Geophysically Consistent Values of the Perovskite to Post-Perovskite Transition Clapeyron Slope
John Hernlund, Stéphane Labrosse

To cite this version:

HAL Id: hal-00583859
https://hal.archives-ouvertes.fr/hal-00583859
Submitted on 6 Apr 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Geophysically consistent values of the perovskite to post-perovskite transition Clapeyron slope

J. W. Hernlund1 and S. Labrosse2

Received 30 November 2006; revised 4 February 2007; accepted 13 February 2007; published 15 March 2007.

[1] The double-crossing hypothesis posits that post-perovskite bearing rock in Earth’s Dm layer exists as a layer above the core-mantle boundary bounded above and below by intersections of a curved thermal boundary layer geotherm and a relatively steep phase boundary. Increasing seismic evidence for the existence of pairs of discontinuities predicted to occur at the top and bottom of this layer motivates an examination of the consistency of this model with mineral physics constraints for the Clapeyron slope of this phase transition. Using independent constraints for a lower bound on temperature in Earth’s deep mantle and the temperature of Earth’s inner core boundary, we show that a post-perovskite double-crossing is inconsistent with plausible core temperatures for a Clapeyron slope less than about 7 MPa/K, with the higher range of experimental values yielding better agreement with recent estimates of the melting temperature of Earth’s core. Citation: Hernlund, J. W. and S. Labrosse (2007), Geophysically consistent values of the perovskite to post-perovskite transition Clapeyron slope, Geophys. Res. Lett., 34, L05309, doi:10.1029/2006GL028961.

1. Introduction

[2] The experimentally and theoretically predicted occurrence of post-perovskite(pPv)-bearing rock in Earth’s lowest mantle [Murakami et al., 2004; Oganov and Ono, 2004; Tsuchiya et al., 2004] has been invoked to explain the presence of discontinuous increases in seismic velocity observed in some regions atop the Dm layer [Lay and Helmberger, 1983; Wysession et al., 1998]. A deeper rapid seismic velocity decrease has also been proposed beneath the Cocos region [Thomas et al., 2004a] and Eurasia [Thomas et al., 2004b] underneath the velocity increase, and while the detectability of this deeper feature has been questioned [Flores and Lay, 2005] or can be interpreted differently in some regions [Hutko et al., 2006], recent analyses support the presence of this feature beneath Cocos [Sun et al., 2006] and the mid-Pacific [Lay et al., 2006]. The existence of such discontinuity pairs is predicted by the “double-crossing” hypothesis [Hernlund et al., 2005], in which a layer of pPv-bearing rock appears above the core-mantle boundary (CMB), with the upper and lower interfaces identified with intersections of the Dm boundary layer geotherm and the perovskite(Pv)-pPv phase boundary at two different depths (Figure 1).

[3] More importantly, the double-crossing hypothesis offers a simple way to explain why some regions exhibit no detectable discontinuities at all [Wysession et al., 1998] as the consequence of a geotherm that doesn’t pass into the pPv stability field. If the latter effect occurs, pPv should be present in lens-like structures that laterally pinch out and disappear, which is precisely what is observed in a new high density reflectivity survey of the mid-Pacific [Lay et al., 2006]. On the other hand, if the pPv phase boundary temperature were greater than the CMB temperature, pPv would exist as a globally present layer because the CMB is essentially isobaric and isothermal. This alternative scenario is termed the “single-crossing” because the geotherm can only pass through the pPv phase boundary once, rather than twice, and in this case some other mechanism would be required to hide the ubiquitous pPv layer from seismic detection where a discontinuity is not observed.

[4] If correct, the double-crossing model also provides a means for mapping temperature at two different depths based upon observed seismic discontinuities. Furthermore, the model gives bounds on core-mantle heat flux since it requires that the temperature of the core-mantle boundary be greater than the Pv-pPv phase boundary temperature at CMB pressure (∼136 GPa). While chemical influences upon the phase boundary are probably necessary to explain the presence of pPv lenses in tomographically fast and slow regions of Dm [Wysession et al., 1998; Lay et al., 2006], the relative temperature requirement at the CMB must always hold true in order to produce these kinds of structures in any setting. Here we leverage this constraint, which would not be possible in a single-crossing scenario, against geophysically consistent estimates for the temperature of the deep mantle and inner core boundary (ICB) to define a plausible range of Clapeyron slopes for the post-perovskite phase transition, ΓpPv, in a way that is independent of the absolute temperature of the phase boundary, the latter of which is subject to large uncertainties. We find that values higher than about 7 MPa/K are required for the double-crossing model to be consistent with even the most conservative upper bounds on the temperature at the inner core boundary, bisecting the range of experimental uncertainty for ΓpPv that lies between 4 MPa/K and 13 MPa/K [Hirose et al., 2006]. A consistent extrapolation of the geotherm is obtained for the value ΓpPv = 11.5 ± 1.4 MPa/K obtained by using a MgO pressure standard in laser-heated diamond anvil cell (LHDAC) experiments, in agreement with some ab inito values as well as recent estimates for the temperature of the ICB.

2. Basic Temperature Bounds

[5] The procedures and uncertainties involved in estimating temperatures in the deep Earth are reviewed by Williams...
The density of the outer core just above the CMB depends upon the Gru¨neisen parameter, which is estimated to be in the range 1.3–2.0 for the ICB and CMB and are adiabatically linked by $T_{icb} = T_{cmb}(\rho_{icb}/\rho_{cmb})^{\gamma}$, with $\rho_{icb}$ and $\rho_{cmb}$ the density of the outer core just above the ICB and below the CMB respectively. In a review of recent ab initio models, Voˇcadoˇlo et al. [2003] have derived a remarkably constant adiabatic value of $\gamma \approx 1.51 \pm 0.01$, with the usual density dependence being balanced by an additional temperature dependence. The ratio $\rho_{icb}/\rho_{cmb}$ can be obtained from PREM [Dziewonski and Anderson, 1981], from which we obtain $T_{icb} = 1.36 T_{cmb}$, or $T_{icb} = 3900–8600$ K. Note that this lower bound is not biased, since discontinuities arising from material warmer than the coldest scenario estimated above would give rise to even higher estimates for ICB temperature.

7. The melting temperature of iron at ICB pressure provides a completely independent constraint upon plausible temperatures in the deep Earth. Most experimental estimates for the melting temperature of pure Fe, when extrapolated to ICB pressure, fall in the range 5600–6500 K [Anderson and Duba, 1997], while 5980 ± 70 K is obtained from thermal physics estimates [Anderson et al., 2003], 6160 ± 250 K from a dislocation theory of melting [Poirier, 1986; Poirier and Shankland, 1993], and 6350 ± 300 K from recent ab initio calculations [Alf et al., 2004]. To the melting temperature of pure iron, we must also subtract a depression due to the presence of light alloying elements, which is estimated to be 700 ± 100 K from ab initio calculations for compositions agreeing with seismic properties of the inner and outer core [Alf et al., 2002]. The combined ab initio results yield a $T_{icb}$ around 5600 K, in close agreement with the value of 5700 K using elasticity constraints for the inner core [Steinle-Neumann et al., 2001]. It is worth noting that even a very conservative upper bound of $T_{icb} < 6500$ K [Williams, 1998] already falls in the middle of the range of the lower bound of 4000–9400 K required of the double-crossing model. Therefore, a range of independent constraints are mutually inconsistent with one another when linked together by the double-crossing model, even accounting for the large range of uncertainties.

8. It is useful to isolate, as much as possible, the contribution of $\Gamma_{pPv}$ to the lower bound for $T_{icb}$. We plot the trade-offs between $\Gamma_{pPv}$, $h_{min}$, and $T_{icb}$ in Figure 2. If we...
Figure 2. Lower bound of the temperature at the inner core boundary implied by the double-crossing model as a function of the pPv Clapeyron slope $\Gamma_{pPv}$, and the shallowest displacement of the upper D" layer discontinuity above the CMB, $h_{\text{min}}$. (top) The most conservative lower bound for the ICB temperature as discussed in the text, given by $1.36(1500 + \rho g h_{\text{min}}/\Gamma_{pPv})$ K. (bottom) A more moderate estimate, using $1.36(1800 + 400 + \rho g h_{\text{min}}/\Gamma_{pPv})$ K, where the extra 400 K is an arbitrary estimate of the temperature increment between the CMB and the pPv phase boundary temperature in Figure 1. Various experimental and ab initio constraints are indicated at the top of Figure 2. The bold contours indicate recent ICB temperature estimates of 5600 K [Alfe et al., 2002] and 5700 K [Steinle-Neumann et al., 2001], while the light grey region indicates values that are too extreme to be supported by any estimates.

apply the most conservative bounds discussed above, it is clear that $\Gamma_{pPv}$ less than about 6–7 MPa/K implies ICB temperatures that are unreasonably high. We note that the predicted lower bound for $T_{ib}$ would be higher if we chose a larger mantle adiabatic gradient, smaller temperature anomaly due to the slab, or non-zero temperature increment between the CMB and the pPv phase boundary at CMB pressure. We also plot the lower bound for $T_{ib}$ using a temperature increment of 400 K and average mantle adiabatic gradient 0.375 K/km, the latter of which is similar to the ab initio value preferred by Ono and Oganov [2005]. Various estimates of the Pv-pPv Clapeyron slope are also given [for a recent review see Hirose [2006]]. It is interesting that the upper limit on $T_{ib}$ bisects the range of experimental uncertainty in $\Gamma_{pPv}$ induced by the various pressure standards used in LHDAC experiments [Hirose et al., 2006]. The smallest $\Gamma_{pPv}$ of about 4.7 ± 0.5 MPa/K was obtained using an Au pressure standard [Tsuchiya, 2003], while an MgO pressure standard [Speziale et al., 2001] in the same experiments yields $\Gamma_{pPv} = 11.5 \pm 0.4$ MPa/K. Therefore, if this particular Au pressure standard is correct, then the possibility for a double-crossing appears to be incompatible with plausible core temperatures.

3. Discussion and Conclusion

[Hirose et al. [2006] argue that the Speziale et al. [2001] MgO standard, which also yields better agreement with experiments conducted using a Pt standard, is probably the best choice for geophysical applications. The MgO pressure standard is also recommended by Fei et al. [2004] since it yields the best agreement with the post-spinel phase boundary for plausible temperatures at depths of the 660 km seismic discontinuity. Thus we could also argue here that consistency of the experimentally determined values of the Clapeyron slope with plausible models for the occurrence of post-perovskite in Earth's D" layer also supports the geophysical consistency of the MgO pressure standard. However, the strength of such an argument by itself is not as convincing in this setting, since the experimental and seismic data bearing upon the question at hand is significantly less certain than data regarding the much shallower 660 km seismic discontinuity.

Any future study that incorporates a pPv double-crossing should consider the kinds of trade-offs described above. In particular, where a range of parameters is to be explored, values of the Clapeyron slope less than about 8 MPa/K should not be considered appropriate, and larger values should be implemented if a lower range of temperature estimates for the core is assumed [e.g., Boehler, 1993]. The finding that only the higher range of Clapeyron slopes yields reasonable temperatures in the deep Earth also carries implications for the heat flow implied by the double-crossing model, favoring the lower range of values given in previous studies [Hernlund et al., 2005; Lay et al., 2006]. However, when comparing these constraints it is also important to consider the possibility that Pv-pPv transitions in chemically distinct regions may exhibit different effective Clapeyron slopes [e.g., Spera et al., 2006].

Acknowledgments. We thank Orson Anderson, Edward Garnero, Abby Kavner, Thorne Lay, William B. Moore, Paul H. Roberts, Gerald Schubert, David Stevenson, and Paul Tackley for productive discussions. Reviews by Allen McNamara and Christine Reif helped to improve the clarity of the presentation. This work is supported by the French Ministry of Research and the INSU DyETI program.

References


J. W. Hernlund, Institut de Physique du Globe de Paris, 4 Place Jussieu, F-75252 Paris Cedex 05, France. (hernlund@ipgp.jussieu.fr)

S. Labrosse, Laboratoire des Sciences de la Terre, Ecole Normale Supérieure de Lyon, 46 Allée d’Italie, F-69364 Lyon Cedex 07, France. (stephanie.labrosse@ens-lyon.fr)