

# Phase transitions in pyrolite and MORB at lowermost mantle conditions: Implications for a MORB-rich pile above the core–mantle boundary

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## Abstract

Subduction of mid-oceanic ridge basalt (MORB) gives rise to strong chemical heterogeneities in the Earth's mantle, possibly extending down to the core–mantle boundary. Phase relations in both pyrolite and MORB compositions are precisely determined at high pressures and temperatures corresponding to lowermost mantle conditions. The results demonstrate that the post-perovskite phase transition occurs in pyrolite between 116 and 121 GPa at 2500 K, while post-perovskite and SiO<sub>2</sub> phase transitions occur in MORB at ~4 GPa lower pressure at the same temperature. Theory predicts that these phase changes in pyrolite and MORB cause shear wave velocity increase and decrease, respectively. Near the northern margin of the large low shear velocity province in the lowermost mantle beneath the Pacific, reflections from a negative shear velocity jump near 2520-km depth are followed by reflections from a positive velocity jump 135 to 155-km deeper. These negative and positive velocity changes are consistent with the expected phase transitions in a dense pile containing a mixture of MORB and pyrolitic material. This may be a direct demonstration of the presence of accumulations of subducted MORB crust in the deep mantle.

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**Keywords:** D<sup>''</sup>; post-perovskite; core–mantle boundary; perovskite; superplume

## 1. Introduction

The ~6-km thick basaltic oceanic crust (MORB) is injected into the mantle in significant quantities as oceanic lithosphere sinks at subduction zones. The average oceanic crust production rate during Mesozoic to present time is estimated to be about 25 km<sup>3</sup> per year (Reymer and Schubert, 1984). Assuming this production (=subduction) rate has been constant during the last 4 billion years (a much larger production rate has been suggested for the Archean (Komiya, 2004)), the total amount of oceanic crust that has subducted corresponds to at least 11% of

the Earth's mantle in volume. It is thus probable that there are large quantities of MORB residing in the mantle.

Subducting MORB crust undergoes phase transitions as pressure and temperature increase with depth, and MORB's distinct chemistry from the balance of the slab and surrounding mantle produces chemical and density heterogeneities over the depth range of subduction, possibly extending down to the core–mantle boundary (CMB). The chemical composition of subducted MORB crust is not significantly modified in the Earth's deep interior because the solid-state diffusion rate is very slow especially in the lower mantle (Holzapfel et al., 2005), although the upper part of MORB crust is hydrated before subduction and loses minor amounts of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> upon dehydration (Kessel et al., 2005). Previous density measurements (Ono et al., 2005; Hirose et al., 2005) and geodynamical simulations (Christensen and Hofmann, 1994; Tackley, 1998; McNamara and Zhong, 2004; Nakagawa and Tackley, 2005) suggest that dense MORB

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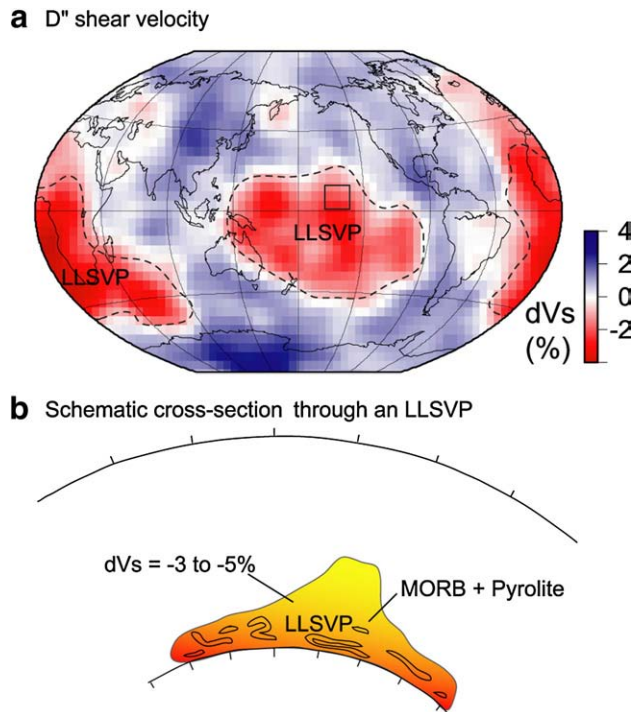


Fig. 1. (a)  $S$ -wave velocity variations in the lowermost 200-km of the mantle in the seismic tomography model of Grand (2002). The large low shear velocity provinces (LLSVP) regions appear to be dense and chemically distinct from surrounding mantle (Lay and Garnero, 2004). (b) Schematic cross-section through an LLSVP, suggesting that a mix of dense, separated MORB and pyroclitic mantle comprises the pile. Phase transitions within the pile give rise to the reflectivity (Fig. 8) shown for the northern edge of the Pacific LLSVP (see small box in (a) corresponds to Fig. 2c).

crust may plausibly have accumulated in chemically distinct piles in the  $D''$  region at the bottom of the mantle. While strong seismic velocity heterogeneities in the lowermost mantle have been detected (see Lay and Garnero, 2004 for a review), direct seismological evidence for the presence of MORB piles has not been presented, in part because the properties of MORB are not well characterized for lowermost mantle conditions and in part because there are alternate interpretations of seismic heterogeneities in the lower mantle. Nishihara (2003) calculated seismic velocities of pyroclite and MORB, showing that they are very similar to each other at lower mantle conditions except around 1600-km depth where the velocities significantly decrease in MORB materials due to ferroelastic-type phase transition in  $\text{SiO}_2$  phase; however, absolute seismic velocities do not uniquely resolve specific mineralogical structure in the deep mantle because there are strong trade-offs with temperature. The non-uniqueness of interpretation of seismic structure can be reduced if phase transitions in the medium are detected and can be compared to the expectations for a given mineralogy.

$\text{MgSiO}_3$ -rich perovskite is expected to be the most abundant mineral in both pyroclite and MORB materials under lower mantle conditions down to great depths (e.g., Kesson et al., 1994, 1998). However, the perovskite to post-perovskite phase transition recently discovered in  $\text{MgSiO}_3$  (e.g., Murakami et al., 2004; Tsuchiya et al., 2004; Oganov and Ono, 2004) is expected for pressure–temperature ( $P$ – $T$ ) conditions a few hundred kilometers

above the CMB. Subsequent high-pressure experimental studies have shown that the post-perovskite phase transition also occurs in pyroclite and MORB compositions for lowermost mantle conditions (Ono et al., 2005; Hirose et al., 2005; Murakami et al., 2005; Ono and Oganov, 2005). However, the exact locations of the phase transition boundary and its width have not yet been determined for pyroclite and MORB. In addition, a phase transition in  $\text{SiO}_2$  takes place in MORB at similar high  $P$ – $T$  conditions (Murakami et al., 2003; Hirose et al., 2005). If the effects of these phase changes in pyroclite and MORB can be related to observed deep mantle seismic velocity discontinuities, there may be seismological indicators of the presence of any MORB accumulations near the base of the mantle.

In this study, we examine the deep mantle phase relations in both pyroclite and MORB compositions based on X-ray diffraction measurements *in-situ* at high  $P$ – $T$  conditions appropriate for the  $D''$  region. We also analyze new seismic data to further resolve the seismic velocity discontinuity structure in the lowermost mantle near the northern margin of the Pacific large low shear velocity province (LLSVP) (Fig. 1a) (Avants et al., 2006; Lay et al., 2006). The LLSVPs under the Pacific and Africa appear to be chemically distinct from the surrounding deep mantle, and it has been proposed that they may involve dense debris from ancient oceanic slabs (Fig. 1b) (see Tackley, 1998; McNamara and Zhong, 2004; Lay and Garnero, 2004; Nakagawa and Tackley, 2005). The possible accumulation of subducted MORB crust in a pile in the  $D''$  region is discussed, based on joint consideration of our mineral physics and seismological findings.

## 2. Methods

### 2.1. High-pressure experiments

High  $P$ – $T$  conditions were generated in a laser-heated diamond-anvil cell (LHDAC). Starting materials were prepared as amorphous gels with chemical compositions of natural KLB-1 peridotite (Takahashi, 1986), which is similar in composition to pyroclite, and normal MORB (Hirose et al., 1999) (Table 1). The starting materials, sample configurations, and high-pressure experimental techniques are the same as those used in our previous studies (Hirose et al., 2005; Murakami et al., 2005). The samples were mixed with fine gold powder and loaded into a hole in a rhenium gasket together with thermal insulation layers of NaCl or

Table 1  
Compositions of starting materials

	KLB-1	MORB
$\text{SiO}_2$	44.80	49.80
$\text{TiO}_2$	0.16	1.65
$\text{Al}_2\text{O}_3$	3.62	14.93
$\text{FeO}^a$	8.16	11.47
$\text{MgO}$	39.50	8.54
$\text{CaO}$	3.46	10.58
$\text{Na}_2\text{O}$	0.30	2.91
$\text{K}_2\text{O}$	–	0.12
Total	100.00	100.00

<sup>a</sup> Total Fe as FeO.

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