Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL097550

Anisotropic Tomography and Dynamics of the Big Mantle Wedge

Xuran Liang1,2, Dapeng Zhao3, Yi-Gang Xu1,2,4, and Yuanyuan Hua1,2

1State Key Laboratory of Isotope Geochemistry and CAS Center of Excellence in Deep Earth Science, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China; 2School of Earth and Planetary Science, University of Chinese Academy of Sciences, Beijing, China; 3Department of Geophysics, Graduate School of Science, Tohoku University, Sendai, Japan; 4Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou, China

Abstract We determine high-resolution 3-D tomographic images of P-wave isotropic velocity, radial anisotropy and azimuthal anisotropy beneath NE Asia down to 800 km depth. Our results show negative radial anisotropy (i.e., \( V_{\text{horizontal}} < V_{\text{vertical}} \)) in the asthenosphere of the big mantle wedge (BMW), which may reflect mineral alignment caused by vertical flow in the asthenosphere. Across the Tanlu fault zone (TLF), the western and eastern parts of the BMW exhibit high and low P-wave velocities, respectively. Combining our tomographic results with surface geological features, we speculate that convection in the BMW includes upwelling asthenosphere beneath the Japan Sea and the Korean Peninsula and downwelling asthenosphere beneath the Songliao and North China basins. The downwelling asthenosphere beneath the two basins is associated with diminishing volcanism and anomalous tectonic subsidence since \(\sim 110\) Ma. The great TLF is an important boundary for the BMW structure and dynamics.

Plain Language Summary The subducting Pacific plate becomes flat in the lower part of the mantle transition zone beneath NE Asia, and a big mantle wedge (BMW) has formed above the flat slab. The BMW controls tectonic and geological activities in NE Asia, which are characterized by large-scale sedimentary basins, lithospheric thinning, large strike-slip faults, deep earthquakes and intraplate volcanism. However, the convection pattern in the BMW is still unclear. We determine the first 3-D P-wave radial anisotropy model down to 800 km depth beneath NE Asia, as well as high-resolution tomographic images of isotropic P-wave velocity and azimuthal anisotropy. We find predominant negative radial anisotropy in the BMW and east-west variations of velocity structure. Combining the tomographic results with surface geological features, we speculate that convection in the BMW may include upwelling flows beneath the SW Japan Sea and the southern Korean Peninsula and downwelling flows beneath the Songliao and North China basins.

1. Introduction

Active tectonics in NE Asia are characterized by large strike-slip faults, shallow and deep seismicity, intraplate volcanism, metamorphic core complex, and large-scale sedimentary basins. The subduction of the western Pacific plate (or the paleo-Pacific plate) has controlled the extensive deformation and volcanism in NE Asia since the late Cretaceous (Ward et al., 2021; Zhao, 2021). To date, many studies of global and regional tomography have revealed a flat stagnant slab in the mantle transition zone (MTZ) beneath East Asia, and the slab has reached the North-South Gravity Lineament (NSGL) in East China (e.g., Zhao, 2004; J. Huang & Zhao, 2006; X. Liu et al., 2017; J. Ma et al., 2019). A big mantle wedge (BMW) has formed above the flat slab beneath East Asia (Zhao et al., 2004, 2007; Lei & Zhao, 2005). Strong interactions between the lithosphere and asthenosphere in the BMW play an important role in the NE Asian tectonic evolution, including lithospheric thinning of the North China Craton (Carlson et al., 2005; Wu et al., 2009; L. Chen et al., 2009), formation of intraplate volcanoes (S. Choi et al., 2006; Zhao et al., 2009; Zhao & Tian, 2013), and anomalous tectonic subsidence of basins (C. Li & Liu, 2015; Yao et al., 2017). Some geochemical signatures in the intraplate volcanic rocks from the MTZ (e.g., HIMU, Xu et al., 2012; EM1, Base et al., 1991; X. Wang, et al., 2017) indicate that intense slab-mantle interactions and material recycling take place in the BMW. However, the geodynamic pattern in the BMW is still poorly understood (see recent reviews by Zhao, 2021; Q. Ma & Xu, 2021).

Seismic anisotropy is a powerful geodynamic indicator, which describes the directional variation of seismic wave propagating velocity (e.g., Savage, 1999; Park & Levin, 2002). Large-scale seismic anisotropy in the continental...
mantle is mainly caused by mantle flow in the asthenosphere (Holtzman et al., 2003), tectonic stress in the lithosphere (S. Zhang & Karato, 1995), and fossil preferred orientation in the past frozen-in deformation (Fouch & Rondenay, 2006). The upper mantle anisotropy above 400 km depth mainly depends on the lattice preferred orientation of olivine, the most abundant mineral in the mantle. In deformation induced by mantle flow, five types of olivine slip system corresponding to A-E fabrics are formed in different conditions of temperature, stress and water content (Karato et al., 2008). A fast seismic wave parallel to the mantle flow direction can be seen in A-, C-, D-, and E-type olivine fabrics corresponding to [100](010), [001](100), [100]{0kl}, and [100](001) slip systems (Mainprice et al., 2005). Only one exception (B-type olivine fabric corresponding to [001](010) slip system) may appear in low-temperature and hydrous-rich environment, especially the subducting slab bending zone near the forearc mantle (Kneller et al., 2005). Previous seismic studies focused on the azimuthal anisotropy (AAN) structure of variable scales in East Asia (H. Chen et al., 2017; X. Fan et al., 2020; Z. Huang et al., 2014; Lü et al., 2019; J. Ma et al., 2019; Tian & Zhao, 2013; Wei et al., 2015; Jia et al., 2022) and radial anisotropy structure beneath the North China craton (Ai et al., 2020; Cheng et al., 2013; Fu et al., 2015; J. Wang et al., 2014). However, there has been no study of 3-D P-wave radial anisotropy of the BMW in East Asia, especially in its asthenosphere.

To better understand the BMW structure and dynamics, we conduct anisotropic tomography using 673,208 P-wave travel-time data of local earthquakes and teleseismic events recorded at 2,388 seismic stations in NE Asia (Figure 1). Our high-resolution tomographic models of isotropic P-wave velocity (Vp), radial anisotropy and AAN shed new light on the mantle structure and dynamics beneath NE Asia.
2. Data and Method

In this work, we use two sets of $P$-wave arrival-time data (Figure 1). The first data set is selected from that of C. Chen et al. (2017), which includes 4,311 local/regional earthquakes recorded at 2,388 seismic stations in Japan, South Korea and East China. The second data set is provided by the China Earthquake Networks Center, National Earthquake Data Center (CENC; http://data.earthquake.cn), which includes 5,969 local events recorded at 202 seismic stations in NE China. Details of the two data sets are shown in Table S1 in the Supporting Information S1. We carefully selected and processed these data according to the following criteria: (a) All overlapping or inconsistent earthquakes in the different data sets are removed; (b) The average epicentral distance of each local earthquake is larger than 100 km (Figure S1 in the Supporting Information S1), because this work focuses on the regional mantle structure rather than local crustal structure; (c) After relocating all the local events using a 1-D velocity model including depth variations of the sedimentary layer, the Conrad and the Moho discontinuities derived from the CRUST1.0 model (Figure S2 in the Supporting Information S1; Laske et al., 2013), the uncertainty of the epicentral location is smaller than 0.1° (∼10 km), and the focal depth error is smaller than 15 km (Figure S3 in the Supporting Information S1); and (d) the cut-off travel-time residual is taken to be 2.5 s in the tomographic inversion. As a result, our local data set contains 399,697 $P$-wave arrival times of 10,280 local/regional earthquakes (Figures 1 and S4 in the Supporting Information S1). The root-mean-square (RMS) travel-time residual for all the local/regional event data is reduced from 1.726 to 1.503 s after the earthquake relocation (Figure S1 in the Supporting Information S1).

The teleseismic events are selected from the data set of C. Chen et al. (2017) with the following criteria: (a) Each event was recorded at more than 15 seismic stations in the study region; (b) the epicentral distance of each event is limited to 30° to 90°; and (c) the cut-off travel-time residual is taken to be 2.5 s in the tomographic inversion (Figure S1 in the Supporting Information S1). As a result, our data set contains 273,511 relative travel-time residuals of 8,988 teleseismic events (Figures 1c and S4 in the Supporting Information S1).

We apply tomographic methods (Zhao et al., 2009; J. Wang & Zhao, 2008, 2013) to our data set to determine 3-D images of isotropic $V_p$, radial anisotropy (RAN) and AAN beneath NE Asia (Figures 2, 3 and S5–S8 in the Supporting Information S1). The RMS travel-time residual is reduced to 0.691, 0.664 and 0.672 s after the isotropic, AAN and RAN tomographic inversions, respectively (Figure S5 in the Supporting Information S1). We performed extensive resolution tests to examine the robustness of the obtained tomographic models (Table S2 and Figures S9–S43 in the Supporting Information S1). The test results show that the $P$-wave rays of our data set crisscross very well in the study volume (Figure S4 in the Supporting Information S1). The lateral resolution is ∼1.0° for the isotropic $V_p$ model and ∼1.5° for the RAN and AAN models. The depth resolution is ∼80 km for the isotropic $V_p$ model and ∼150 km for the RAN and AAN models (Figures S10–S19 in the Supporting Information S1). A potential problem of anisotropic tomography is that there may be trade-off between isotropic $V_p$ structure and anisotropy (e.g., Z. Huang et al., 2015; Z. W. Wang et al., 2022). We performed extensive synthetic tests to examine the trade-off issue, and the test results show that our isotropic and anisotropic images are robust and the trade-off effect is very small (Figures S30–S41 in the Supporting Information S1). Details of the resolution and synthetic tests can be found in the Supporting Information S1.

3. Results

Our tomographic model shows an expected geometry of the subducting Pacific slab beneath the Japan Islands and the Japan Sea, as well as the stagnant slab in the MTZ beneath the Korean Peninsula and NE China (e.g., J. Huang & Zhao, 2006; Wei et al., 2015; C. Chen et al., 2017; J. Ma et al., 2018, 2019; Zhao, 2021). Positive RAN, that is, $V_{\text{horizontal}} > V_{\text{vertical}}$ occurs in the stagnant slab, reflecting horizontal movement and deformation of the slab in the MTZ. Our 3-D isotropic $V_p$ model (Figure 2a) shows a high-$V_p$ anomaly in the western BMW (W-BMW) beneath the Songliao and North China basins and a low-$V_p$ anomaly in the eastern BMW (E-BMW) beneath the Japan Sea and the Korean Peninsula (Figure 2a; J. Ma et al., 2019). The lateral $V_p$ variations from the W-BMW to E-BMW are the most significant feature in the BMW.

The boundary between the W-BMW and E-BMW roughly runs along the Tanlu fault zone (TLF), which is a great trans-lithospheric fault with strike-slip motions in East China (e.g., Lei et al., 2020). G. Zhu et al. (2018) suggested that the TLF has been a tectonics-sensitive weak zone in the lithosphere since the Mesozoic. Our tomographic
images of isotropic $V_p$ and anisotropy clearly show different patterns across the TLF (Figure 2). Hence, we deem that the great TLF has acted as an important boundary for the structure and dynamics of the BMW.

Previous regional tomographic models show a low-$V_p$ anomaly in the asthenosphere beneath the Songliao basin and the North China basin (e.g., J. Huang & Zhao, 2006; Koula, 2011; J. Ma et al., 2019; Ward et al., 2021), but local tomographic models (C. Chen et al., 2017; X. Fan et al., 2021; Guo et al., 2016; J. Ma et al., 2018; Wei et al., 2019; Jia et al., 2022) and our present model show a high-$V_p$ anomaly there. The discrepancy is attributed to the resolution differences between the local and regional models. The larger-scale regional models are generally determined with larger grid intervals and stronger damping and smoothing regularizations, so small-scale velocity anomalies do not show up. However, even in large-scale tomographic models (e.g., J. Huang & Zhao, 2006; Wei et al., 2015; J. Ma et al., 2019), the mantle beneath the two basins exhibits relatively higher velocities than that beneath the SW Japan Sea and South Korea, reflecting lateral structural variations in the BMW.

Our anisotropic $V_p$ models also reveal significant differences between the W-BMW and E-BMW (Figures 2 and 3). The two domains exhibit negative RAN ($V_{horizontal} < V_{vertical}$) but are separated by a narrow zone with
positive RAN beneath the TLF (Figures 2b and 3b). Previous RAN tomographic studies of East Asia focused on the Japan Islands and the North China craton. Beneath SW Japan, body-wave and surface-wave tomographic results show trench-normal fast-velocity directions (FVDs) and negative RANs, which are consistent with our results and interpreted to reflect the C-type fabric of olivine (X. Liu & Zhao, 2016, 2017). Beneath the eastern North China craton, negative RANs are revealed in the asthenosphere (J. Wang et al., 2014), which are consistent with our model beneath the North China basin, although some models show positive RANs in the crust (Ai et al., 2020; Cheng et al., 2013; Fu et al., 2015).

Our AAN model shows that the FVD is nearly NWW-SEE in the E-BMW, NNW-SSE in the W-BMW, and NW-SE beneath the TLF (Figure 2c). Previous AAN tomographic studies (H. Chen et al., 2018; Du et al., 2022; X. Fan et al., 2020; He et al., 2019; Jia et al., 2022) revealed nearly N-S FVDs in the crust and shallow mantle, reflecting fossil anisotropy related to crustal deformation during the Meso-Cenozoic. J. Ma et al. (2019) determined a 3-D AAN model beneath the whole East Asia, which is similar to our model in the BMW asthenosphere. The east-west anisotropic variations in the BMW may reflect heterogeneous distribution of volatiles and the mode of mantle flow, which is probably a distinctive feature of the BMW since its formation.

Measuring shear-wave splitting (SWS) is an effective method to detect seismic anisotropy, which represents the integration of anisotropy beneath a seismic station along a seismic ray path. Previous SWS studies (Figure S8 in the Supporting Information S1) show nearly NW-SE FVDs under the Songliao basin (J. Li & Niu, 2010; Lu et al., 2020), and nearly E-W FVDs under the North China basin (Y. Yang et al., 2018; T. Zheng et al., 2019; T. Zhu & Ma, 2021). Near the TLF, the FVDs are normal to the strike of the Tanlu fault (K. Liu et al., 2008; Z. Huang et al., 2011), which represent an integration of the NE-SW anisotropy in the lithosphere and NW-SE anisotropy in the asthenosphere (Bi et al., 2020). Beneath the North China basin, the FVDs change slightly at depths of 100–300 km (Figures 2c and S8 in the Supporting Information S1), which may reflect the contribution of fossil anisotropy in the crust and/or lithosphere. In other areas of the W-BMW, our AAN model is generally consistent with the SWS results (Figure S8 in the Supporting Information S1).

4. Discussion

4.1. The Eastern Big Mantle Wedge (E-BMW)

In the E-BMW, rotational motions of SW Japan yielded a board pull-apart zone during the Miocene, where a newly created oceanic crust outcrops in some extensional areas (Otofuji et al., 1991; Jolivet et al., 1994). Cenozoic intraplate volcanoes (e.g., Ulleung, Changbai, Longgang, etc.) are located above the E-BMW. Hence, wet and hot upwelling flow in the BMW (Zhao et al., 2004, 2009; Lei & Zhao, 2005) may explain the low-$V_p$ anomaly and negative RAN in the E-BMW. Tang et al. (2014) attributed the Changbai basaltic magmatism to lower-mantle material upwelling through a slab hole in the MTZ, but the slab hole is not observed in our images (Figure 3) and other recent tomographic models (see a detailed review by Zhao, 2021).

Most tomographic studies made so far indicate that the intraplate volcanoes in NE Asia (including Changbai) are more likely to originate from hot and wet upwelling flows in the BMW (Zhao et al., 2004, 2009; C. Chen et al., 2017; Zhao, 2021), which are also supported by most petrological and geochemical studies (e.g., Su et al., 2017; Xu et al., 2018; Kuritani et al., 2019; H. Choi et al., 2020; Q. Ma & Xu, 2021). Assuming that the AAN FVD is parallel to the regional mantle flow (Holtzman et al., 2003), melt-rich upwelling may have a
component orientated nearly in the N-S direction, which is related to the oceanic trench shape and the subducting slab geometry (Funiciello et al., 2006). For example, laboratory modeling shows that the width of a subducting plate strongly affects the vigor of both poloidal and toroidal advection since initial subduction (Funiciello et al., 2006).

Large deep earthquakes \((M \geq 7.0;\) focal depths >500 km) take place actively in the subducting Pacific slab in the MTZ beneath the NW Japan Sea and NE China (Figure 1b) where the slab bends abruptly (Figure 3a). These large deep earthquakes may invoke release of fluids from the slab in the MTZ to the overlying BMW, which may facilitate higher degree of partial melt feeding the Changbai and Ulleung intraplate volcanoes (Zhao & Tian, 2013). Hence, the bottom of the E-BMW may be a relatively melt-rich layer (J. Yang & Faccenda, 2020), which forms a source pool of the intraplate magmatism and provides a crucial driving force for the upwelling flow in the E-BMW and mantle convection in the entire BMW.

4.2. The Western Big Mantle Wedge (W-BMW)

In the W-BMW, the high-\(V_p\) anomaly beneath the Songliao and North China basins is distinct and robust according to our extensive resolution tests (Figures 2a, 3a and Table S2 in the Supporting Information S1). A common explanation of this high-velocity anomaly is a delaminated lithospheric fragment (Cheng et al., 2013; Wei et al., 2019; Y. Zhang et al., 2011), but Guo et al. (2016) attributed it to downwelling asthenosphere. Our model cannot exclude the contribution from the delaminated lithosphere, but we prefer the latter explanation because the bottom of the high-\(V_p\) anomaly in the W-BMW reaches ~300 km depth and a lithospheric fragment is insufficient to form such a thick anomaly (see Figures S31 and S32 in the Supporting Information S1). Numerical modeling shows that the surface topography associated with delamination is rapid uplift (Gogus & Pysklywec, 2008). Since such uplift is not observed in the Songliao and North China basins, thermal-mechanical erosion associated with ongoing mantle flow in the asthenosphere is more likely to occur in the W-BMW (Xu, 2007) instead of lithospheric delamination.

Anomalous tectonic subsidence is observed in intraplate rift basins (e.g., the Songliao and North China basins) above the W-BMW, which is thought to be a dynamic topography caused by the negative buoyancy due to mantle cooling (Ren et al., 2002; C. Li & Liu, 2015; Yao et al., 2017). Therefore, the high-\(V_p\) anomaly in the W-BMW beneath the two basins should represent a colder and denser mantle, and its negative RANs (i.e., \(V_{\text{vertical}} > V_{\text{horizontal}}\)) most likely reflect mineral alignment caused by vertical shear due to asthenospheric downwelling (Karato et al., 2008). In addition, the downwelling asthenosphere in the W-BMW is consistent with the absence of volcanism within the two basins since ~100 Ma, because upwelling mantle flows would produce intraplate volcanism (Zhao et al., 2004, 2007; X. Wang et al., 2017; Wei et al., 2019; J. Yang & Faccenda, 2020). In fact, most Cenozoic volcanism occurs at the basin margins in NE China (Figure 1a; Q. Fan & Hooper, 1991; Jia et al., 2022). This feature of the Cenozoic basalt distribution suggests the absence of hot and wet upwelling material beneath the two basins. Hence, the asthenospheric downwelling very possibly extends southward to the North China basin.

4.3. Convection in the Big Mantle Wedge

Previous geophysical studies have found some fingerprints of mantle convection in the BMW. Xu (2007) integrated geophysical data, isotopic composition, and paleogeographic configuration and considered the NSGL to be the western boundary of vigorous convection induced by the stagnant slab in the MTZ and the old major lithospheric weak zones. R. Zhang et al. (2014) and A. Zhang et al. (2021) investigated the seismic lithosphere-asthenosphere boundary (LAB) and the thermal LAB, respectively, in the W-BMW beneath the Songliao basin. A. Zhang et al. (2021) suggested that interactions between asthenospheric circulation and lithosphere control the intraplate volcanism. Surface wave tomography shows the existence of local sub-lithosphere downwelling in the W-BMW beneath the Songliao basin (Guo et al., 2016). X. Fan et al. (2020) suggested that the regional flow field in the E-BMW is oriented from the SW Japan Sea to East and NE China, which is consistent with a SWS result (S. Li et al., 2017).

Our 3-D AAN model (Figures 2c and 3c) reveals NW-SE orientated mantle flow between the E-BMW and W-BMW at 100–300 km depths, which may represent volume compensation direction due to vertical flow in the asthenosphere. Since the subducting Pacific and Philippine Sea plates block recharge from the east and the
southeast, respectively, the recharge of asthenospheric upwelling in the E-BMW is likely from the W-BMW. Thus, asthenospheric horizontal flow from the W-BMW to E-BMW may cause the NW-SE FVDs beneath the TLF and the northern Korean Peninsula at ∼300 km depth (Figure 2c), which coincides well with a previous result about mantle flow beneath the eastern North China craton (Tian & Zhao, 2013).

Mantle flow above 200 km depth could be variable because asthenospheric upwelling is blocked by the lithospheric lid. The NW-SE FVDs beneath the TLF may be explained by asthenospheric flow from the E-BMW to W-BMW due to the volume compensation of vertical mantle flow in the BMW, which is consistent with the flow pattern beneath NE China derived from surface wave tomography (Guo et al., 2016). On the basis of the anisotropic tomographic models and geological evidence, we deem that 3-D mantle convection occurs in the whole BMW (Figures 3a and 4), which may include asthenospheric upwelling beneath the SW Japan Sea and South Korea, asthenospheric downwelling beneath the Songliao and North China basins, and horizontal flow beneath the TLF.

All these results suggest that mantle convection associated with the Pacific plate deep subduction may have controlled the lithospheric deformation and occurrence of intraplate volcanism. On the one hand, volcanism disappeared in both two basins since the middle-late Cretaceous (Figure 1a), in line with the asthenosphere downwelling detected in the W-BMW. A similar tectonic setting is passive continental margin, where an absence of volcanism is thought to result from mantle downwelling of edge-driven convection (King & Anderson, 1998). On the other hand, the anomalous tectonic subsidence of the Songliao basin also occurred during the late Cretaceous, which is attributable to deficit in the negative buoyancy induced by mantle convection (C. Li & Liu, 2015). Hence, the BMW convection could be traced back at least to the late Cretaceous, which is consistent with a recent study based on the tempo-spatial pattern of late Mesozoic magmatism in northern North China Craton (Q. Ma & Xu, 2021). Moreover, mantle xenoliths brought to the surface by the Cenozoic basalts in the W-BMW show an oceanic mantle affinity in terms of bulk rock Mg#, olivine Fo, spinel Cr#, and Sr-Nd-Os isotopes (Gao et al., 2002; Xu & Bodinier, 2004). Because they are much more fertile than typical cratonic peridotites, the replacement of the ancient cratonic root by newly accreted lithosphere must have taken place (Xu & Bodinier, 2004; J. Zheng et al., 2012), probably as a result of BMW convection.

Figure 4. A schematic diagram showing that downwelling asthenosphere in the western big mantle wedge (BMW) triggers intraplate volcanism (red triangles) around the Songliao basin (SLB) and anomalous tectonic subsidence (TS, the yellow patch) of the SLB. Gray patches denote surface topography. Blue and red patches denote high and low Vp anomalies, respectively, in the BMW. White arrows denote mantle flow directions. Horizontal and vertical short bars denote positive and negative radial anisotropies, respectively. MTZ, mantle transition zone; NSGL, the North-South Gravity Lineament; TLF, the Tanlu fault zone.
5. Conclusions

We obtain the first 3-D model of P-wave radial anisotropy beneath NE Asia in addition to new 3-D models of isotropic P-wave velocity and AAN of the region. Our high-resolution tomographic results reveal east-west variations in the structure and dynamics of the BMW under NE Asia. On the basis of the tectonic history and surface geology since the late Cretaceous, we speculate that 3-D convection occurs in the whole BMW beneath NE Asia, which contains upwelling asthenosphere beneath the Japan Sea and the Korean Peninsula and downdwelling asthenosphere beneath the Songliao and North China basins. The great TLF has acted as an important boundary for the structure and dynamics of the BMW.

Data Availability Statement

In this work, we used two sets of P-wave arrival-time data (Figure 1). The first data set was selected from the data used by C. Chen et al. (2017), which contains 4,311 local/regional earthquakes and 8,988 teleseismic events recorded at 2,388 seismic stations. The second data set was downloaded from the database of the China Earthquake Networks Center, National Earthquake Data Center (http://data.earthquake.cn), which contains 5,969 local events recorded at 202 seismic stations in NE China. Locations of the Cenozoic intraplate basalts are downloaded from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/Start.asp). We used the seismic data provided by the China Earthquake Networks Center, National Earthquake Data Center (http://data.earthquake.cn), as well as data centers of the Japanese and South Korea seismic networks.

Acknowledgments

We appreciate helpful discussions with Drs. Mingda Sun, Chengyuan Wang, Xiaojun Long, Chuanmao Yang, Zhe Liu and Zhou Zhang. This work was partially supported by research grants from the National Natural Science Foundation of China (No. 41688103, 42106066), the CAS Strategic Priority Research Program (No. XDB18000000), Japan Society for the Promotion of Science (No. 19H01996), Key Special Project for Introduced Talents Team of Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) (GML2019ZD0202), and Director’s Fund of Guangzhou Institute of Geochemistry (CAS). Locations of the Cenozoic intraplate basalts in Figure 1a are compiled from the GEOROC database (Sarbas & Nohl, 2008), the CAS Strategic Priority Research Program (No. XDB18000000), Japan Society for the Promotion of Science (No. 19H01996), Key Special Project for Introduced Talents Team of Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) (GML2019ZD0202), and Director’s Fund of Guangzhou Institute of Geochemistry (CAS). Locations of the Cenozoic intraplate basalts in Figure 1a are compiled from the GEOROC database (Sarbas & Nohl, 2008). Most of the figures are plotted using the GMT software (Wessel & Smith, 1998). We are very grateful to Prof. Lucy Flesch (the Editor) and two anonymous reviewers for their thoughtful review comments and suggestions, which have improved this paper. This is contribution NO. IS-3144 from GIGCAS.

References

Ai, S., Zheng, Y., & Wang, S. (2020). Crustal deformations of the Central North China craton constrained by radial anisotropy. Journal of Geophysical Research: Solid Earth, 125, e2019JB018374. https://doi.org/10.1029/2019JB018374

Base, A., Wang, J., Huang, W., Xie, G., & Tatsumoto, M. (1991). Major element, REE, and Pb, Nd and Sr isotopic geochemistry of Cenozoic volcanic rocks of eastern China: Implications for their origin from suboceanic-type mantle reservoirs. Earth and Planetary Science Letters, 105, 149–169. https://doi.org/10.1016/0012-821X(91)90127-4

Bi, Y., Huang, Z., Wang, H., & Wu, H. (2020). Upper-mantle anisotropy and dynamics beneath Northeast Asia: Insight from SKS and local S splitting analysis. Geochemistry, Geophysics, Geosystems, 21, e2020GC009160. https://doi.org/10.1029/2020GC009160

Carlson, R., Pearson, D., & James, D. (2005). Physical, chemical, and chronological characteristics of continental mantle. Reviews of Geophysics, 43. https://doi.org/10.1029/2004RG001156

Chen, C., Zhao, D., Tian, Y., Wu, S., Hasegawa, A., Lei, J., et al. (2017). Mantle transition zone, stagnant slab and intraplate volcanism in Northeast China. Geophysical Journal International, 209, 68–85. https://doi.org/10.1093/gji/ggw491

Chen, H., Ni, S., Chu, R., Chong, J., Liu, Z., & Zha, L. (2018). Influence of the off-great-circle propagation of Rayleigh waves on event-based surface wave tomography in Northeast China. Geophysical Journal International, 214, 1105–1124. https://doi.org/10.1093/gji/ggy185

Chen, H., Niu, F., Obayashi, M., Grand, S., Kawakatsu, H., Chen, Y., et al. (2017). Mantle seismic anisotropy beneath NE China and implications for the lithospheric delamination hypothesis beneath the southern Great Xing’an range. Earth and Planetary Science Letters, 471, 32–41. https://doi.org/10.1016/j.epsl.2017.04.030

Chen, L., Cheng, C., & Wei, Z. (2009). Seismic evidence for significant lateral variations in lithospheric thickness beneath the central and western North China Craton. Earth and Planetary Science Letters, 286, 171–183. https://doi.org/10.1016/j.epsl.2009.06.022

Cheng, C., Chen, L., Yao, H., Jiang, M., & Wang, B. (2013). Distinct variations of crustal shear wave velocity structure and radial anisotropy beneath the North China Craton and tectonic implications. Gondwana Research, 21, 25–38. https://doi.org/10.1016/j.gr.2012.02.014

Choi, H., Choi, S., Soo, Y., Ryu, J., Lee, D., Lee, S., et al. (2020). Petrogenesis and mantle source characteristics of the late Cenozoic b arkudus (Changbaishan) basalts, north China craton. Gondwana Research, 78, 156–171. https://doi.org/10.1016/j.gr.2019.08.004

Choi, S., Mukasa, S., Kwon, S., & Andronikov, A. (2006). Sr, Nd, Pb and HF isotopic compositions of late Cenozoic alkali basalts in South Korea: Evidence for mixing between the two dominant asthenospheric mantle domains beneath East Asia. Chemical Geology, 232, 134–151. https://doi.org/10.1016/j.chemgeo.2006.02.014

Du, M., Lei, J., Zhao, D., & Lu, H. (2022). Ph anisotropic tomography of Northeast Asia: New insight into subduction dynamics and volcanism. Journal of Geophysical Research: Solid Earth, 127, e2021JB030350. https://doi.org/10.1029/2021JB030350

Fan, Q., & Hooper, P. (1991). The Cenozoic basaltic rocks of eastern China: Petrology and chemical composition. Journal of Petrology, 32, 765–810. https://doi.org/10.1093/petrology/32.4.765

Fan, X., Chen, Q., Ai, Y., Chen, L., Jiang, M., Wu, Q., & Guo, Z. (2021). Quaternary sodic and potassic intraplate volcanism in northeast China controlled by the underlying heterogeneous lithospheric structures. Geology, 49, 1260–1264. https://doi.org/10.1130/G48932.1

Fan, X., Chen, Q., Legendre, C., & Guo, Z. (2020). Intraplate volcanism and regional geodynamics in NE Asia revealed by anisotropic Rayleigh-wave tomography. Geophysical Research Letters, 47, e2019GL085623. https://doi.org/10.1029/2019GL085623

Fouch, M., & Rondenay, S. (2006). Seismic anisotropy beneath stable continental interiors. Physics of the Earth and Planetary Interiors, 159, 292–320. https://doi.org/10.1016/j.pepi.2006.03.024

Fu, Y. V., Gao, Y., Li, A., & Shi, Y. (2015). Lithospheric shear wave velocity and radial anisotropy beneath the northern part of North China from surface wave dispersion analysis. Geochimica, Geophysica, Geosystems, 16, 2619–2636. https://doi.org/10.1002/2015GC005825

Funicello, F., Moroni, M., Pirramallo, C., Facenna, A., & Cenedese, H. (2006). Mapping mantle flow during retreating subduction: Laboratory models analyzed by feature tracking. Journal of Geophysical Research: Solid Earth, 111, B03402. https://doi.org/10.1029/2005JB003792

Gao, S., Rudnick, R., Carlson, R., McDonough, W., & Liu, Y. (2002). Re-Os evidence for replacement of ancient mantle lithosphere beneath the North China Craton. Earth and Planetary Science Letters, 198, 307–322. https://doi.org/10.1016/S0012-821X(02)00489-2
Su, B., Hu, Y., Teng, F., Xiao, Y., Zhou, X., Sun, Y., et al. (2017). Magnesium isotope constraints on subduction contribution to Mesozoic and Cenozoic East Asian continental basins. *Chemical Geology*, 466, 116–122. https://doi.org/10.1016/j.chemgeo.2017.05.026

Tang, Y., Obayashi, M., Niu, F., Grand, S., Chen, Y., Kawakatsu, H., et al. (2014). Changbaishan volcanism in northeast China linked to subduction-induced mantle upwelling. *Nature Geoscience*, 7, 470–475. https://doi.org/10.1038/ngeo2166

Tian, Y., & Zhao, D. (2013). Reactivation and mantle dynamics of North China Craton: Insight from P-wave anisotropy tomography. *Geophysical Journal International*, 195, 1796–1810. https://doi.org/10.1093/gji/ggt333

Wang, J., Wu, H., & Zhao, D. (2014). P-wave radial anisotropy tomography of the upper mantle beneath the North China Craton. *Geochemistry, Geophysics, Geosystems*, 15, 2195–2210. https://doi.org/10.1002/2014GC005279

Wang, J., & Zhao, D. (2008). P-wave anisotropic tomography beneath northeast Japan. *Physics of the Earth and Planetary Interiors*, 170, 115–133. https://doi.org/10.1016/j.pepi.2007.07.042

Wang, J., & Zhao, D. (2013). P-wave tomography for 3-D radial and azimuthal anisotropy of Tohoku and Kyushu subduction zones. *Geophysical Journal International*, 195, 1166–1181. https://doi.org/10.1093/gji/ggt086

Wang, X., Chen, L., Hofmann, A. W., Mao, F., Liu, J., Zhong, Y., et al. (2017). Mantle transition zone-derived EM1 component beneath NE China: Geochemical evidence from Cenozoic potassic basalts. *Earth and Planetary Science Letters*, 465, 16–28. https://doi.org/10.1016/j.epsl.2017.02.028

Wang, Z. W., Zhao, D., & Chen, X. (2022). Seismic anisotropy and intraslab hydrated faults beneath the NE Japan forearc. *Geophysical Research Letters*, 49, e2021GL097266. https://doi.org/10.1029/2021GL097266

Ward, G., Rosenbaum, G., Ubede, T., Wu, J., Caulfield, J., Sandiford, M., & Gurur, D. (2021). Geophysical and geochemical constraints on the origin of Holocene intraplate volcanism in East Asia. *Earth-Science Reviews*, 218, 103624. https://doi.org/10.1016/j.earscirev.2021.103624

Wei, W., Hammond, J., Zhao, D., Xu, J., Liu, Q., & Gu, Y. (2019). Seismic evidence for a mantle transition zone origin of the Wudalianchi and Halaha volcanoes in Northeast China. *Geochemistry, Geophysics, Geosystems*, 20, 398–416. https://doi.org/10.1029/2018GC007663

Wei, W., Zhao, D., Xu, J., Wei, F., & Liu, G. (2015). P and S wave tomography and anisotropy in Northwest Pacific and East Asia: Constraints on stagnant slab and intraplate volcanism. *Journal of Geophysical Research, 120*, 1642–1666. https://doi.org/10.1002/2014JB011254

Wessel, P., & Smith, W. (1998). New, improved version of generic mapping tools re-leased. EOS Transactions of the American Geophysical Union, 79(47), 579. https://doi.org/10.1029/98EO00426

Wu, F., Yang, J., Xu, Y.-G., Wilde, S., & Walker, R. (2009). Destruction of the north China craton in the Mesozoic. *Annual Review of Earth and Planetary Sciences*, 47, 173–195. https://doi.org/10.1146/annurev-earth-050109-060342

Wu, X.-G. (2007). Mantle dynamics of western Pacific to East Asia: New insight from seismic tomography and mineral physics. *Gondwana Research*, 1401–1408. https://doi.org/10.1016/j.gr.2006.06.006

Xu, X.-G. (2017). Crustal and lithospheric structure of Northeast China from S-wave receiver functions. *Earth and Planetary Science Letters*, 401, 196–205. https://doi.org/10.1016/j.epsl.2014.06.017

Xu, Y.-G., Zhang, H., Qiu, H., Ge, W., & Wu, F. (2012). Oceanic crust components in continental basaits from Shuangliao, Northeast China: Derived from the mantle transition zone? *Chemical Geology*, 328(18), 168–184. https://doi.org/10.1016/j.chemgeo.2012.01.027

Yang, J., & Faccenda, M. (2020). Intraplate volcanism originating from upwelling hydrous mantle transition zone. *Nature*, 579, 88–91. https://doi.org/10.1038/s41586-020-2045-y

Yang, Y., Yao, H., Zhang, P., & Chen, L. (2018). Crustal azimuthal anisotropy in the trans-North China orogen and adjacent regions from receiver functions. *Science China Earth Sciences*, 61, 903–913. https://doi.org/10.1007/s11430-017-9209-9

Yao, X., Liu, S., Yu, B., & Ji, H. (2017). Neogene residual subsidence and its response to a sinking slab in the deep mantle of eastern China. *Journal of Asian Earth Sciences*, 143, 269–282. https://doi.org/10.1016/j.jseaes.2017.03.032

Zhang, R., Wu, Q., Sun, L., He, J., & Gao, Z. (2014). Crustal and lithospheric structure of Northeast China from S-wave receiver functions. *Earth and Planetary Science Letters*, 401, 196–205. https://doi.org/10.1016/j.epsl.2014.06.017

Zhang, S., & Karato, S. (1995). Lattice preferred orientation of olivine aggregates deformed in simple shear. *Nature*, 375, 774–777. https://doi.org/10.1038/375774a0

Zhang, Y., Liu, C., Ge, W., Wu, F., & Chu, Z. (2011). Ancient sub-continental lithospheric mantle (SCLM) beneath the eastern part of the Central Asian Orogenic Belt (CAOB): Implications for crust-mantle coupling. *Lithos*, 126, 233–247. https://doi.org/10.1016/j.lithos.2011.07.022

Zhao, D. (2004). Global tomographic images of mantle plumes and subducting slabs: Insight into deep Earth dynamics. *Physics of the Earth and Planetary Interiors*, 146, 3–34. https://doi.org/10.1016/j.pepi.2003.07.032

Zhao, D. (2021). Seismic imaging of northwest Pacific and east Asia: New insight into volcanism, seismogenesis and geodynamics. *Earth-Science Reviews*, 214, 103507. https://doi.org/10.1016/j.earscirev.2021.103507

Zhao, D., Lei, J., & Tang, Y. (2004). Origin of the Changbai intraplate volcanism in northeast China: Evidence from seismic tomography. *Chinese Science Bulletin*, 49, 1401–1408. https://doi.org/10.1360/04wd0125

Zhao, D., Maruyama, S., & Omori, S. (2007). Mantle dynamics of western Pacific to East Asia: New insight from seismic tomography and mineral physics. *Gondwana Research*, 11, 120–131. https://doi.org/10.1016/j.gr.2006.06.006

Zhao, D., & Tian, Y. (2013). Changbai intraplate volcanism and deep earthquakes in East Asia: A possible link? *Geophysical Journal International*, 195, 706–724. https://doi.org/10.1093/gji/ggt289

Zhao, D., Tian, Y., Lei, J., Liu, L., & Zheng, S. (2009). Seismic image and origin of the Changbai intraplate volcano in East Asia: Role of big mantle wedge above the stagnant Pacific slab. *Physics of the Earth and Planetary Interiors*, 173, 197–206. https://doi.org/10.1016/j.pepi.2008.11.009

Zheng, J., Griffin, W., Ma, Q., O’Reily, Y., Xiong, Q., Tang, H., et al. (2012). Accretion and reworking beneath the north China craton. *Lithos*, 149, 61–78. https://doi.org/10.1016/j.lithos.2012.04.025

Zhang, S., & Karato, S. (1995). Lattice preferred orientation of olivine aggregates deformed in simple shear. *Nature*, 375, 774–777. https://doi.org/10.1038/375774a0