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Seismic evidence for water transport out of the mantle transition zone beneath the European Alps

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ABSTRACT

The mantle transition zone has been considered a major water reservoir in the deep Earth. Mass transfer across the transition-zone boundaries may transport water-rich minerals from the transition zone into the water-poor upper or lower mantle. Water release in the mantle surrounding the transition zone could cause dehydration melting and produce seismic low-velocity anomalies if some conditions are met. Therefore, seismic observations of low-velocity layers surrounding the transition zone could provide clues of water circulation at mid-mantle depths. Below the Alpine orogen, a depressed 660-km discontinuity has been imaged clearly using seismic tomography and receiver functions, suggesting downwellings of materials from the transition zone. Multitaper-correlation receiver functions show prominent ~0.5–1.5% velocity reductions at ~750–800-km depths, possibly caused by partial melting in the upper part of lower mantle. The gap between the depressed 660-km discontinuity and the low-velocity layers is consistent with metallic iron as a minor phase in the topmost lower mantle reported by laboratory studies. Velocity drops atop the 410-km discontinuity are observed surrounding the Alpine orogeny, suggesting upwelling of water-rich rock from the transition zone in response to the downwelled materials below the orogeny. Our results provide evidence that convective penetration of the mantle transition zone pushes hydrated minerals both upward and downward to add hydrogen to the surrounding mantle.

1. Introduction

Water exists in Earth's deep mantle as hydrogen defects in sub-solidus minerals or dissolved water in melts. Water transport in Earth's interior has great impact on the geophysical properties of mantle materials and global material circulation (Bercovici and Karato, 2003; Ohtani et al., 2004; Hirschmann, 2006). The water-storage capacity of typical upper-mantle or lower-mantle minerals is likely much less than for typical mineral-phases in the mantle transition zone (MTZ) at ~410–660 km depth (e.g. Kohlstedt et al., 1996; Bolfan-Casanova, 2005). Therefore, the MTZ has been considered to be a potentially large water reservoir in Earth's mantle. Water transported out of the MTZ into the surrounding upper mantle or lower mantle could cause dehydration melting near the transition-zone discontinuities. These partial melts could produce low seismic-velocity anomalies (e.g., when melt wets the grain-boundaries well, see Yoshino et al., 2007) that can be imaged using seismic tools such as receiver functions and travel-time analyses (Song et al., 2004; Tauzin et al., 2010; Hier-Majumder and Courtier, 2011; Hier-Majumder and Tauzin, 2017).

The partially molten rocks surrounding the MTZ may form thin layers with sharp velocity-reductions. At transition-zone depths, body-wave tomographic models can reveal large-scale lateral velocity-anomalies, but the vertical extent of velocity-anomalies may not be constrained well due to smearing effects and path coverage. Surface wave tomography can resolve structures near the bottom of the upper mantle with a vertical resolution of tens of kilometers, but suffer from low lateral resolution at mid-mantle depths (Nolet et al., 2007). Thin low-velocity layers surrounding the transition zone can be detected well using travel-time analysis (e.g. S-waveform triplication modeling Song et al., 2004; Song and Helmberger, 2006) or P-to-S converted waves which are primarily estimated by high-frequency receiver functions (Schmandt et al., 2014; Liu et al., 2016).

The water-storage capacity of wadsleyite and ringwoodite, which are the major mineral phases in the MTZ, has been estimated to be ~1–3 wt% (Kohlstedt et al., 1996). Electrical conductivity in the MTZ is highly sensitive to hydration, as inferred from rheological experiments (Karato, 2011) and electromagnetic induction studies (Kelbert et al., 2009). These studies suggest a regional variation of MTZ water content from ~0.5–1 wt% to ~0.1 wt%. Alternatively, Fei et al. (2017) suggested from mineral-viscosity constraints that the MTZ may be nearly water-saturated

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with ∼1–2 wt%. In addition, a ∼1.5 wt% hydrous ringwoodite inclusion in a diamond has been discovered (Pearson et al., 2014), suggesting that the MTZ may contain a substantial amount of water regionally.

In contrast to the mantle transition zone, the water content of major upper-mantle and lower-mantle minerals should be much lower. Water content in upper-mantle rocks, in the form of hydrogen within the mineral lattices, has been estimated to be ∼0.01 wt% using mid-ocean-ridge basalts (Saal et al., 2002; Hirschmann, 2006). Water-storage capacity of bridgmanite and magnesiowustite, the main mineral phases in the lower mantle, have been inferred to be less than ∼0.1 wt% (Bolfan-Casanova, 2005). Consequently, transportation of water-rich materials into the lower mantle will cause partial melting if there are no other phases that could incorporate a substantial amount of water. If melt completely wets the grain-boundaries (Yoshino et al., 2007), then a small amount of melt reduces the strength of grain-boundaries and hence will cause a substantial velocity drop (Hier-Majumder et al., 2014).

However, Frost et al. (2004) showed that some metallic Fe could exist in the lower mantle. Since metallic Fe is known to accept a large fraction (∼10 wt%) of water (e.g., Fukai and Suzuki, 1986), the presence of metallic Fe will suppress partial melting. Therefore, one expects dehydration melting in the lower mantle only in regions that do not contain a substantial amount of metallic Fe.

Vertical mantle flow may introduce water-rich materials from the MTZ into the surrounding mantle. Water release could occur due to large contrasts in water-storage capacities, which may cause dehydration melting and produce seismic low-velocity zones (LVZs) near the MTZ boundaries. Schmandt et al. (2014) observed intermittent low-velocity anomalies in the uppermost lower mantle (∼730 km) beneath North America, which they associated with downward flows from the MTZ into the lower mantle. They suggest that the presence of seismic LVZ is correlated with the direction of water transport, i.e. a seismic LVZ below the 660-km discontinuity would occur where downwelling mantle flow is inferred, but not in regions with upward mantle flow across the 660-km discontinuity. However, they did not explain why velocity reduction occurs at ∼730 km instead of just below the 660-km discontinuity.

In the Japan subduction zone, a similar situation occurs. Seismic tomography studies have observed a stagnant flat-slab in the MTZ (Fukao et al., 1992, 2001; Huang and Zhao, 2006; Fukao and Obayashi, 2013). Beneath northeast China, a local depression of the 660-km discontinuity by ∼20–35 km has been imaged using seismic receiver-functions (Li and Yuan, 2003; Li et al., 2008), which may indicate the penetration of transition-zone materials into the uppermost lower mantle. A downwelling current of cold materials due to gravitational instability (Honda et al., 1993; Tackley et al., 1993) may entrain water-rich materials in the MTZ into the uppermost lower mantle, causing dehydration melting that would produce low seismic-velocity anomalies if some conditions are met such as the low dihedral angle. Liu et al. (2016) observed seismic-velocity reductions below the depressed 660-km discontinuity in this area, but no obvious evidence of LVZs outside the region where the 660-km discontinuity is depressed, suggesting a correlation between the downward flow across the 660-km discontinuity and the presence of LVZs near the top of lower mantle.

In addition, Liu et al. (2016) observed LVZs atop the 410-km discontinuity near the subducting slab, which may indicate partial melts formed by an upward flow of water released from the top of the flat-slab in the MTZ. Their results support the correlation between the direction of water transfer and the presence of velocity reductions as proposed by Schmandt et al. (2014). Testing this hypothesis in other regions with deep slabs is important to understanding Earth's internal water cycle.

The European Alps formed as a result of continental collision between the Eurasian plate and the Adriatic microplate, a promontory attached to Africa, involving the accretion and subduction of oceanic terranes such as the Piedmont-Liguria Ocean and Valais Ocean, during late Cretaceous to early Cenozoic interval (e.g. Stampfli et al., 1998; Handy et al., 2010). P-wave tomographic models have imaged positive velocity anomalies at ∼500–660 km depths within the Alpine MTZ, which may indicate the subducted lithosphere that stagnates at the 660-discontinuity (Spakman et al., 1993; Wortel and Spakman, 2000; Piromallo and Morelli, 2003). Similar results from a joint inversion of regional waveforms and teleseismic S-wave arrival-times also confirm high-velocity anomalies in the MTZ beneath the Alpine Mountains (Schmid et al., 2008).

In addition, the 660-discontinuity in this region has been revealed to be ∼10–40 km deeper than predicted depth by the global IASP91 velocity-model using seismic receiver functions, suggesting accumulation and penetration of cold subducted slab-materials across the 660-discontinuity (Lombardi et al., 2009). Comparing to observations by Liu et al. (2016), we hypothesize that the remnant oceanic-slabs at the depressed 660-discontinuity may entrain water-rich minerals from the MTZ to the top of lower mantle, causing dehydration melting beneath the depressed 660-discontinuity. Therefore, the Alpine mid-mantle is an ideal location to test the water-transport hypothesis of Schmandt et al. (2014) with high-frequency receiver functions.

In this study, we use multi-taper receiver functions (Park and Levin, 2000) to investigate seismic structures with sharp velocity-changes surrounding the MTZ below the Alps. The receiver functions (RFs) are computed to focus on various depth-targets using RF-migration (Park and Levin, 2016). We use the common conversion point (CCP) stacking technique (Dueker and Sheehan, 1997) to construct continuous seismic profiles. In the following sections of this paper, we show the CCP images and discuss the geophysical implications of our results.

2. Data and method

We use three-component teleseismic data recorded by 88 broadband stations in the Alpine region, from multiple networks. We include 40 permanent stations from National Seismic Networks of Switzerland (SED at ETH Zurich, 1983), 17 stations from Regional Seismic Network of North Western Italy (University of Genova, 1967), 18 stations from RESIF and other broadband and accelerometric permanent networks in metropolitan France (RESIF, 1995) and 13 stations from Austrian Seismic Network and Province Sudtirol in Austria.

Waveforms are retrieved from the web interface WebDC3 operated by Observatories and Research Facilities for European Seismology (ORFEUS). We select a total of ∼12500 seismic records with epicentral distance $30° < \Delta < 95°$ and magnitude $M > 5.9$ during 2012–2017. All seismic records are high-passed at $f = 0.03$ Hz to avoid long-period noise. We rotate the horizontal (E and N) components to radial-transverse (R–T) system for RFs processing. We use a cut-off frequency $f_c = 0.6$ Hz to achieve a high vertical resolution of ∼9 km.

We estimate P-to-S RFs in the frequency domain using multi-taper spectrum correlation, which is leakage resistant, allowing low-amplitude P-wave spectrum to be useful in RF-estimation (Park and Levin, 2000). We obtain the first three Slepian eigentapers (Prieto et al., 2009) by choosing a time-bandwidth product of 2.5. We compute statistically independent eigenspectra by applying the first three eigentapers to the first 90 s of seismic data series.

Individual RFs are calculated by deconvolving the horizontal (R and T) components from the vertical (Z) component via a least-