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Pervasive seismic low-velocity zones within stagnant plates in the mantle transition zone: Thermal or compositional origin?

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ABSTRACT

We exploit conversions between P and S waves for large-scale, high-resolution imaging of the mantle transition zone beneath Northwest Pacific and the margin of Eastern Asia. We find pervasive reflectivity concentrated in two bands with apparent wave-speed reduction of −2% to −4% about 50 km thick at the top of the transition zone and 100 km thick at the bottom. This negative reflectivity associated with the scattered-waves at depth is interpreted jointly with larger-scale mantle tomographic images, and is shown to delineate the stagnant portions of the subducted Pacific plate in the transition zone, with largely positive shear-wave velocity contrasts. The upper reflectivity zone connects to broad low-velocity regions below major intra-plate volcanoes, whereas the lower zone coincides locally with the occurrence of deep-focus earthquakes along the East Asia margin. Similar reflectivity is found in Pacific Northwest of the USA. We demonstrate that the thermal signature of plates alone is not sufficient to explain such features. Alternative explanations for these reflective zones include kinetic effects on olivine phase transitions (meta-stability), compositional heterogeneities within and above stagnant plates, complex wave-propagation effects in the heterogeneous slab structure, or a combination of such factors. We speculate that part of the negative reflectivity is the signature of compositional heterogeneities, as revealed by numerous other studies of seismic scattering throughout the mantle, and that such features could be widespread across the globe.

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1. Introduction

The 250 km-thick boundary layer of the mantle transition zone (MTZ) is delimited by two seismic interfaces, the ‘410’ and ‘660’-km discontinuities, and separates the upper mantle from the more viscous lower mantle. The seismic discontinuities at the top and bottom of the MTZ are commonly attributed to solid–solid mineralogical phase changes from olivine (*ol*) to wadsleyite (*wa*) at 410 km depth, and ringwodite (rw) to perovskite+magnesiowustite ($pv + mw$) at 660 km depth (e.g. Bina and Helffrich, 1994).

There are many observations of scattering of seismic waves near or within the MTZ. In the shallow to mid-lower mantle, seismic array studies have located many small-scale scatterers in association with subducted plates in the circum Pacific region (e.g. Niu, 2014; see Kaneshima, 2016 for a review). Within the MTZ, Bentham and Rost (2014) showed from P-P scattering that a good correlation exists between the location of scatterers and the edges of high seismic wave speeds in tomographic models, delineating subducted plates below Western Pacific. These scatterers have dominantly a low-velocity signature (Kaneshima, 2016). Such scattering is usually attributed to the presence of small-scale and compositionally distinct remnants of subducted oceanic crust. The mid-oceanic ridge basalts (MORB), in large proportion in the oceanic crust, have indeed a different seismic signature than the harzburgite (the underlying depleted mantle layer in subducted oceanic plates), or pyrolite (the parental mantle) in various pressure ranges (e.g. Ricard et al., 2005; Stixrude and Lithgow-Bertelloni, 2005).

Larger-scale coherent zones of scattering exist also with dispersed geographical and depth distributions within and surrounding the MTZ. These zones have mainly been reported from P-to-S receiver function studies and described as low shear-wave velocity (*vs*) layers. The estimated shear-wave velocity contrast, Δvs, at the top of these layers ranges from −2 to −8%. An early observation came from a multiple-ScS reverberation study by Revenaugh and Sipkin (1994), who imaged a ∼5.8% impedance decrease be-

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neath the Sea of Japan (East Sea), Yellow Sea and easternmost Asia at around 330 km depth on top of the *ol* → *wa* transition. Subsequently, other studies from receiver functions, P-wave triplications, and ScS reverberations, reported many apparent low-velocity zones (LVZs) with thicknesses varying from 20 to 90 km on top of the 410-km discontinuity. These zones were found in various geodynamical settings: the subduction zones in the western US and southwest Pacific (Song et al., 2004; Courtier and Revenaugh, 2007; Tauzin et al., 2013); regions of hot upwelling in the vicinity of ancient continental platforms (Vinnik and Farra, 2007); or globally, in regions with no particular affinity with a specific geodynamical context (Tauzin et al., 2010).

Apparent low shear-wave velocity layers have also been found atop the *rw* → *pv*+*mw* phase change. Shen and Blum (2003) found a layer in an area of ancient slab subduction in southern Africa. In the western US, the top of these zones appears near 590 km depth in close association with the subducted Farallon plate (Tauzin et al., 2013). In northeastern China and probably extending beneath the Eurasian continent, Shen et al. (2008), Gao et al. (2010) and Liu et al. (2015) reported from receiver functions a zone of negative reflectivity within or near the stagnant Pacific plate. Similar seismic signatures have been reported for subduction zones in Europe although these may result in part from imaging artifacts, due in particular to seismic wave reverberations in the shallow upper mantle (Cottaar and Deuss, 2016).

Negative reflectivity zones atop and at the bottom of the MTZ are usually reported and discussed separately so there is currently no common ground for interpretation. They have often been attributed to different mechanisms involving variations in mantle major and minor element chemistry. In this way, the negative reflectivity detected above the *ol* → *wa* transition is often interpreted as arising from partial melting, induced by the dehydration of mantle rocks (Revenaugh and Sipkin, 1994; Bercovici and Karato, 2003; Song et al., 2004; Vinnik and Farra, 2007; Tauzin et al., 2010). The reflective zone atop the *rw* → *pv* + *mw* phase change is enigmatic. It is often attributed to compositional stratification due to the accumulation of low-velocity oceanic crust through crustal decoupling from subducted plates (Ringwood and Irifune, 1988; Van Keken et al., 1996; Shen and Blum, 2003; Shen et al., 2014). Shen et al. (2014) suggest that these zones above the 660 could be global in nature, resulting from crustal accumulation during the 3 to 4.1 Gyr long history of plate subduction in the Earth's mantle.

Regionally in the coldest subduction zones, zones of anomalous reflectivity can arise from solid–solid phase transformations. When subducted oceanic plates penetrate into the deep mantle and reach the depth of the top of the transition zone, *ol* in the subducted plate transforms into the higher-pressure and higher-density form *wa*. Within the coldest core of the subducting plate, this transformation may be delayed due to kinetic effects, which would allow metastable olivine to persist deeper than 410 km depth. The *ol* having slower seismic signature than *wa*, the resulting seismic response is an apparent low-velocity zone. Several lines of evidence point toward the existence of a meta-stable olivine wedge (MOW) within the Pacific slab under northeast Asia (Iidaka and Suetsugu, 1992; Kawakatsu and Yoshioka, 2011). The wedges are reported down to 4500–570 km depth and with a −3 to −9% Δvs contrast. Kawakatsu and Yoshioka (2011) presented from receiver function imaging with the Hi-Net network in southwest Japan an image of the MOW in the subducting Pacific plate as a thin (10–15 km) westward dipping low-velocity layer surrounded by sharp boundaries at depths between ~350 km and 450 km.

Widespread Cenozoic to recent intraplate volcanism in northeast China and the Korean Peninsula, and deep focus earthquakes within the MTZ below the Japan Sea, may well be linked to the presence of deep compositional heterogeneities or a MOW

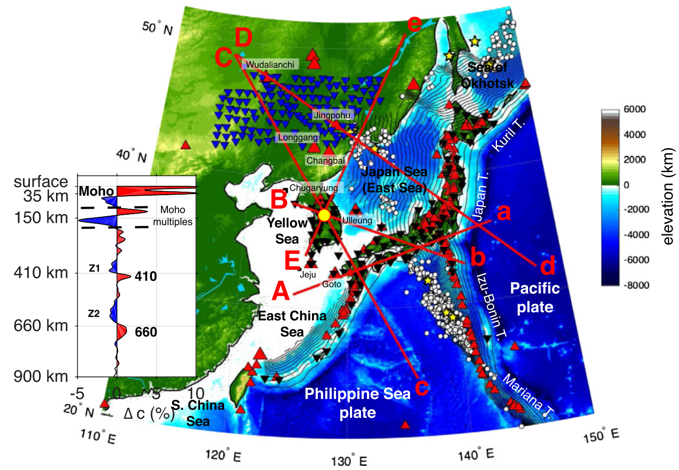

Fig. 1. Map of study region with the 232 stations used in our receiver function analysis, along with the lines for cross sections for the 2D images shown in Figs. 2–6. The subducted Pacific and Philippine plate depth contours are shown with black lines from 20 to 720 km depth. Small red triangles indicate arc-related volcanoes. Larger red triangles designate intra-plate volcanoes. White dots correspond to the location of deep focus subduction zone earthquakes within the transition zone from the U.S. Geological Survey (USGS), the yellow stars representing events with magnitude greater than 7.0. Seismic stations are shown with inverted triangles: in blue the NECESSArray, in black F-Net in Japan, and in black the permanent networks in Korea. Our 2D images are constructed from the juxtaposition of radial profiles such as shown in the inset for the location marked by the yellow dot in South Korea.

in the northwest Pacific subduction zones. The Changbai volcano (Fig. 1), located at the border between China and North Korea, is the largest and most active intraplate volcano in northeast Asia. Some authors have related this volcano as well as others (Wudalianchi, Jingpohu, Longgang, Chugaryung, Ulleung, Jeju and Goto; see Fig. 1) to hot and hydrated upwellings from the Pacific plate that is stagnant within the MTZ. This model proposes that the Pacific slab brings hydrous minerals down to MTZ depths, either as in-slab dense hydrous magnesium silicates (e.g. the phase A; e.g. Ohtani et al., 2001) or through entrainment of hydrated nominally anhydrous minerals above the slab (olivine, garnet, pyroxene). Convective instabilities may occur from the top of the stagnant plate, which is heated from above (Richard and Bercovici, 2009). Due to the lower water solubility in *ol* (Kohlstedt et al., 1996), these upwelling plumes in the *wa* stability field may release their water and induce partial melting when transforming to *ol* atop the 410-km discontinuity (Bercovici and Karato, 2003; Richard and Bercovici, 2009). This water-rich upwelling might further ascend through the asthenosphere and lithosphere, and lead to intraplate volcanism through fluid-assisted decompression melting (e.g., Richard and Iwamori, 2010; Kim et al., 2016). In these circumstances, variations in MTZ hydration could support the occurrence of vigorous small-scale convection in the mantle below northeast China, and a hydrous partial melt layer atop the 410 (a LVZ) would be a key marker of this model.

Deep-focus earthquakes occur in the subducted Pacific plate east of the Changbai, Jingpohu and Ulleung intraplate volcanoes at depths beyond 550 km (Fig. 1). The physical mechanism that triggers and sustains earthquake ruptures at such depths remains controversial (Green and Houston, 1995; Kawakatsu and Yoshioka, 2011). Mechanisms include transformational faulting triggered by metastable *ol* transforming to *wa* in the cold core of the slab, thermal instability and runaway shear melting when the deformation of material occurs rapidly enough in comparison with the time scale of thermal diffusion, grain size assisted thermal runaway, dehydration embrittlement upon exsolution of a volatile component

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