The Structure of the Upper Mantle Transition Zone Beneath Northeast China Associated With Mantle Plume Migration

Chuansong He

1Institute of Geophysics, China Earthquake Administration, Beijing, China

Abstract  The stagnation and dehydration of the Pacific Plate slab in the mantle transition zone (MTZ) are widely accepted to have resulted in Mesozoic and Cenozoic volcanic activities and the formation of the Songliao Basin in NE China. However, this notion has been challenged by recent seismic studies. Alternatively, a mantle plume may have generated the large-scale volcanism and may have led to the formation of the Songliao Basin. In this study, a detailed analysis involving common conversion point stacking of receiver functions was carried out. The results reveal a significantly deepened region of the 410 km discontinuity and an elevated region of the 660 km discontinuity in the center of NE China (specifically, the Songliao Basin). The combination of these results with those of a previous study suggests that an upwelling mantle plume was located under the Songliao Basin in the Mesozoic. Furthermore, the distinctive structure of the MTZ beneath the southern part of the Songliao Basin identified in this study corresponds to mantle plume upwelling (a mushroom-shaped low-velocity anomaly), which may be related to the Changbaishan volcanic activity in the Cenozoic.

1. Introduction

NE China is located on the eastern margin of the Eurasian continent and includes the Xingan Massif, Jiamusi Massif, and Songliao Massif. It is part of the Central Asian Orogenic Belt, which is bounded by the Siberian craton to the north and the North China Craton to the south (Figure 1). This region experienced the final closure of the Paleo-Asian Ocean and the westward subduction of the Paleo-Pacific Plate from the late Paleozoic to the early Mesozoic (Ryu & Lee, 2017; Sun et al., 2018; J. Tang et al., 2018; F. Wang et al., 2019; Xiao et al., 2015), as well as intense Mesozoic-Cenozoic volcanism and the establishment of the Songliao Basin (He et al., 2014).

Since the 1990s, the concept of a stagnant slab in the mantle transition zone (MTZ, which is bounded by the 410 and 660 km discontinuities) generated by the subducted Pacific Plate has been widely accepted, and dehydration of this stagnant slab may be related to extensive volcanism in the Mesozoic and Cenozoic (Chen & Faccenda, 2019; Maruyama et al., 2009; D. Zhao et al., 1994; Y. Zhao et al., 2019). This process is proposed to have resulted in related metallogenesis, tectonic extension, rifting processes, and the formation of the Songliao Basin (Bao & Niu, 2017; Wu et al., 2003; Yang et al., 2018). However, whether the volcanism, rifting processes, and formation of the Songliao Basin can be attributed to a stagnant slab in the MTZ is a matter of debate. Specifically, some tomographic studies have failed to observe significant high-velocity anomalies (or a stagnant slab) in the MTZ (e.g., He & Santosh, 2016; Y. Tang et al., 2014). Additionally, receiver function studies have defined the topographies of the upper mantle discontinuities associated with thermal upwelling of the mantle (He, 2019; He et al., 2014).

However, previous studies cannot define a relationship between the global and detailed topographies of the 410 and 660 km discontinuities corrected with a global 3-D P- and S-wave velocity model (e.g., C. Lu et al., 2019) and mantle plume upwelling due to the limitations of the methods and data sets (e.g., Ai et al., 2003; He, 2019; He et al., 2014; X. Q. Li & Yuan, 2003). For example, common conversion point (CCP) stacking of receiver functions in previous studies used a 1-D or pseudo 3-D velocity model (He, 2019; He et al., 2014), a local 3-D velocity model (R. Zhang et al., 2016), and combined global 3-D velocity model. Thus, the relationship between an upwelling mantle plume and the detailed topography of the upper mantle remains vague. Although a number of recent tomographic and receiver function studies have been carried out in NE China and nearby regions (e.g., X. Fan et al., 2020; Kim et al., 2016; M. Lu et al., 2020; Sun...
et al., 2020; M. Zhang et al., 2019; H. Zhu et al., 2019), the detailed structure of the MTZ beneath NE China is still unclear.

In this study, I collected teleseismic data recorded by permanent stations from 2007 to 2020 and extracted 21,627 high-quality receiver functions, which is far more than any previous receiver function study in this region, and a 3-D global P- and S-wave velocity model (C. Lu et al., 2019) and a local velocity model (He & Santosh, 2016) are used to correct the apparent depths of the 410 and 660 km discontinuities. Finally, the detailed topographies of the 410 and 660 km discontinuities were inferred from the CCP stacking of receiver functions. The results indicate that there are significant variations in the 410 and 660 km discontinuities beneath the center of the Songliao Basin and its southern part, which might be related to the vestiges of the upwelling mantle plume. Based on the topography of the upper mantle discontinuity in this area and tomographic images, it is suggested that the Mesozoic mantle plume beneath the Songliao Basin may have migrated to the current location or the southern part of the Songliao Basin, which is an important discovery in the geoscience field.

2. Method and Data

In the study region, a total of 1,220 teleseismic events were extracted from 127 permanent seismic stations and 282 teleseismic events were collected from 148 temporary seismic stations (Figure 1). The events were limited to Ms > 6.0, and the earthquake epicentral distances ranged from 30° to 90° for individual event-station pairs. A Butterworth band-pass filter between 0.05 and 1 Hz was applied to the raw record, which was cut from 15 s before to 150 s after the P-wave arrival. To obtain a high signal-to-noise ratio for all events, the waveform cross-correlation technique (VanDecar & Crosson, 1990) was used to select consistent raw data (for example, please see Figure S1). In total, 21,627 high-quality receiver functions were calculated by a modified frequency-domain deconvolution with a 1 Hz Gaussian filter and 0.01 water level (Langston, 1979; L. Zhu & Kanamori, 2000) (e.g., please see Figure S2).

The topographies of the 410 and 660 km discontinuities in the study region are defined by the CCP technique (Eagar et al., 2010; VanDecar & Crosson, 1997; L. Zhu, 2000). I use spherical coordinates to calculate the Ps-P differential time $T_{Ps}$, using (Eagar et al., 2010):
where \( p_{Ps} \) and \( p_T \) are the ray parameters of the direct \( Ps \) and \( P \) phases, respectively, and \( V_{Ps} \) and \( V_S \) are the \( P \)- and \( S \)-wave velocities, respectively, in the \( i \)th layer. \( R_i \) and \( \Delta T \) are the Earth’s semidiameter at each \( i \)th depth shell \((r)\) and depth interval, respectively. To ensure the reliability of the results, a 3-D global \( P \)- and \( S \)-wave velocity model by C. Lu et al. (2019) and a local 3-D velocity model in the area by He and Santosh (2016) are employed to remove the velocity heterogeneity effects in the upper mantle. The \( Ps-P \) differential times in the 3-D model are presented as follows:

\[
T_{Ps3D} = T_{Ps} + \Delta T
\]

where \( \Delta T \) is related to the 3-D velocity perturbations or the travel-time correction. Simply, tomography obtained the velocity perturbation relative to the 1-D velocity model (e.g., IASP91) in this area. The travel-time increase or decrease \((\Delta T)\) of the ray induced by the low- and high-velocity anomalies in the upper mantle can lead to changes in the real depths of the 410 and 660 km discontinuities, which should be removed.

A depth interval of 1 km and a lateral grid interval of 0.5° were designed in the grid of CCP stacking of receiver functions, and a radius (or bin) of 75 km was used to search for the migrated receiver functions (Xu et al., 2018). In each bin, a total of 2,000 resampling iterations of bootstrap resampling (Efron & Tibshirani, 1986) are employed to calculate the standard deviation and mean value.

### 3. Results

In Figure 2, the CCP stacking results of receiver functions have been corrected by a 3-D global \( P \)- and \( S \)-wave velocity model (C. Lu et al., 2019), and there are no obvious changes in the 410 and 660 km discontinuities in profiles (a and b) (Figures 2a and 2b). In contrast, at the centers of profiles (c and d), the 410 km discontinuity shows significant deepening by \( \sim 15 \) km (Figures 2c and 2d; blue rectangle), whereas the 660 km discontinuity exhibits significant shallowing by \( \sim 20 \) km, and its amplitude becomes weak (Figures 2c and 2d). Previous receiver function studies show results similar to those of the (c) profile (He, 2019); however, the 410 and 660 km discontinuities of the (d) profile did not have any signature of the anomaly (He, 2019). The 660 km discontinuity appears topographically elevated in the centers of profiles (e and f) (Figures 2e and 2f; yellow rectangle).

To further clarify the relationship between the upwelling mantle plume and the upper mantle discontinuities, the \( P \)-wave velocity perturbation profiles (He & Santosh, 2016) (e and f profiles of Figure S3) are overlain on the CCP stacking profiles of the receiver functions (e and f profiles of Figure 2) (Figure 3). The results indicate that the elevated location of the 660 km discontinuity corresponds well to that of an upwelling mantle plume (Figures 3e and 3f; white rectangular region).

Additionally, six CCP stacking profiles (g–l) of receiver functions were created (the CCP stacking results of receiver functions were corrected by a 3-D global \( P \)- and \( S \)-wave velocity model (C. Lu et al., 2019) (Figure 4; for the locations of the profiles, please see Figure 1)). The images from the CCP stacking of receiver functions show a deepened region for the 410 km discontinuity, an elevated region for the 660 km discontinuity and a weakened amplitude for the 660 km discontinuity at the centers of the profiles (Figures 4i and 4j; regions indicated by the blue rectangles). An elevated region for the 660 km discontinuity at the centers of the (k and l) profiles corresponds to the location of the upwelling mantle plume (Figures 4k and 4l; regions indicated by the yellow rectangles).

The depths of the 410 and 660 km discontinuities and the MTZ thickness in the study region were extracted (Figures 5a–5g). The results show a deepened region for the 410 km discontinuity (Figure 5e, white circle region) and an elevated region for the 660 km discontinuity (Figure 5f, white circle region), resulting in thinning of the MTZ thickness (Figure 5g, white circle region) in the center of NE China (or the Songliao Basin). In the southern part of the Songliao Basin, the 410 km discontinuity appears to be relatively deep, with slight shallowing in a localized region (Figure 5e, blue circle region); the 660 km discontinuity appears...
Figure 2. Common conversion point (CCP) stacking profiles of the receiver functions (a–f) corrected by a 3-D global \( P \)- and \( S \)-wave velocity model (C. Lu et al., 2019). Blue rectangle: deepened region of the 410 km discontinuity and elevated region of the 660 km discontinuity at the centers of profiles (c and d). Yellow rectangle: elevated region of the 660 km discontinuity in the southern part of the Songliao Basin. The data set was resampled and calculated with stacked amplitudes 2,000 times by employing the bootstrapping method, and the final mean receiver functions corresponding to the 95% confidence level were calculated. The yellow points I picked for both the depths of the 410 km and the 660 km discontinuities on the CCP stacking of receiver functions.

Figure 3. \( P \)-wave perturbation profiles overlain on common conversion point (CCP) stacking profiles of receiver functions (profiles e and f of Figure 2; for the locations of the profiles, please see Figure 1). White rectangle: elevated region of the 660 km discontinuity in the southern part of the Songliao Basin. The yellow points I picked for both the depths of the 410 km and the 660 km discontinuities on the CCP stacking of receiver functions.
to be relatively shallow (Figure 5f, blue circle region); and the MTZ is therefore relatively thin (Figure 5g, blue circle region).

Meanwhile, a local 3-D velocity model (He & Santosh, 2016) was used to correct the CCP stacking results of the receiver function, and the S-wave velocity was calculated from the Vp/Vs ratio of the AK135 velocity model (Kennett et al., 1995). The results indicate that the topographies of the 410 and 660 km discontinuities and the MTZ thickness beneath the center of NE China and its southern part inferred from this model are basically consistent with those from the 3-D global P- and S-wave velocity model (C. Lu et al., 2019). Therefore, the CCP stacking results of receiver function in this study might be reliable and convincing.

X. Q. Li and Yuan (2003) carried out a receiver function analysis in NE China by using a temporary PASSCAL seismic network containing 18 broadband seismic stations with data for one year and extracted the topography of the 410 and 660 km discontinuities using the 1-D IASP91 velocity model (Kennett & Engdahl, 1991). They revealed a deepened region in both the 410 and 660 km discontinuities at the center of NE China, which is similar to the results of He et al. (2014). Z. Liu et al. (2015) reported a deepened region in the 410 km discontinuity, an elevated region in the 660 km discontinuity and thinning of the MTZ beneath the center of the Songliao Basin using a global 3-D velocity model (Fukao et al., 2003; Grand, 2002) with
Figure 5.
data from two years. However, they did not reveal thinning of the MTZ in the southern part of the Songliao Basin. R. Zhang et al. (2016) used a local 3-D velocity model (Y. Li et al., 2013) and 1-D IASP91 velocity model (Kennet & Engdahl, 1991) and found a deepened region in the 410 km discontinuity, an elevated region in the 660 km discontinuity and thinning of the MTZ.

4. Discussion

4.1. Mesozoic Mantle Plume and Migration of the Mantle Plume

Receiver functions are a popular tool for investigating the 410 and 660 km discontinuities and the structure of the MTZ. Imaging the topographies of the 410 and 660 km discontinuities and the MTZ thickness plays a key role in understanding the thermal conditions of the MTZ (Aguis et al., 2017; He et al., 2014; M. Zhang et al., 2019), thereby providing an indication of mantle convection within the Earth (Foulger, 2012).

Based on seismic imaging and mineral physical experiments (Deuss et al., 2006; Ito & Takahashi, 1989; Katsura & Ito, 1989; Ringwood, 1975), the 410 discontinuity involves the phase transition of olivine to wadsleyite and exhibits a positive Clapeyron slope with a 3.1 MPa K⁻¹ phase transition response (Frost, 2008; Helffrich, 2000; Jenkins et al., 2016; Kawai et al., 2013), and it occurs at greater depths in the region with increased mantle temperatures and can be depressed by ~8 km/100°C (Foulger, 2012). In contrast, the 660 discontinuity is likely associated with the phase transition of ringwoodite to perovskite and magnesiowüstite, and it exhibits a negative Clapeyron slope with a phase transition response of ~2.0 MPa K⁻¹ (Helffrich, 2000; Jenkins et al., 2016; Kawai et al., 2013) and occurs at shallower depths in regions with increased mantle temperatures.

Mantle plumes are expected to affect the topographies of the 410 and 660 km discontinuities and the MTZ thickness because they pass through the MTZ and have higher temperatures than the surrounding mantle (Deuss, 2007). Generally, mantle plumes can form a 200–300°C temperature anomaly and deepen the topography of the 410 km discontinuity by 15–20 km (Foulger, 2012; Sleep, 2004) and elevate the topography of the 660 km discontinuity, resulting in MTZ thinning (Shen et al., 2002). The depth of the 410 km discontinuity beneath the center of NE China is ~430 km, which represents a deepening of an average of ~20 km relative to the average depth of the 410 km discontinuity globally (e.g., Houser et al., 2008). In contrast, the depth of the 660 km discontinuity beneath NE China is ~640 km, which represents an uplift of an average of ~20 km relative to the average depth of the 660 km discontinuity globally (e.g., Flanagan & Shearer, 1999). Therefore, the structure of the MTZ in this area has a sufficient temperature anomaly (~300°C) and can be attributed to an upwelling mantle plume. Thus, the features of the 410 and 660 km discontinuities and the MTZ in the center of NE China might be related to a relic of mantle plume upwelling (Figures 5 and 6). I also consider that the weak amplitude of the 660 km discontinuity might be generated by mantle plume upwelling (Figures 2c and 2d, blue rectangle and Figures 4i and 4j, blue rectangle).

Upwelling mantle plumes can generate lower crustal underplating (Pirajno, 2007), which leads to a high Vp/Vs ratio in the crust (or lower crust). A previous receiver function study (He & Santosh, 2016) concluded that high Vp/Vs ratios (possibly related to lower crustal magmatic underplating induced by an upwelling mantle plume) and crustal thinning existed in the center of NE China (or beneath the Songliao Basin) (Figures 7a and 7b), which further demonstrates that there was an upwelling mantle plume beneath the center of NE China.

Figure 5. Piercing points at a depth of 410 km (a) and a depth of 660 km (b), as calculated by the 1-D AK135 velocity model (Kennett et al., 1995). The piercing points are reasonably distributed at depths of 410 and 660 km (a and b). The numbers of stacking amplitudes at the 410 km discontinuity (c) and 660 km discontinuity (d), which are greater than 100. Depths of the 410 km discontinuity (e) and 660 km discontinuity (f) and the mantle transition zone (MTZ) thickness (g). Depths of the 410 and 660 km discontinuities and the MTZ thickness after correction on the basis of a 3-D global P- and S-wave velocity model (C. Lu et al., 2019) and removal of the effects of velocity heterogeneities in the upper mantle. The data set was resampled and calculated with stacked amplitudes 2,000 times by employing the bootstrapping method, and the final mean receiver functions corresponding to the 95% confidence level were calculated. The topography of the 410 km discontinuity is defined by identifying the maximum peak between 350 km and 450, and the topography of the 660 km discontinuity is determined by identifying the maximum peak between 600 and 700 km. CBS, Changbaishan volcano zone; WDL, Wudalianchi volcano region. White circle region of Figures 5e–5g, deepened region for the 410 km discontinuity, an elevated region of the 660 km discontinuity, and thinning of the MTZ thickness in the center of NE China. Blue circle region of Figures 5e–5g (current location of the upwelling mantle plume): deepened region for the 410 km discontinuity, an elevated region of the 660 km discontinuity and thinning of the MTZ thickness in the southern part of the Songliao Basin.
The large areas of continental rift basalt that formed in NE China during the Late Jurassic to Late Cretaceous are associated with an upwelling mantle plume (Ren et al., 2002) and have had the effects of velocity heterogeneities in the upper mantle removed. The number of stacking amplitude points is greater than 100. The data set was resampled and calculated with stacked amplitudes 2,000 times by employing the bootstrapping method, and the final mean receiver functions corresponding to the 95% confidence level were calculated. The topography of the 410 km discontinuity is defined by identifying the maximum peak between 350 and 450 km, and the topography of the 660 km discontinuity is determined by identifying the maximum peak between 600 and 700 km. CBS, Changbaishan volcano zone; WDL, Wudalianchi volcano region. White circle region of Figures 5e–5g: deepened region for the 410 km discontinuity, an elevated region of the 660 km discontinuity, and thinning of the MTZ thickness in the center of NE China. Blue circle region of Figures 5e–5g (current location of the upwelling mantle plume): deepened region for the 410 km discontinuity, an elevated region of the 660 km discontinuity, and thinning of the MTZ thickness in the southern part of the Songliao Basin.

Figure 6. Depths of the 410 km discontinuity (a) and 660 km discontinuity (b) and the mantle transition zone (MTZ) thickness (c), which have been corrected on the basis of a local 3-D velocity model (He & Santosh, 2016) and have had the effects of velocity heterogeneities in the upper mantle removed. The data set was resampled and calculated with stacked amplitudes 2,000 times by employing the bootstrapping method, and the final mean receiver functions corresponding to the 95% confidence level were calculated. The topography of the 410 km discontinuity is defined by identifying the maximum peak between 350 and 450 km, and the topography of the 660 km discontinuity is determined by identifying the maximum peak between 600 and 700 km. CBS, Changbaishan volcano zone; WDL, Wudalianchi volcano region. White circle region of Figures 5e–5g: deepened region for the 410 km discontinuity, an elevated region of the 660 km discontinuity, and thinning of the MTZ thickness in the center of NE China. Blue circle region of Figures 5e–5g (current location of the upwelling mantle plume): deepened region for the 410 km discontinuity, an elevated region of the 660 km discontinuity, and thinning of the MTZ thickness in the southern part of the Songliao Basin.

The large areas of continental rift basalt that formed in NE China during the Late Jurassic to Late Cretaceous are associated with an upwelling mantle plume (Ren et al., 2002). Geological studies have also found that basalts erupted from more than 590 volcanoes across an area of ~50,000 km² in the Songliao Basin in the Mesozoic (J. Liu et al., 2001), and this activity may have been related to an upwelling mantle plume (Sleep, 2008). In contrast, volcanism was relatively rare on the margins of the Songliao Basin in the Mesozoic (J. Liu et al., 2001). These results support the interpretation that the MTZ structure beneath NE China
Earth and Space Science

(or the Songliao Basin) may be a relic of Mesozoic mantle plume upwelling, which might be related to the formation of the Songliao Basin (He et al., 2014).

However, tomographic data defined a relic of mantle plume upwelling under the southern margin of the Songliao Basin rather than beneath the Songliao Basin (Figures S3e and S3f) (He & Santosh, 2016; Y. Tang et al., 2014). Relics of upwelling mantle plumes can be retained for several million to several billion years (Burke & Torsvik, 2004; Chang & Van der Lee, 2011). Thus, the relic of the upwelling Mesozoic mantle plume should not have disappeared. Therefore, it is proposed that the upwelling mantle plume beneath the Songliao Basin may have migrated to its current position in the southern part of the Songliao Basin as defined by tomography (He & Santosh, 2016) and identified in this study (Figure 8). Based on the tomographic results (He & Santosh, 2016) (Figure 3), it is suggested that the upwelling mantle plume might have tilted from west to east during the migration process.

Volcanism showed a spatial shift from the center of the Songliao Basin to the edges of the basin, and the products of this volcanism decrease in age from west to the east in NE China (Sun et al., 2020). This age progression may be related to the migration and tilting of the upwelling mantle plume. Seismic evidence for migrating mantle plumes has been reported in the literature. For example, a recent seismic study reported that the plume beneath Hawaii has also migrated rather than remaining stationary (Torsvik et al., 2017). Although a number of studies have reported evidence that the Pacific plate subducted beneath the NE China or NE Asia, there is no evidence or any studies suggesting the migration of NE China since the Mesozoic. Instead, it is widely accepted that the Eurasian continent is stable.

4.2. Cenozoic Mantle Plume

Since ~2.77 Ma, Changbaishan (CBS), located on the eastern margin of the Songliao Basin, has produced a series of eruptions (Y. Wang et al., 2003) that has affected an area with a diameter of 300 km (Kuritani et al., 2011). The distinctive structure of the MTZ (Figures 2e and 2f, yellow rectangle; Figures 5 and 6, blue circle) identified in this study might be indicative of an upwelling mantle plume in the southern part of the Songliao Basin; moreover, the surface projection of the upwelling mantle plume identified by tomography (He & Santosh, 2016) corresponds to CBS (Figures 1 and S3, profiles e and f). Therefore, mantle plume upwelling may have contributed to the Cenozoic volcanism of the CBS. Rare earth element studies indicate
that the magmatism of the CBS is related to a mantle source and might be associated with mantle plume upwelling in the Cenozoic (Basu et al., 1991; Q. C. Fan et al., 2007).

5. Conclusions

The results identified in this study indicate that a relic of an upwelling mantle plume exists beneath the Songliao Basin, which may be related to large-scale volcanism and the formation of the Songliao Basin in the Mesozoic. There is a possibility that the Mesozoic plume may have migrated to the southern part of the Songliao Basin and tilted during the Mesozoic-Cenozoic.

A deepened region of the 410 km discontinuity and an elevated region of the 660 km discontinuity, along with consequent thinning of the MTZ, in the southern part of the Songliao Basin identified in this study correspond to the mushroom-shaped low-velocity anomaly (or upwelling mantle plume) identified in previous tomography. Its surface projection corresponds to the CBS, which implies that mantle plume upwelling might have resulted in the formation of the CBS volcanism in the Cenozoic.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The raw data used in this study, the data involved in the CCP stacking of receiver functions, and the digital results can be accessed at https://doi.org/10.5281/zenodo.3762789.

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