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Research paper

Conjecture with water and rheological control for subducting slab in the mantle transition zone

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A B S T R A C T

Seismic observations have shown structural variation near the base of the mantle transition zone (MTZ) where subducted cold slabs, as visualized with high seismic speed anomalies (HSSAs), flatten to form stagnant slabs or sink further into the lower mantle. The different slab behaviors were also accompanied by variation of the "660 km" discontinuity depths and low viscosity layers (LVLs) beneath the MTZ that are suggested by geoid inversion studies. We address that deep water transport by subducted slabs and dehydration from hydrous slabs could affect the physical properties of mantle minerals and govern slab dynamics. A systematic series of three-dimensional numerical simulation has been conducted to examine the effects of viscosity reduction or contrast between slab materials on slab behaviors near the base of the MTZ. We found that the viscosity reduction of subducted crustal material leads to a separation of crustal material from the slab main body and its transient stagnation in the MTZ. The once trapped crustal materials in the MTZ eventually sink into the lower mantle within 20–30 My from the start of the plate subduction. The results suggest crustal material recycle in the whole mantle that is consistent with evidence from mantle geochemistry as opposed to a two-layer mantle convection model. Because of the smaller capacity of water content in lower mantle minerals than in MTZ minerals, dehydration should occur at the phase transformation depth, ~660 km. The variation of the discontinuity depths and highly localized low seismic speed anomaly (LSSA) zones observed from seismic P waveforms in a relatively high frequency band (~1 Hz) support the hypothesis of dehydration from hydrous slabs at the phase boundary. The LSSAs which correspond to dehydration induced fluids are likely to be very local, given very small hydrogen (H^+) diffusivity associated with subducted slabs. The image of such local LSSA zones embedded in HSSAs may not be necessarily captured in tomography studies. The high electrical conductivity in the MTZ beneath the northwestern Pacific subduction zone does not necessarily require a broad range of high water content homogeneously.

1. Introduction

In the past three decades many seismic tomography models have visualized common long-wavelength features of high seismic speed anomalies (HSSA) associated with subducted cold plates. The tomography models captured images of different behaviors of subducted cold plates from region to region as they sink into the mantle transition zone (MTZ), some flatten to form stagnant slabs with a lateral extent of over a few thousand kilometers, or others penetrate into the lower mantle (e.g., van der Hilst et al., 1991, 1997; Widiyantoro et al., 1999; Fukao et al., 2001; Grand, 2002; Zhao, 2004).

The tomography studies led numerical studies to produce a new class of global mantle convection models with a link to seismic models (e.g., Bunge and Richards, 1996; Bunge et al., 1998; Becker and Boschi, 2002; Schuberth et al., 2009a). Simultaneous joint inversions of global seismic and geodynamic data (e.g., Simmons et al., 2006) have shown greatly improved fits to the global

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convection-related data using the mantle flow theory and provided supports to reconcile tomography models with geodynamics of large-scale mantle heterogeneity (Forte, 2007). The large-scale heterogeneity is generated by the mantle convection process that is driven by thermal anomalies and agrees well with seismic tomography images except in the MTZ (Schuberth et al., 2009b; see Fig. 1).

On the other hand there are still substantial differences among the published models in their relatively short wavelength features, in particular, in the MTZ and the upper-most lower mantle where the major phase transformations of subducted slab minerals and associated dehydrations occur. Shorter wavelength features in this depth range should have clues to probe micro processes that govern macro physics in mantle dynamics. Nonetheless, interpretations of anomaly features are still non-unique and can be equivocal in terms of effects of temperature, water and geochemical properties. Different interpretations of anomaly features could lead only to diverse modeling and hypotheses.

The separation of the crustal layer from the main body of subducting lithosphere in the MTZ has long been debated (e.g., Anderson, 1979; Ringwood and Irifune, 1988; Ringwood, 1994). Numerical studies have tested mantle convection models with physical parameters that were measured under high pressure and temperature conditions. Only a few of them considered models that are composed of the crust and mantle components with different densities but the same homogeneous viscosity in two-dimensional (2D) convection simulation (e.g., Richards and Davies, 1989; Gaherty and Hager, 1994). These studies did not produce separation between the two components and concluded that a separation of the crustal component from the subducting lithosphere should not occur at the 660 km phase boundary. van Keken et al. (1996) have shown a simplified sandwich model, in which a thin, weak layer between the crust and the cool slab interior can effectively decouple the crust from the slab main body, and the lighter crust can rise, leading to a garnet enriched MTZ.

A number of researchers carried out seismic waveform modeling with a focus on the MTZ structure or the topography of the seismic discontinuity depths that bound the MTZ using relatively short-wavelength body waves in an attempt to supplement long-wavelength seismic tomography studies (e.g., Tajima and Grand, 1995, 1998; Brudzinski et al., 1997; Tajima et al., 1998). These studies resolved the finer structure beneath the flattened slabs in the northwestern Pacific (NWP) subduction zones with discontinuity depth variations. The result is an important implication for mantle dynamics. However, the seismic rays used in these studies were too sparse to constrain the anomaly structure of the flattened subducted slabs.

More recent studies attempted to determine the MTZ structure associated with stagnant slabs using broadband data recorded by the dense seismic networks in China (Wang and Chen, 2009; Wang and Niu, 2010, 2011; Ye et al., 2011; Li et al., 2013). Nonetheless, the methods adopted for the waveform modeling are similar to previous one-dimensional (1D) studies and did not fully utilize the advantage of data from the dense networks. There are also studies that determined discontinuity depth variations using long-period precursors to SS and PP (e.g., Flanagan and Shearer, 1998), short-period precursors (Collier et al., 2001), or differential travel-times between sScS and sScSSdS (reflections from the discontinuities) recorded in the dense seismic networks in Japan (Tono et al., 2005).

Recent laboratory experiments determined the phase relations in the peridotite-water system up to the top of the lower mantle where dehydration may occur from subducting slabs. Dehydration is presumed because of the much smaller capacity of hydration of lower mantle minerals than minerals in the MTZ (e.g., Ohtani et al., 2004). Further, Ohtani and Litasov (2006) have shown clear

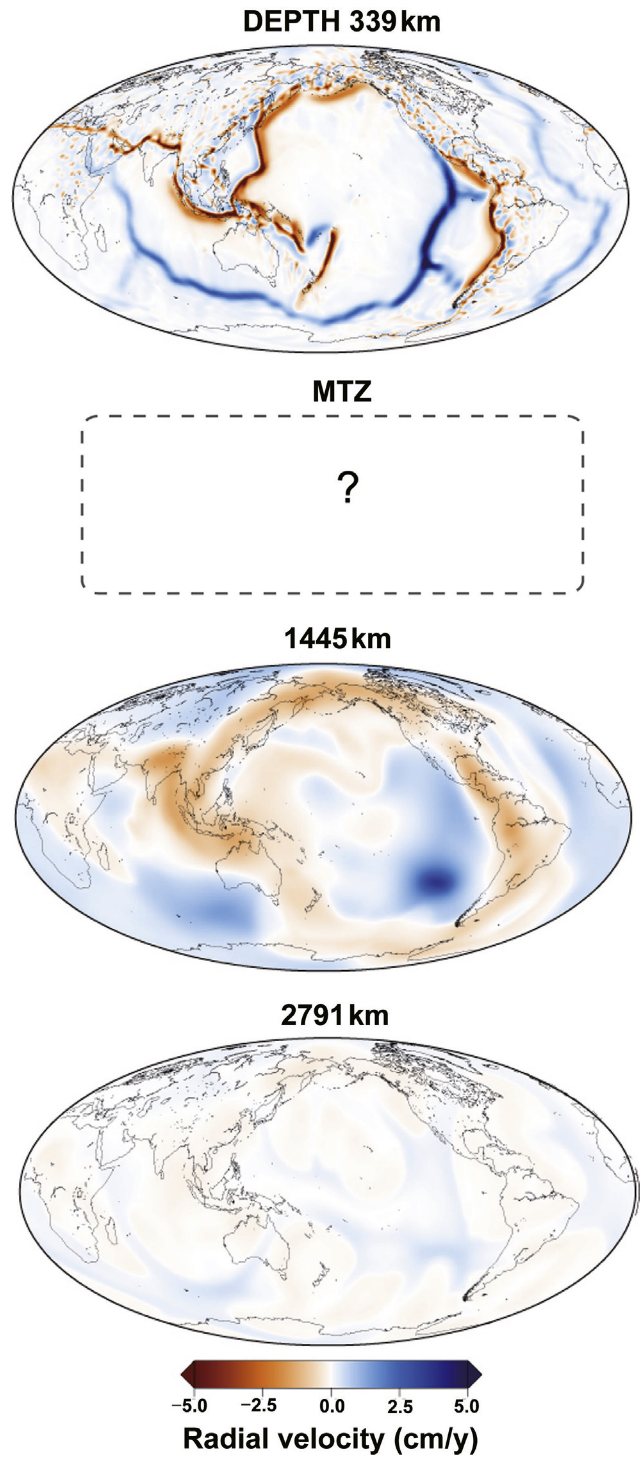

Figure 1. Radial mantle flow magnitudes based on the convection model by Schuberth et al. (2009a) are shown in the upper mantle (∼340 km), mid-mantle (∼1450 km), and near the base of lower mantle (∼2800 km). Coherent patterns were not obtained in the MTZ. Note that the radial flows (orange for downward up to −5 cm/y and navy for upward up to +5 cm/y) concentrate around the plate boundaries in the upper mantle but diffuse (up to ±2 cm/y) in the mid-mantle. The original figures were provided by B. Schuberth.

difference in the Clapeyron slope for synthetic mantle minerals under dry (dehydrated) and wet (hydrous) conditions, and suggested a possibility of wet condition for subducted slabs in the regions where the seismically observed depression of the 660 km