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Waveform inversion of *SS* precursors: An investigation of the northwestern Pacific subduction zones and intraplate volcanoes in China

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ABSTRACT

The arrival time and amplitude of underside reflections from mantle seismic discontinuities (*SS* precursors) have made major contributions to the understanding of mantle composition and dynamics. In this study, we introduce a nonlinear waveform inversion technique to simultaneously constrain shear velocities and discontinuity depths beneath the northwestern Pacific subduction system. Based exclusively on a large *SS* precursor waveform dataset, we are able to clearly delineate the morphology of the descending Pacific plate, which flattens at the base of the upper mantle and extends westward by ~1500 km toward northern-central China. Our grid search yields the maximum correlation between shear velocity and transition zone thickness at an angle of ~30°, consistent with the reported average slab dip beneath the study region. The strongly positive correlation suggests predominantly thermal, rather than compositional, variations along the descending Pacific plate. The joint depth-velocity solution also shows a 5–10 km depression of the 410 km discontinuity and an average decrease of 1.2% in upper mantle shear velocity beneath the intraplate volcanic fields in northeastern China. This anomaly, which reaches the middle of the upper mantle transition zone beneath the Changbai hotspot, initiates at a significantly shallower (~320 km) depth beneath the Wudalianchi region. High amplitude reflections at depths greater than 410 km suggest a water-poor melt layer in possible association with 1) decompression melting from passive upwelling and/or 2) active upwelling through a slab window.

1. Introduction

Intraplate volcanic activities have been well documented in both continental and oceanic regions at distances of hundreds to thousands of kilometers away from plate boundary zones. The origin and mechanism of intraplate volcanism vary broadly (Niu, 2005; Zhao, 2007; Tang et al., 2014) and often require the presence of deep mantle plumes (Campbell, 2007; Chen et al., 2007; Zhao, 2007). An ideal laboratory for the study of intraplate volcanism is northeastern (NE) Asia, where Cenozoic magmatic centers are densely distributed along the north-south oriented Changbai Mountain range and Wudalianchi volcanic field in NE China. The former is a stratovolcano located approximately 1200 km west of the Japan trench, while the latter consists of cinder volcanoes covering an area of 500 km^2 toward the north. The origin of these volcanic fields has been linked to mantle plumes as well as subduction-related back-arc spreading and thinning of the lithosphere (Basu et al., 1991; Niu, 2005), though compatible helium isotopic compositions between the Cenozoic basalts from the same region and mid-ocean ridge basalt favor an upper mantle origin (Chen et al., 2007). Further insights were provided by seismic tomography where a horizontally deflected and stagnant Pacific plate at the base of the upper mantle could play a key role in melt generation (Gorbatov and Kennett, 2003; Zhao et al., 2004; Obayashi et al., 2006; Lebedev and van der Hilst, 2008; Li and van der Hilst, 2010).

Models of seismic velocities are complemented by observations of mantle transition zone (MTZ) discontinuities. For the upper mantle assemblage of olivine composition, phase transitions from olivine to wadsleyite and ringwoodite dissociation are widely accepted origins of the 410 km discontinuity (from here on, 410) and 660 km discontinuity (from here on, 660), respectively, at the top and bottom of the MTZ (Anderson, 1967; Ito and Takahashi, 1989). These two mineralogical phase boundaries exhibit opposite Clapeyron slopes (Navrotsky, 1980; Ito and Takahashi, 1989; Katsura and Ito, 1989; Weidner and Wang, 1998), and their sensitivities to temperature and composition have been frequently explored in mantle seismic imaging (Shearer, 1993; Gu et al., 1998; Gu and Dziewonski, 2002; Lawrence and Shearer, 2006a; Deuss, 2009). Based on mantle reflections (Heit et al., 2010; Gu et al., 2012) and conversions (Li and Yuan, 2003; Liu et al., 2015), a depression in excess of 30 km has been observed at the base of the MTZ beneath the intraplate volcanic fields in NE China. This topographic anomaly coincides with a distinctive low velocity asthenosphere, which has been interpreted as the potential source of melting beneath

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the volcanic centers (Zhao et al., 2004; Lei and Zhao, 2005; Niu, 2005; Li and van der Hilst, 2010; Tang et al., 2014).

A known source of error in the independent analyses of seismic velocity and discontinuity topography is the trade-off between them (Flanagan and Shearer, 1998; Gu and Dziewonski, 2002; Zhao et al., 2004; Obayashi et al., 2006; Li et al., 2008; Li and van der Hilst, 2010). Time corrections are typically adopted to minimize the excess topography caused by heterogeneous mantle structures, whereas models of seismic velocities are mostly derived under the assumption of unperturbed mantle interfacial depths. This trade-off was reduced by Gu et al. (2003) and Lawrence and Shearer (2006a) through joint inversions of seismic velocity and discontinuity topography, though much of the information embedded in the waveforms of the secondary reflections was underutilized. In this study we characterize the upper mantle and MTZ beneath the northwestern Pacific region (Fig. 1) using waveform inversions of stacked *SS* precursors (Fig. 1d). Our full waveform nonlinear inversion approach recovers a simultaneous solution for the travel times of *SS* precursors, which are sensitive to mantle temperatures surrounding olivine phase boundaries (Ohtani et al., 2004; Deuss, 2009; Lessing et al., 2014), and the impedance contrasts imprinted onto the *SS* precursor amplitudes (Shearer, 1991; Chambers et al., 2005; Gu and Sacchi, 2009; Lessing et al., 2015). We will demonstrate that a dense precursor dataset alone is sufficient to resolve major upper mantle seismic anomalies in the northwestern Pacific subduction system.

2. Data and method

We utilize a global dataset of broadband and long-period seismograms, recorded between 2006 and 2014, from the Incorporated Research Institutions for Seismology (IRIS). The midpoints of the source-receiver pairs densely sample the structure beneath NE China and the northwestern Pacific subduction zones. We restricted the maximum depth of earthquakes to 75 km to mitigate the interference of depth phases (Schmerr and Garnero, 2006; An et al., 2007) and adopt a minimum magnitude (Mw) cutoff of 5.5 to ensure sufficient reflection amplitudes. We further constrain the distance from 100° to 160° to minimize the interferences from *ScSScS* (Shearer, 1993; Schmerr and Garnero, 2006) and topside reflections from upper mantle discontinuities. After deconvolving the instrument responses, we apply a Butterworth bandpass filter with corner periods at 15 s and 75 s to the transverse component seismograms. We eliminate all traces with signal-to-noise ratios (SNR) less than 4.0 according to the definition of Gu et al. (2012), which is more restrictive than the majority of earlier studies due to a substantially larger data volume. The filtered seismograms are then inspected visually to eliminate duplicate records

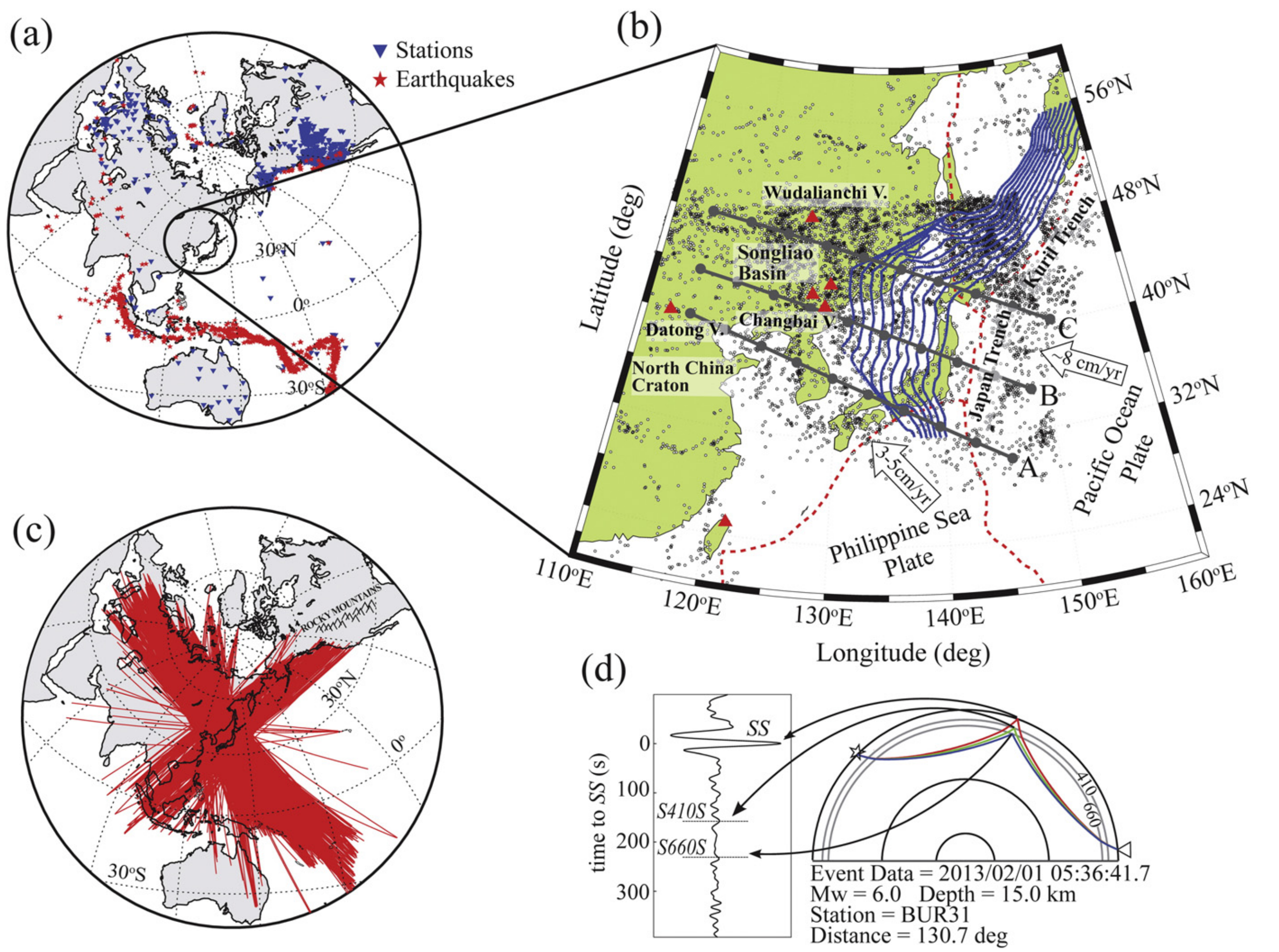

Fig. 1. (a) Global distribution of the earthquake (red stars) and station (blue triangles) locations used in this study. (b) The locations of *SS* bouncepoints from the earthquake-station pairs. The convergent plate boundaries and slab contours are indicated by the red and blue lines, respectively. The contour lines are taken at constant intervals of 50 km starting at 100 km depth (Hayes et al., 2012). The *SS* precursor waveforms are stacked into 30 bins along three parallel profiles A, B and C. (c) Path coverage of the *SS* precursors used in the stacking and inversion procedures. (d) A graphical representation of the theoretical ray paths of *SS* and its precursors for a source-receiver distance of 130.7°. The left panel shows an observed seismogram aligned on the maximum amplitude of *SS*. *S410S* and *S660* are marked based on the predicted arrival times from PREM (Dziewonski and Anderson, 1981).