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# Seismically deduced thermodynamics phase diagrams for the mantle transition zone

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ABSTRACT

Seismic discontinuities at 410 and 660 km depth are usually attributed to solid phase changes within the olivine component of the mantle. The Clapeyron slopes $\gamma_{410}$ and $\gamma_{660}$, *i.e.* the thermal dependence of the depths of reactions, have been shown experimentally to be of opposite signs. Yet, their values are not well constrained by laboratory measurements. Seismological observations have not been more precise due to the difficulty to separate the competing effects of background wave-velocities and of temperature on the topography of discontinuities. In this study we use conversion imaging of interfaces under western US. We propose a new approach to derive a seismological estimate of the Clapeyron slopes with respect to $\gamma_{410}$ for the major and minor phase changes of the transition zone. We obtain $\gamma_{660} \approx -3$ MPa K$^{-1}$ for $\gamma_{410} \approx +3$ MPa K$^{-1}$. We construct "seismic phase diagrams" of the transition zone that can be directly compared with experimental phase diagrams. We also apply a "$Z$–$\Gamma$" transform to better constrain the Clapeyron slopes $\gamma$ of the minor phase changes. Although tenuous, signals in seismic phase diagrams suggest that minor phase transitions, both in the olivine and the non-olivine component of the mantle, have visible seismic expressions. They can tentatively be described as follows. The '410' is overlaid at low temperature by an interface corresponding to a decrease of velocity with depth and $\gamma \approx +3$ MPa K$^{-1}$. The '660' widens at high temperature and is preceded at low temperature by an interface, the '620', with $\gamma \approx +7$ MPa K$^{-1}$. A '520' is suggested with $\gamma \approx 2$–$3$ MPa K$^{-1}$. These last two interfaces correspond to velocity increases with depth. At last, near 590 km depth, an interface may be associated with a velocity reduction showing a weak dependence on temperature ($\gamma \sim 0$ MPa K$^{-1}$).



## 1. Introduction

In the mantle, two sharp seismic discontinuities bounding the transition zone (TZ) are usually attributed to pressure-induced solid phase changes of the olivine $(Mg,Fe)_2SiO_4$ mineral. These reactions involve the transitions from olivine to wadsleyite (ol → wd) at 410 km depth (the '410'), and ringwoodite to perovskite + ferropericlase (rw → pv + fp) at 660 km depth (the '660'). Seismological observations of the depths of discontinuities can be used to probe the mantle pressure–temperature $(P, T)$ conditions. This requires the knowledge of their Clapeyron slopes $\gamma = dP/dT$, *i.e.* the thermal dependence of the pressure at which the phase changes occur.

Laboratory experiments agree on the opposite signs of the two Clapeyron slopes. The slope $\gamma_4$ of the ol → wd transformation at 410 km depth has been measured in a +1.5 to +4 MPa K$^{-1}$ range (Akaogi et al., 1989; Katsura et al., 2004; see Supplement Table S.1). Reports of $\gamma_6$ for the endothermic rw → pv + fp reaction at 660 km depth are even more scattered with values ranging from −4 MPa K$^{-1}$ to −0.2 MPa K$^{-1}$ (Ito et al., 1990; Litasov et al., 2005b). The reaction at 410 km depth should occur at higher pressure (*i.e.*, greater depth) in a hotter mantle while the '660' should occur at lower pressure (*i.e.*, lower depth) under the same condition, leading to anti-correlated topographies.

A long standing debate exists among seismologists on the degree of anti-correlation of the topographies of the '410' and '660' discontinuities. The main source of information comes from converted/reflected body-wave imaging (see Shearer, 2000, for a review). The topography of the '410' has been observed smaller than that of the '660' (Shearer, 1991; Helffrich, 2000). The unique seismological study to provide direct constraints on olivine Clapeyron slopes (Lebedev et al., 2002) found $\gamma_4 = +2$ MPa K$^{-1}$ and $\gamma_6 = -3.3$ MPa K$^{-1}$ below east Asia and Australia. In some cases, seismological observations are even in disagreement with the experimental expectation of anti-correlated topographies for the '410' and the '660' discontinuities. Gu et al. (1998) and

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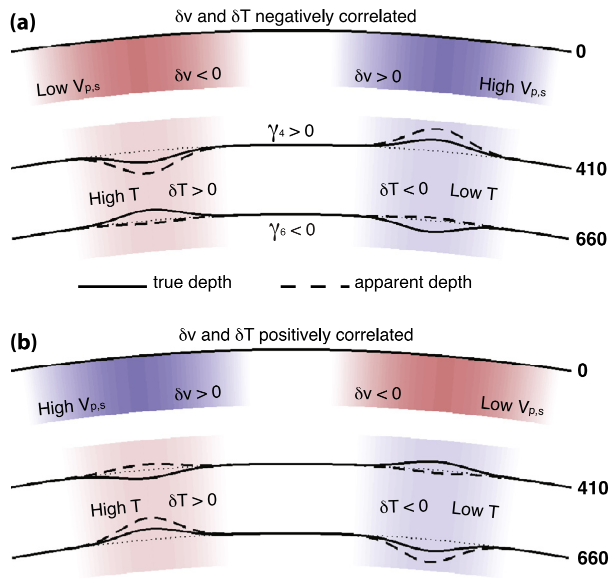


**Fig. 1.** Behavior of discontinuities with thermal anomalies in the transition zone and strong velocity heterogeneities in the lithosphere. Topographies of opposite signs expected from mineral physics are shown with plain lines whereas seismological observations, influenced by the uppermost velocity structure, are shown with dashed lines. In the absence of shallow corrections, an apparent correlation between the interface topographies may be observed. (a) Case of a slower lithosphere on top of a hotter mantle (left) and reciprocally (right). (b) Case of a faster lithosphere (*e.g.* due to a thin crust) on top of a hotter mantle (left) and reciprocally (right).

Houser et al. (2008) found a slight positive global correlation between them. This observation is further evidenced below hotspots (Deuss, 2007; Tauzin et al., 2008) or in the Pacific (Houser and Quentin, 2010) where the apparent $\gamma_4/\gamma_6 > 0$ has been attributed to a transition in the non-olivine component of the mantle, from majorite-garnet to perovskite in $MgSiO_3$, occurring below the '660' with a positive Clapeyron slope (Hirose, 2002).

However uncertainty remains on the reliability of the corrections for uppermost velocity structure. Interface mapping relies on the analysis of travel-times of body waves converted or reflected at discontinuities. These travel-times not only depend on the depth of conversion/reflection but also on the velocity heterogeneities encountered along the ray paths above the discontinuities. This results in a trade-off between the apparent depths of discontinuities and the velocity heterogeneities above the TZ. As depicted in Fig. 1a, shallow velocity anomalies negatively correlated with the temperature in the transition zone apparently enhance the '410' topography and reduce the '660' topography (*e.g.* the case of a hot lithosphere on top of a hot mantle, Fig. 1a, left, or reciprocally, right). Shallow velocity anomalies positively correlated with the temperature in the transition zone could lead to an overestimate of the '660' topography compared to that of the '410' (*e.g.* a thin crust on top of a hotter mantle, Fig. 1b, left, or reciprocally, right). In general, the absence or the inaccuracy of velocity corrections obscure the anti-correlation between the discontinuity depths (*e.g.* Stammler and Kind, 1992). In extreme cases where the contribution from shallow velocity heterogeneities exceeds the contribution from the temperature (*i.e.*, all 4 cases in Fig. 1), the topographies appear correlated and the apparent Clapeyron slope ratio $\gamma_4/\gamma_6$ becomes positive, contrary to experimental expectations. This could be especially the case for up-going P waves converted into shear waves under seismological stations (P-to-S conversions) whose travel-times are strongly velocity-dependent (Li et al., 2003).

In this study, we propose a method to separate the competing effects of uppermost velocity structure and temperature on the topography of TZ discontinuities. This method makes possible the determination of the ratio $\gamma_4/\gamma_6$ with little information on the background velocity structure. From this estimate, we can correct the structure of the TZ from the effect of velocities, estimate the temperature, and build diagrams that may be used as a proxy for thermodynamics phase diagram of solid–solid transitions. Then we develop and apply a new method, the "$Z$–$\Gamma$ stacking", to test the presence of unknown phase transitions in the mantle and measure their relative Clapeyron slopes.

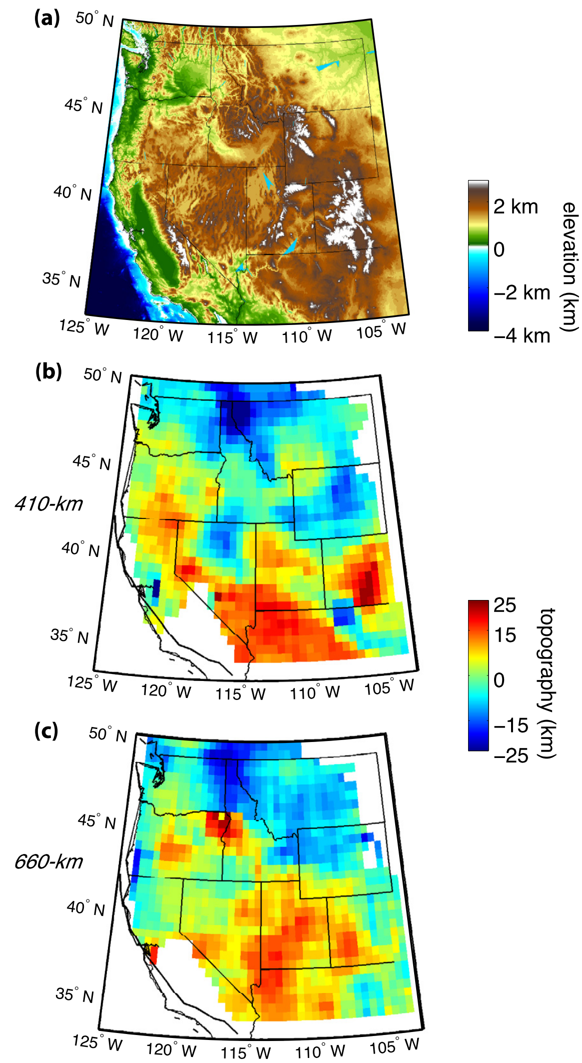


**Fig. 2.** (a) Surface topography with state borders. (b) Apparent topography $\delta Z_4$ of the '410' seismic discontinuity. (c) Apparent topography $\delta Z_6$ of the '660' discontinuity (both panels from Tauzin et al., 2013).

## 2. Seismic observations under western US

We make use of a dataset of P-to-S conversions obtained from the Transportable Array component of USArray. This dataset is described in detail in Tauzin et al. (2013). Using receiver functions, the mantle structure of the western half of the US (Fig. 2a) has been characterized in the 5–75 s period range. Seismic images of mantle discontinuities have been produced by a migration method, stacking the receiver functions by common conversion point (CCP) (Dueker and Sheehan, 1997; Wittlinger et al., 2004). The imaged volume is thus called a "CCP volume". By picking in this volume the seismic signal of conversions at the '410' and '660', high resolution maps of their apparent topographies ($\delta Z_4$ and $\delta Z_6$) have been obtained on a 0.5° grid in latitude and longitude (Fig. 2b, c). The observed average depths of the '410' and '660' over the area