M. Dziewonski and E. Bosci eds., pp. 432-463, North Holland Publishing Co., Amsterdam, 1980b.

Yuen, D.A., Marc Monnereau, Ulrich Hansen, Masanori Kameyama, Ctirad Matyska, Dynamics of superplumes in the lower mantle, in *Superplumes: Beyond Plate Tectonics*, David A. Yuen, Shigenori Maruyama, Shun-Ichiro Karato and Brian F. Windley eds., pp. 1-24, Springer, 2007, 550 pp.

Zhao, D., Global tomographic images of mantle plumes and subducting slabs: insight into deep Earth dynamics, *Phys. Earth Planet. Int.*, 146, 3-34, 2004.

W. R. Peltier, Department of Physics, University of Toronto, 60 St. George St., Toronto, Ontario M5S 1A7 Canada