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Pervasive upper mantle melting beneath the western US

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ABSTRACT

We report from converted seismic waves, a pervasive seismically anomalous layer above the transition zone beneath the western US. The layer, characterized by an average shear wave speed reduction of 1.6%, spans over an area of $\sim 1.8 \times 10^6$ km^2 with thicknesses varying between 25 and 70 km. The location of the layer correlates with the present location of a segment of the Farallon plate. This spatial correlation and the sharp seismic signal atop of the layer indicate that the layer is caused by compositional heterogeneity. Analysis of the seismic signature reveals that the compositional heterogeneity can be ascribed to a small volume of partial melt (0.5 ± 0.2 vol% on average). This article presents the first high resolution map of the melt present within the layer. Despite spatial variations in temperature, the calculated melt volume fraction correlates strongly with the amplitude of P–S conversion throughout the region. Comparing the values of temperature calculated from the seismic signal with available petrological constraints, we infer that melting in the layer is caused by release of volatiles from the subducted Farallon slab. This partially molten zone beneath the western US can sequester at least 1.2×10^{17} kg of volatiles, and can act as a large regional reservoir of volatile species such as H or C.

1. Introduction

The mantle transition zone plays a unique role in controlling the Earth's volatile cycle. Nominally anhydrous silicate minerals in the transition zone can dissolve substantially larger quantities of H in their crystal structure, compared to the major mantle minerals above and below (Bolfan-Casanova, 2002; Kohlstedt et al., 1996). The gradient in H solubility across the transition zone has been posited as a source for volatile-induced melting atop and below the transition zone in regions of upwelling or downwelling (Bercovici and Karato, 2003; Schmandt et al., 2014). In addition, a recent study of melting of slab carbonates suggests that carbonate phases in subducting slabs can lead to the generation of carbonatitic melts near the base of the upper mantle (Thomson et al., 2016). These constraints from laboratory experiments, as well as constraints on melt density (e.g., Ghosh et al., 2007), indicate the likelihood of a partially molten layer atop the transition zone. Several features of such a layer provide important information regarding the transport and storage of volatiles in and around the transition zone.

Owing to the compositional contrast arising from melting, seismic signature of a partially molten layer should be marked by a sharp boundary, unlike thermal anomalies that can have diffuse boundaries. In addition, thickness and spatial extent of the layer, magnitude of seismic wave speed reduction, and spatial correlation with tectonic features such as subduction can provide additional insight into the origin and nature of melting within the layer. Spatial correlation between the partially molten layer and cold regions of the transition zone can indicate the possibility of volatile-induced melting, as the solidus of dry mantle peridotite is likely higher than the temperature within the zone. In studying such partially molten layers, it is crucial to quantify the amount of melt in the layer as the melt content and its spatial variations can provide indirect evidence for processes associated with the origin, transport, and storage of the melt. While a number of previous studies reported the presence of melting atop the transition zone, detailed regional maps of partial melt, derived from seismic observations, still remain scarce.

Several previous studies reported the occurrence of low seismic velocity layers (LVLs) 350 km below the surface (Courtier and Revenaugh, 2007; Gao et al., 2006; Revenaugh and Sipkin, 1994; Song et al., 2004; Tauzin et al., 2010; Vinnik and Farra, 2007). The sharp reduction of velocity at the onset of the LVL is sometimes referred to as the 350 discontinuity (Vinnik and Farra, 2007). Recent studies suggest that the LVL can be present on a global

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scale (Tauzin et al., 2010; Vinnik and Farra, 2007), with the distance above the 410 discontinuity changing laterally from 20 km to as much as 90 km over a few hundred kilometers. Correlations of these variations with hot (Hier-Majumder et al., 2014; Vinnik and Farra, 2007) or cold (Courtier and Revenaugh, 2007; Hier-Majumder and Courtier, 2011; Song et al., 2004) tectonic environments have remained elusive (Tauzin et al., 2010), suggesting that the variations in position cannot be explained by temperature alone.

In the western US, studies reporting an LVL are based either on P–S receiver functions and P-wave triplication (Song et al., 2004), P–S receiver functions (Fee and Dueker, 2004; Jasbinsek and Dueker, 2007; Jasbinsek et al., 2010; Schmandt et al., 2011), or S–P receiver functions (Vinnik et al., 2010). The LVLs have been found beneath the border between Oregon and Washington (Song et al., 2004), Yellowstone (Fee and Dueker, 2004; Jasbinsek and Dueker, 2007), the northern Rocky Mountains (Jasbinsek and Dueker, 2007), the southern Colorado Plateau and the Rio Grande Rift (Jasbinsek et al., 2010), and under California (Vinnik et al., 2010) (Fig. 1a).

Due to the lack of coverage and absence of extensive analysis involving rock physics and melt microstructure, however, these studies were unable to quantify the spatial expanse and local variations in the melt content in the LVL. Using limited coverage underneath the Coral Sea and Hawaii, the LVLs were estimated to contain approximately 1 vol% melt (Hier-Majumder and Courtier, 2011; Hier-Majumder et al., 2014). The seismic data in these two studies, however, were too sparse to create a detailed regional map of melting. Such detailed regional maps of melting are crucial in understanding the global volatile cycle, as they allow correlation between the structure and geometry of the melt zone and the tectonic environment, potentially identifying processes involved in melt generation, metasomatism, and melt storage.

In this study, we address the issue of a detailed regional map of melting underneath the western US, using high resolution seismic data. The seismic signature of the LVL was derived from 820 seismometers of the dense broad-band US Transportable Array (Fig. 1b). We applied the P-to-S receiver function (RF) technique to the records of 932 teleseismic earthquakes giving a set of 65,000 RFs (Tauzin et al., 2013). The RF technique uses compression-to-shear (P–S) converted seismic waves to detect sharp shear-wave velocity changes beneath stations. With such a dense seismic array, the RF technique enables the detection of thin layers in the transition zone over a semi-continental scale and with a high lateral resolution.

In the following sections we outline our findings for the western US. We discuss the methods of analysis of the RF data and the rock physics analysis in Section 2, present our key findings in Section 3, and discuss the implications for the regional volatile cycle in Section 4.

2. Methods

2.1. Receiver function data analysis

2.1.1. Data

In this study, we used 3-component broad-band records of passive seismicity at stations deployed during the US Transportable Array experiment between January 2004 and November 2009 (Tauzin et al., 2013). Waveforms were obtained from the IRIS Data Management Center for 932 teleseismic earthquakes, occurring at depths shallower than 350 km, with epicentral distances between 40° and 95°, and magnitudes of at least 5.5. These earthquakes were recorded during the two first deployments of the Transportable Array covering the western half of the US at 820 sites (Fig. 1b).

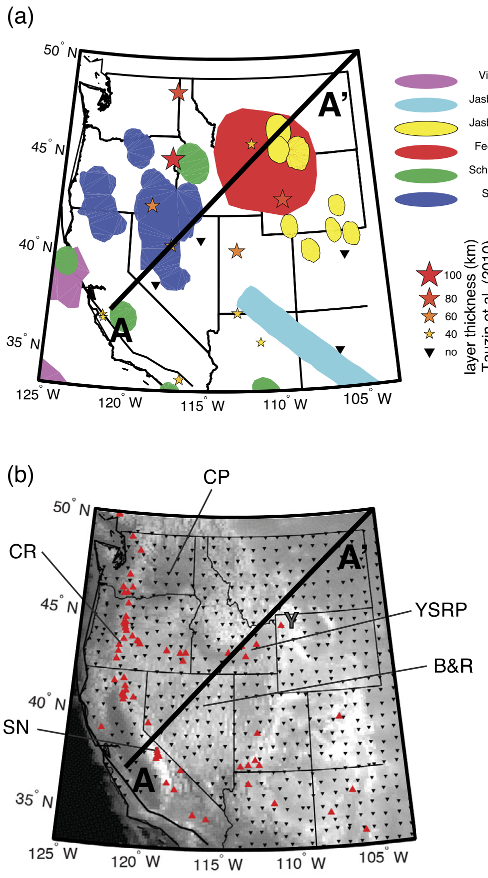

Fig. 1. Low-velocity layer observations from dense seismic arrays. (a) A map summarizing previous observations of the LVLs across western US. These observations have been obtained from several independent studies using small-aperture seismic networks. (b) The larger-aperture seismic network used in this study is the Transportable Array (black triangles), covering the western half of the US with an average station spacing of 70 km. The Caltech Regional Seismic Network has not been processed, explaining a gap in coverage in the extreme South of California. The seismic profile discussed in this study is labeled A–A′ and marked with a black line. Important physiographic features of the western US are labeled, such as the Cascadia ranges (CR), the Yellowstone Snake River plain (YSRP), the Yellowstone caldera (Y), the Columbia plateau (CP), the Sierra Nevada (SN), and the Basin and Range province (B&R). Major Quaternary active volcanoes (red triangles) are either arc-related, due to the present subduction of the Juan de Fuca plate below the Cascadia ranges, or possibly hotspot-related in the Snake River plain and Yellowstone regions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

To extract the signal of waves converted from P-to-S (P–S) at seismic boundaries beneath the receivers, we built receiver functions (RFs) by deconvolving the records of the P-wave rotated along the radial component by the records rotated along the vertical component. The original records are low-pass filtered at 5 s period, then deconvolved using an iterative time domain deconvolution method (Ligorria and Ammon, 1999). In this deconvolution method, the applied Gaussian function has a width $L = 1.125$ s at half the maximum amplitude to respect the vertical resolution of converted waves at TZ depth ($\lambda/2$ where λ is the wavelength of the shear-wave). Quality control were made, with a selection based on the ratio of the RMS amplitudes of the signal after the P-wave and of the noise before the P-wave (Tauzin et al., 2013). The data set consists of 64,578 RFs and provides a good coverage in P-to-S piercing points at transition zone discontinuities. A precise map of this coverage is shown in the study from Tauzin et al. (2013). This coverage is highlighted by the area that is not shaded in Figs. 3 and 4. The data collected in this study have been obtained from the mobile Transportable Array and do not include the data from