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On velocity anomalies beneath southeastern China: An investigation combining mineral physics studies and seismic tomography observations

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ABSTRACT

Seismic tomography studies reveal distinct velocity and V_P/V_S anomalies in the mantle transition zone (MTZ) beneath the Yangtze Craton and Cathaysia Block in southeastern China. The anomalies under the Yangtze Craton are characterized by high velocity (both V_P and V_S) and low V_P/V_S ratio, while those beneath the Cathaysia Block are characterized by low velocity (especially V_S) and high V_P/V_S ratio. Here, we conduct analyses of phase relations and thermoelasticity to model the effects of thermal and chemical homogeneities in the MTZ, by taking advantage of recent simultaneous V_P and V_S seismic tomography results under southeastern China. We attempt to quantify the seismic tomography results and examine the effects of temperature, chemical composition, and water (or protonization) on velocity anomalies in the deep mantle. We find V_P/V_S to be a powerful parameter in distinguishing the various effects of temperature, chemical composition, and protonization. We conclude that an ancient stagnated oceanic slab is most likely the main cause of the observed fast velocity and low V_P/V_S anomalies in the MTZ under the Yangtze Craton. This ancient slab material is most likely a product of paleo Pacific subduction around 100–125 Ma ago, when the oceanic plate abruptly changed its direction of motion. Such an event has been shown to be closely related to the magmatic activities around eastern China, the ultrahigh-pressure metamorphism zone between the Yangtze Craton and the North China Craton, and the destruction of the lower crust of the North China Craton. The anomalies under the Cathaysia Block, on the other hand, are likely due to dehydration-induced partial melting of subducted Pacific slab materials. Here the large low V_S anomaly in MTZ coincides with the extensive Mesozoic to Cenozoic igneous features on the surface, suggesting a state with lower viscosities in the upper mantle. Dehydration-induced partial melting in MTZ may have also promoted deformation of the South China fold belt. Our results suggest that these lithospheric processes are directly related to the tectonic interaction between the oceanic and continental plates in southeastern China and that a better understanding of past deep mantle dynamic processes may place important constraints on the evolution of the cratons in China.

1. Introduction

Processes of plate tectonics in present-day Earth are dominated by mantle convection, which cools down our planet and produces lithospheric plates that make up the strong outermost crust and mantle. Within active subduction zones, large amounts of oceanic slab materials are transported into Earth's interior (Shirey and Richardson, 2011), producing temperature, chemical, and mineralogical heterogeneities in the mantle (e.g., Helffrich and Wood, 2001). Recycled ancient crustal materials, if unmixed through history, are another possible source of present-day mantle heterogeneities. Lithosphere delamination is not limited to Archean times. Local convection may be enhanced due to plate-tectonically induced events, which either increase mantle temperature or decrease melting points of lithospheric materials, causing delamination (e.g., Kawai et al., 2013 and references therein).

Recent seismic tomography studies reveal continuous fast anomalies (with P-wave velocities 1–2% faster than those of the surrounding mantle) in the mantle transition zone (MTZ) beneath northeastern China, extending from the Japan Wadati–Benioff zone to Ordos Block (e.g., Huang and Zhao, 2006; Li and van der Hilst, 2010; Pei and Chen, 2010; Lei, 2012). Under southeastern China, seismic tomography studies reveal consistently fast velocity anomalies (both V_P and V_S) in the MTZ beneath the Yangtze Craton (e.g., Lebedev and Nolet, 2003; Huang and Zhao, 2006; Li and van der Hilst, 2010; Zhao et al., 2012) and slow V_S anomalies under the Cathaysia Block (e.g., Zhao et al., 2012). Unlike the anomalies under northeastern China, however, the anomalies under the Yangtze Craton appear disconnected from the present-day western Pacific subducting slab (e.g., Huang and Zhao,

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2006). It is known that, at least for the last 150 Ma, subduction of the Pacific plate under Eurasia has been episodic with variable subduction directions (e.g., Koppers et al., 2001; Hall, 2002; Sun et al., 2007; Hall, 2012). This is particularly true around the South China Sea and Cathaysia Block. Such tectonic events have profoundly influenced the geology of east China (Sun et al., 2007). In view of this history, several explanations have been proposed for the physical origin of the fast anomalies under the Yangtze Craton: (1) ancient subducted continental slabs (e.g., Lebedev and Nolet, 2003), (2) ancient subducted oceanic lithosphere (e.g., Huang and Zhao, 2006; Li and van der Hilst, 2010; Zhao et al., 2012), and (3) delaminated continental lithosphere (e.g., Li and van der Hilst, 2010). Anomalies under the Cathaysia Block are less-well studied. In their study on P-wave tomography, Li and van der Hilst (2010) interpret the low V_P anomaly immediately above the MTZ to be due to return flow from distant subduction systems. Zhao et al. (2012) reported high V_P/V_S anomalies under the Cathaysia Block and attributed these anomalies to partial melting and temperature anomalies. Clearly, a good understanding of the origin of these deep mantle anomalies will have a significant impact on our understanding of the tectonic processes in southeastern China, not only in the MTZ but also in the upper mantle and the crust.

Numerous geochemical studies on basalts and peridotite in eastern China provide useful characteristic signatures of recycled continental and oceanic crust materials (Zhang et al., 2002; Xu et al., 2004, 2012; Sakuyama et al., 2013). Continental crust materials are more enriched in silica (around 65–68 wt.%; e.g., Yanagi, 2011), incompatible elements, and large-ion lithophile elements (e.g., Rb, Ba, Sr, K, Pb, La, Ce and Th) (Rapp et al., 2008). Oceanic crust materials, in contrast, are characterized by relatively high FeO contents, with positive Eu and Sr anomalies (Xu et al., 2012). As these materials are transported and mixed in the deep mantle, their signatures may be detectable through physical properties such as density and velocities. To date, however, our knowledge on mantle heterogeneities is still largely based on seismological studies alone; few studies on the mineralogy and physical properties of these anomalies are available from a mineralogical viewpoint.

Here we attempt to address the origin of seismic anomalies under the Yangtze Craton, and the Cathaysia Block, by combining seismic tomographic results with mineral physics analyses. We focus on V_P, V_S, and V_P/V_S of representative mineral assemblages of continental crust, subducted oceanic lithosphere, and the “normal” mantle, to address the effects of temperature, chemical composition, and water (or protonization) related heterogeneities in the MTZ. We then discuss possible geochemical, geophysical, and geodynamic effects of the proposed origin of these anomalies on the current state of the Yangtze Craton and the surrounding regions.

2. An attempt to quantify the seismic tomography data on southeastern China

In earlier seismic tomography studies, either P or S wave data were used to explore deep velocity structures beneath southeastern China (e.g., Lebedev and Nolet, 2003; Huang and Zhao, 2006; Li and van der Hilst, 2010; Huang et al., 2014). The lack of simultaneous and self-consistent V_P and V_S data has prevented researchers from examining spatial variations of the V_P/V_S ratio, which is an important parameter in discriminating the physical origins of heterogeneities in the deep mantle (e.g., Afonso et al., 2010). Recently, both P and S wave velocities and V_P/V_S cross-sections have been obtained under southeastern China by Zhao et al. (2012) with high-resolution seismic tomography, using seismic data recorded at 1300 stations from the upgraded China National Seismic Network and 9 temporary arrays. For the current study, we selected a cross-section parallel to the present-day subduction direction of the Pacific plate (Bird, 2003), from the unique 3D dataset reported by Zhao et al. (2012). A regional map of eastern China is shown in Fig. 1, where the start (A) and end (A′) points of the selected cross-section are located at (118°E, 24.5°N) and (105°E, 33°N), respectively, corresponding to a subducting orientation of circa 307°, roughly consistent with previous geophysical studies (e.g., Wen and Anderson, 1995; Zang et al., 2002).

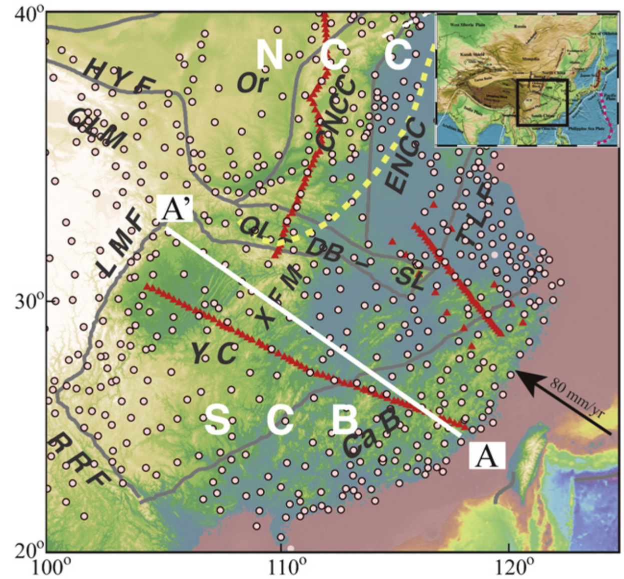

Fig. 1. Regional map showing major tectonic features and seismic station locations used to construct the tomographic model used in this study (modified from Zhao et al., 2012). The black square in the top right inset represents the location of the study area; the red dashed line in the inset indicates the Mariana trench. The open circles mark the permanent stations of the China National Seismic Network; the red triangles mark the portable stations used in the study of Zhao et al. (2012). Gray lines demarcate the major tectonic provinces in eastern China and adjacent areas. The thick yellow dashed line in North China Craton marks possible slab front of the subducted Pacific plate given by a global seismic tomography study (Wen and Anderson, 1995). The white line demarks the location of the cross-section shown in Fig. 3, A and A′ are the start and end points respectively, of the cross-section. Abbreviations: NCC — North China Craton; SCB — South China Block; YC — Yangtze Craton; CaB — Cathaysia Block; ENCC — eastern NCC; CNCC — Central NCC; Or — Ordos Block; QL–DB–SL — Qinling–Dabie–Sulu orogenic belt; XFM — Xuefeng Mountain; QLM — Qilian orogenic belt; HYF — Haiyuan Fault; LMF — Longmenshan Fault; TLF — Tanlu Fault and RRF — Red River Fault. The black arrow shows the orientation of plate motion with present-day subduction speed indicated.

2.1. Quantifying the seismic tomography data

Seismic tomography is a powerful and a unique tool in probing deep heterogeneities in the Earth. However, it has been increasingly recognized that magnitudes of velocity perturbations tend to be underestimated and the physical shape of the perturbations is often distorted or smeared by seismic tomographic reconstructions (e.g., Foulger et al., 2013). Here we attempt to quantify the seismic tomography data for the areas in our study. The seismic tomography data used in this paper were based on analyses of a large dataset (59,512 P-wave relative travel-time residuals over a frequency band of 0.4–0.8 Hz and 37,569 S-wave arrivals over 0.02–0.1 Hz, with an average cross-correlation coefficient of 0.95). Relative travel times of both P- and S-waves were calculated with respect to the IASP91 model (Kennett and Engdahl, 1991). Seismic tomography matrices were then inverted by using the selected seismic data. The widely used least square-QR method was adopted to calculate the seismic tomography matrix (Paige and Saunders, 1982). Damping parameters of circa 83% for both V_P and V_S were used during the construction of the seismic tomography models (Zhao et al., 2012). Cross-correlation analyses show that the arrival-time data are of very good quality as indicated by the standard deviations in delay times of ~0.003 s and 0.01 s, respectively, for P and S-wave data (Zhao et al., 2012).

To our knowledge, this is the first self-consistent and simultaneous V_P and V_S seismic tomography dataset for eastern China. In an attempt