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Mantle seismic anisotropy beneath NE China and implications for the lithospheric delamination hypothesis beneath the southern Great Xing'an range

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ABSTRACT

We measured shear wave splitting from SKS data recorded by the transcontinental NECESSArray in NE China to constrain lithosphere deformation and sublithospheric flows beneath the area. We selected several hundreds of high quality SKS/SKKS waveforms from 32 teleseismic earthquakes occurring between 09/01/2009 and 08/31/2011 recorded by 125 broadband stations. These stations cover a variety of tectonic terranes, including the Songliao basin, the Changbaishan mountain range and Zhangguancai range in the east, the Great Xing'an range in the west and the Yanshan orogenic belt in the southwest. We assumed each station is underlaid by a single anisotropic layer and employed a signal-to-noise ratio (SNR) weighted multi-event stacking method to estimate the two splitting parameters (the fast polarization direction φ, and delay time, δt) that gives the best fit to all the SKS/SKKS waveforms recorded at each station. Overall, the measured fast polarization direction lies more or less along the NW–SE direction, which significantly differs from the absolute plate motion direction, but is roughly consistent with the regional extension direction. This suggests that lithosphere deformation is likely the general cause of the observed seismic anisotropy. The most complicated anisotropic structure is observed beneath the southern Great Xing'an range and southwest Songliao basin. The observed large variations in splitting parameters and the seismic tomographic images of the area are consistent with ongoing lithospheric delamination beneath this region.

1. Introduction

Northeast (NE) China lies between Korea and Mongolia, and is situated partly on the Sino-Korean craton and partly on the Inner Mongolia foldbelt (Fig. 1). Late Jurassic and Cretaceous volcanic rocks are widely distributed in the area with the age of rocks becoming younger towards the east, suggesting a west-to-east migration in magmatism (e.g., Wang et al., 2006; Zhang et al., 2010). The cause for this eastward volcanic migration is, however, still debated. For example, Wang et al. (2006) proposed a lithospheric delamination event, which was triggered by the collision of NE China and Siberia after the closure of the Mongol–Okhotsk ocean around ~160 Ma and then propagated progressively from west to east. The authors suggested that the thickening of the lithosphere is likely driven by the Mongol–Okhotsk subduction from the northwest and the initial stage of the collision. Zhang et al. (2010), on the other hand, believed that the lithospheric delamination is triggered by a flat-to-normal subduction change of the Paleo-Pacific plate beneath the east side of the area in the late Jurassic. These two geodynamic scenarios are expected to produce different fabric structures within the lithosphere, which can be mapped by seismic anisotropy (Silver, 1996).

Volcanism in NE China continued in the Cenozoic, but occurred much less extensively and in a rather episodic way (Liu et al., 2001). The volcanism was initiated at ~86 Ma and was mainly concentrated within the Songliao basin. At around 28 Ma, the vol-

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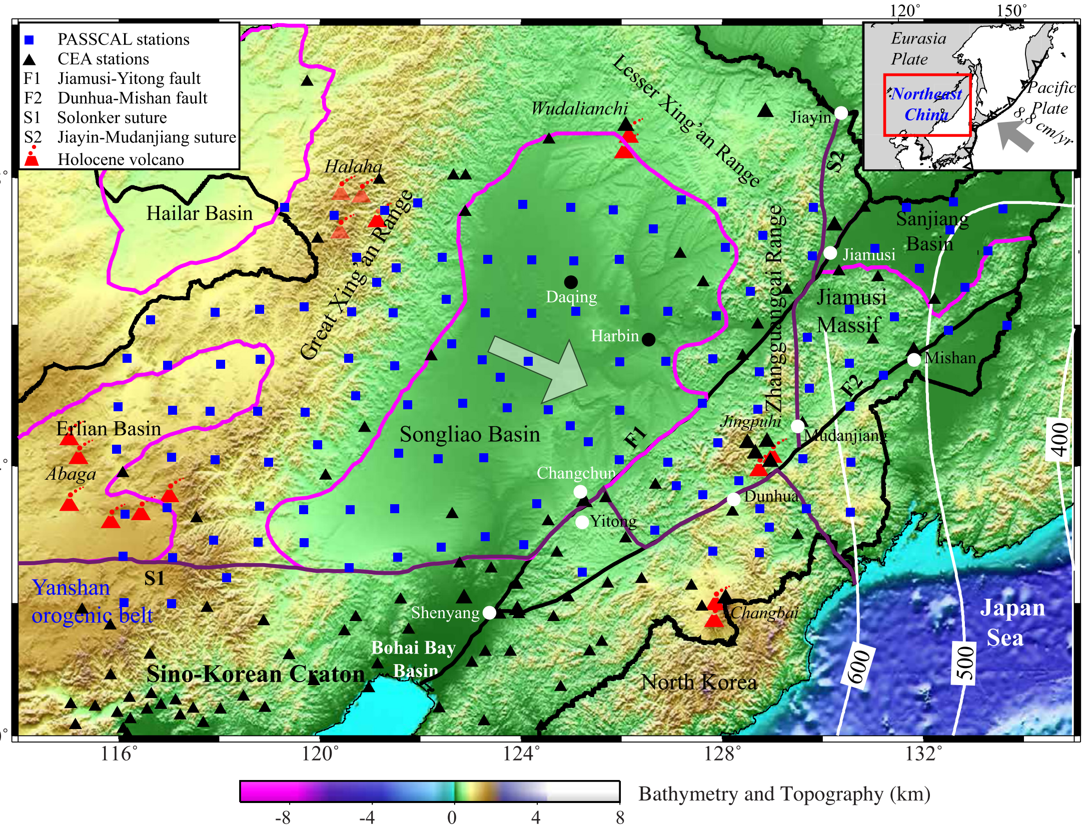

Fig. 1. Map showing topography, major faults, and tectonic units of northeast China. Blue solid squares and black solid triangles represent the 127 temporary and 108 permanent broadband stations of the NECESSArray, respectively. The temporary PASSCAL/ERI stations were deployed under an international collaboration between September of 2009 and August of 2011. The permanent stations are part of provincial seismic networks operated by the China Earthquake Administration (CEA). The array covers an area of 116°–134° east and 40°–48° north, roughly ∼1800 km and ∼800 km in the EW and NS direction, respectively. Red volcanic symbols show the five magmatic centers in the area, Changbaishan, Jingpohu, Wudalianchi, Halaha, and Abaga volcanic complexes. Solid white circles indicate major cities in the area. Pink lines outline the four major basins of the area: Songliao, Erlian, Hailar, and Sanjiang basins. F1 and F2 indicate the two major Quaternary faults; S1 and S2 are the two sutures in the area. The white arrow indicates the absolute plate motion with a velocity of ∼2.6 mm/yr relative to hotspot frame based on the SKS-MORVEL (Zheng et al., 2014). The upper right insect shows the motion of the Pacific plate relative to the Eurasia plate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

canism started to migrate towards the surroundings of the basin, in particular the eastern and western flanks (Liu et al., 2001), for example, the well-known Changbaishan and the Jingpohu volcanic complexes in the east and the Abaga and Halaha volcanoes in the west. Both shallow and deep processes have been invoked to explain the observed Cenozoic magmatism. One suggestion of a shallow mantle origin is edge driven convection along the boundaries of the Songliao basin (Niu, 2005), while many other models involve deep mantle upwelling associated with the subducting Pacific plate (e.g., Lei and Zhao, 2005; Zou et al., 2008; Xu et al., 2012; Tang et al., 2014), which reaches to ∼600 km depth near the eastern edge of NE China. Mapping lateral variations of mantle flow beneath NE China thus has the potential to decipher the origin of the Cenozoic magmatism in the area.

Seismic anisotropy refers to velocity variations as a function of both propagation and polarization directions of seismic waves, which are known as propagation and polarization anisotropy, respectively. Polarization anisotropy is usually described by two parameters: the polarization direction of the fast shear wave, φ, and the delay time between the fast and slow waves, δt. The two parameters can be estimated from splitting or birefringence of shear waves, such as S, ScS and SKS phases, recorded at either local or teleseismic distances (e.g., Crampin, 1987; Silver and Chan, 1991).

Seismic anisotropy in the mantle is generally believed to be caused by preferred alignment of anisotropic minerals in response to mantle deformation. Magnesium-rich olivines are the most abundant constituent of the Earth's upper mantle, and possess a highly anisotropic crystal structure, with up to 25% variation in P- and S-wave velocities. If the anisotropic minerals are preferentially aligned by a geodynamic process, their aggregates can produce a bulk anisotropy, i.e., seismic anisotropy. The amplitude of seismic anisotropy is generally in the order of a few percent because the crystals are only partially aligned (e.g. Silver, 1996). Consequently, seismic anisotropy can be used to constrain the processes that lead to deformation within the lithosphere and/or the underlying asthenosphere if deformation induced mineral alignment is well calibrated in lab (e.g., Mainprice et al., 2000).

A long-standing problem in global tectonics is how to estimate the absolute plate motions (APM) (Zheng et al., 2014), which are usually estimated with hotspot data (e.g., Morgan, 1972; Gripp and Gordon, 2002). The averaged APM of NE China calculated from the HS3-NUVEL1A model (Gripp and Gordon, 2002) is approximately along the N67W direction with an annual velocity of ∼2 cm/yr. Recently, an alternative method with shear wave splitting data has been proposed for estimating APM (e.g., Becker, 2008; Kreemer, 2009; Zheng et al., 2014). Since mantle seismic anisotropy is closely related to the preferred alignments of mantle minerals in response to asthenospheric flow, it is, in principle, possible to constrain the absolute plate motions with shear wave splitting data. Kreemer (2009) and Zheng et al. (2014) compiled a global shear wave splitting dataset with 474 fast polarization directions and obtained a global APM model, SKS-MORVEL. The predicted AMP of NE China by the SKS-MORVEL is along ∼N117E with a much smaller velocity, ∼0.26 cm/yr. We found that the splitting