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Seismic evidence of on-going sublithosphere upper mantle convection for intra-plate volcanism in Northeast China

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ABSTRACT

A 3-D crustal and upper mantle S-wave velocity model of NE China is constructed by inversion of phase velocity dispersion curves at 6–140 s periods from ambient noise tomography and two-plane surface wave tomography. The seismic data used in this study are collected from 120 China Earthquake Administration (CEA) permanent stations and 127 portable stations of NECESSArray. We observe strong low S-wave velocity beneath the Changbaishan volcano in the upper mantle to at least 200-km depth, which is interpreted as a mantle upwelling beneath the Changbaishan volcano that is consistent with the body wave tomographic image. The Songliao Basin is dominated by a high velocity extending to at least 200-km depth. Built upon the observed velocity anomalies, we propose a sub-lithosphere mantle convection model for NE China in which the upwelling of upper mantle materials from the mantle transition zone to the Changbaishan volcano could induce a local sub-lithosphere convection in the upper mantle and the strong high velocity of the upper mantle beneath the Songliao Basin corresponds to the downwelling limb of this convection cell. The downwelling beneath the Songliao Basin could also induce secondary local convection in the asthenosphere to the west, leading to local asthenospheric upwelling beneath the Abaga and Halaha volcanoes in the Xing'an–Mongolia Orogenic Belt.

1. Introduction

Intraplate volcanism on continents is an exception to the theory of plate tectonics (e.g., Morgan, 1968) which states that most of the world's volcanoes both in oceans and on lands occur at plate boundaries. It is well accepted that mantle plumes are capable to create volcanoes anywhere away from plate boundaries. Alternative models, such as small-scale convection triggered by delamination of a thick lithosphere (e.g. Zandt et al., 2004) or edge-driven convection (e.g. King and Anderson, 1998; King and Ritsema, 2000) are commonly invoked to explain the origin of the intra-plate volcanism.

Northeast China is an ideal place to study Cenozoic intraplate volcanism. Though located more than 2000 km west of the Japan trench, Northeast China hosts widely distributed Quaternary volcanism surrounding the Songliao Basin (SLB). Some of the most prominent volcanoes in the area include the well-known Changbaishan volcano in the southeast, Jingpohu volcano in the east, Wudalianchi volcano in the north, and two lesser known volcanoes of Abaga and Halaha in the west (Fig. 1). These Quaternary volcanoes are separated hundreds of kilometers apart, with the Songliao Basin at the center. The Songliao Basin was formed by tectonic rifting in the late Mesozoic and is characterized by relatively thin lithosphere (Zhang et al., 2014; Meng, 2003; Meng et al., 2003). The basin has been in a cooling/subsidence stage after the cessation of rifting about 40 Ma ago (Liu et al., 2001; Wei et al., 2010). Although it is generally agreed that the flat stagnant parts of the subducting Pacific slab in the mantle transition zone have played an important role in the formation of Cenozoic volcanism in NE China (Chen et al., 2007; Zhao et al., 2009; Chen and Pei, 2010; Wu et al., 2011; Guo et al., 2015; Ranasinghe et al., 2015; Takeuchi et al., 2014), there is still a lack of consensus about the mechanism, or mechanisms, responsible for the volcanism, particularly for volcanoes to the west of Songliao Basin.

The international project of NECESSArray (NorthEast China Extended SeiSmic Array) is a recently deployed portable seismic array in NE China. Several seismic studies have been conducted using

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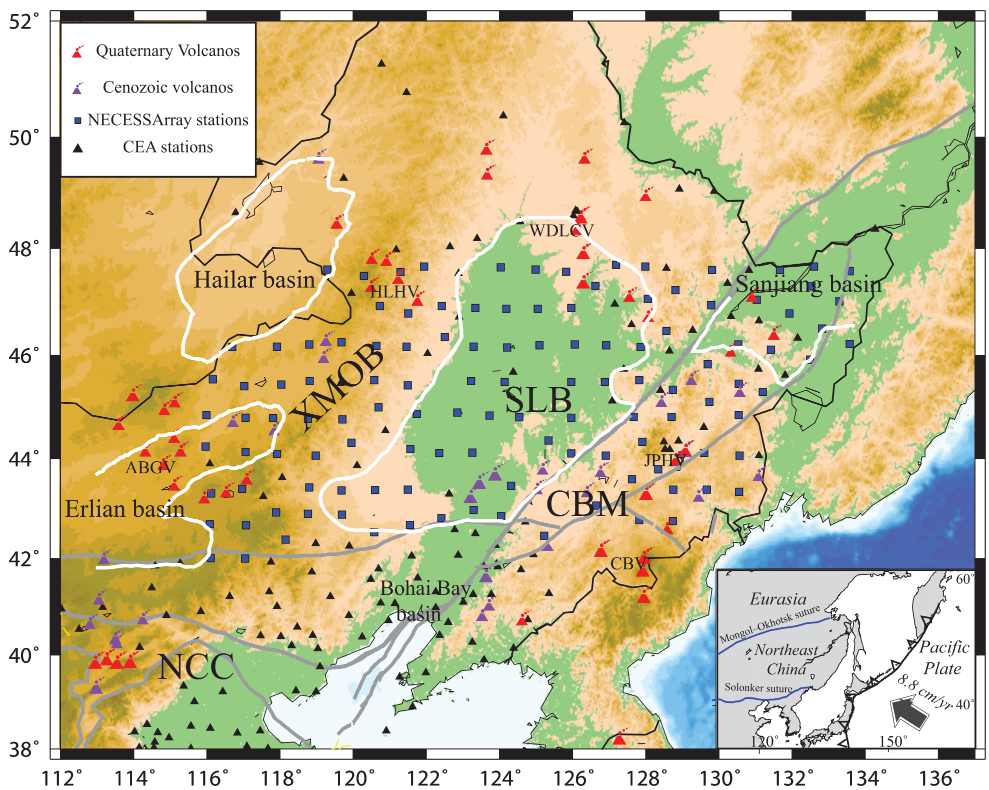

Fig. 1. Stations distribution and geological setting. Blue squares indicate 127 NECESSArray stations and black triangles represent 120 CEA stations. NE China is comprised of the Xing'an–Mongolia orogenic belt (XMOB), the Songliao Basin (SLB) and the Changbai mountain region (CBM). Red and purple volcanic symbols are Quaternary and Cenozoic volcanoes in NE China. White lines outline major Mesozoic basins in NE China. CBV: Changbaishan volcano; JPHV: Jingpohu volcano; WDLCV: Wudalianchi volcano; HLHV: Halaha volcano; ABGV: Abaga volcano. NCC: North China Craton China, respectively.

NECESSArray data to date. For instance, Tao et al. (2014) propose that the high topography in the flanks of the SLB could be dynamically supported by mantle upwelling. Guo et al. (2015) suggest that the mid- and lower crustal low velocity beneath the Xing'an–Mongolia Orogenic Belt (XMOB) could be the consequence of mafic lower crust removal in the Mesozoic. In particular, Tang et al. (2014) conducted a S body-wave tomography model and suggest that subduction-induced mantle upwelling is connected to the Changbaishan volcano at the surface. In order to better understand the causes of widespread magmatism in the area and the mantle processes responsible for the volcanism away from the active plate boundary, it is essential to build a high resolution seismic image of the crust and upper mantle beneath NE China.

Surface-wave tomography has become a routine method to investigate the seismic structure of the upper mantle. In the past two decades, array-based teleseismic surface-wave tomography methods, such as two-plane-wave tomography (TPWT) (Forsyth and Li, 2013; Yang and Forsyth, 2006a, 2006b), eikonal tomography and Helmholtz tomography (Lin and Ritzwoller, 2011), have been developed and applied extensively to both regional (e.g. Li and Burke, 2006), and continental scale arrays (Pollitz and Mooney, 2014). Surface-wave tomography based on cross-correlations of long-term seismic noise data between station pairs (Campillo and Paul, 2003; Gouédard et al., 2008; Shapiro et al., 2005; Yang et al., 2007) provides complementary constraints on crustal and uppermost mantle structure (Yang et al., 2008a). In this study, we employ two-plane surface wave tomography (TPWT) and ambient noise tomography (ANT) to generate phase velocities at 6–140 s. We then use a Markov chain Monte Carlo (MCMC) method to invert these phase velocities for 3-D velocity structure of NE China.

2. Data and methods

Seismic data used in this study are collected from a total of 247 seismic stations (Fig. 1), including 127 stations from the NECESSArray that were deployed from September 2009 to August 2011, and additional 120 permanent stations from China Earthquake Administration Array (CEA). Station spacing is less than 70 km for most of the study region.

2.1. Ambient noise tomography

Here we briefly introduce the data processing procedures of ambient noise tomography, which are similar to those described in detail by Bensen et al. (2007) and Yang et al. (2007). Vertical components of raw continuous seismic data are cut to a series of one-day segments and decimated into 1 sample per second. After the instrument responses are removed, seismic data are band-pass filtered between 5 and 150 s. Then a time domain and spectral whitening is applied to avoid significant spectral imbalance, broaden the bandwidth of the ambient noise and remove the effects of earthquakes and other irregularities. After all these steps are preprocessed, cross-correlation between each station pair is carried out as a daily record and then 2 yrs daily cross-correlations are stacked to obtain the final stacked cross-correlations.

Fig. 2a shows examples of cross-correlations between station NE34 and other stations. Clear and coherent signals are seen both in positive and negative lag times. We follow previous ambient noise tomography studies (Zeng and Ni, 2010; Zheng et al., 2011; Guo et al., 2015) to remove possible disturbances from Kyushu Island in cross-correlations at period less than 18 s. Positive and negative components of cross-correlations are stacked together