Discontinuity structure of the mantle transition zone beneath the North China Craton from receiver function migration

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A better understanding of the significant Phanerozoic tectonic reactivation and destruction of the North China Craton (NCC) demands a detailed knowledge of the deep structural features of the region. We applied the wave equation-based poststack migration technique to a combined receiver function data set from more than 250 broadband seismic stations to construct the structural image of the mantle transition zone beneath the NCC. Our imaging results reveal a relatively simple and flat 410-km discontinuity but a structurally complicated 660-km discontinuity beneath the region. Double discontinuities and a ~30-km depression of the 660-km discontinuity are observed locally in the southern part of the eastern NCC, in contrast to the smoothly varying structure to the north and in the central and western parts of the craton. Distinctly rapid variations in both the 660-km discontinuity structure and mantle transition zone thickness were found across the north-south gravity lineament (NSGL) near the boundary between the eastern and central NCC, which probably reflects different thermal and probably chemical properties on the two sides of the NSGL. These differences are possibly associated with the Pacific slab, which is imaged tomographically as a flat-lying structure in the mantle transition zone under the region east of the NSGL. The structural variation in the deep upper mantle appears to coincide with the sudden changes in surface topography, gravity field, and crustal and lithospheric structures as well, indicating that the two domains may have tectonically deformed differently throughout the whole upper mantle during the Phanerozoic cratonic destruction. The mantle transition zone on the eastern side of the NSGL is up to 30 ~ 40 km thicker than the global average; this thickness and the complex structure of the 660-km discontinuity in this region may reflect the strong influence that the deep subduction and stagnancy of the Pacific slab, and its possible sporadic penetration into the lower mantle, have had on mantle dynamics and lithospheric reactivation in the eastern NCC since the Mesozoic time. On the other hand, the less variable structure and normal-to-thin mantle transition zone imaged beneath the central and western NCC may indicate that the India-Eurasia collision has had a relatively weak effect on the Cenozoic tectonics of these regions.

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1. Introduction

[2] The North China Craton (NCC) in east Asia is composed of the eastern and western NCC of Archean age and the intervening Trans-North China Orogen (central NCC), which was formed by the collision of the eastern and western NCC in the Late Paleoproterozoic [G. C. Zhao et al., 2001, 2005] (Figure 1). Sharp changes in geological features, including both surface topography and the gravity field as marked by the NNE-trending north-south gravity lineament (NSGL), roughly coincide with the boundary between the eastern and central NCC (Figure 1). Recent studies have suggested that the eastern NCC underwent significant tectonic reactivation and destruction in the Phanerozoic, with a thick (>180 km), cold (~40 mW/m²) and refractory Paleozoic lithosphere replaced by a thin (<100 km), hot (~65 mW/m²) and fertile Cenozoic-to-present lithosphere [e.g., Menzies et al., 1993; Griffin et al., 1998; Fan et al., 2000; Xu, 2001; Gao et al., 2002; Zhu et al., 2004; F. Y. Wu et al., 2005; Chen et al., 2006a, 2008]. Although lithospheric thinning and modification may also have taken place beneath some localized areas in the central NCC [e.g., Xu et al., 2004; Tang et al., 2006; Xu, 2007; Chen, 2009], the large part of the craton west of the NSGL is commonly thought to have remained tectonically stable, given the relatively thick crust and lithosphere and low heat flow of the region [Ma et al., 1984; Zhai and Liu, 2003; Kassey et al., 2007].

[3] The cause of the distinctively different crustal and lithospheric structural features on the opposite sides of the NSGL and their concordant changes with surface geology, and how these shallow structures and the variable behavior of

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the lithosphere across the NCC might be correlated with the major tectonic events and deep mantle processes during the Phanerozoic lithospheric reactivation, are still controversial. In particular, to what extent the NCC was affected by the Mesozoic-Cenozoic tectonics of the surrounding plates, such as the Triassic north-south China collision, the deep subduction of the oceanic Pacific plate since Mesozoic, and the intercontinental collision between India and Eurasia in the Cenozoic etc., is hotly debated [e.g., Menzies et al., 1993; Yin and Nie, 1996; Griffin et al., 1998; Xu, 2001; Liu et al., 2004; Deng et al., 2004]. A better understanding of these issues demands detailed knowledge of the structure and properties of the deep mantle under the NCC. The structural features of the 410- and 660-km seismic discontinuities (hereafter referred to as the 410 and the 660) that define the upper and lower boundaries of the mantle transition zone are particularly crucial in this respect.

The 410 and the 660 are generally believed to be associated with the phase transformations of olivine to wadsleyite and ringwoodite to perovskite + magnesiowustite, respectively [Ringwood, 1975; Jackson, 1983; Ito and Takahashi, 1989]. Because of the positive and negative Clapeyron slopes of these two phase transformations, relatively low temperatures would cause an uplift of the 410 and depression of the 660, and hence a thickening of the mantle transition zone, and relatively high temperatures would result in a thinner transition zone. Therefore, the topography of the discontinuities, and especially the mantle transition zone thickness are detected along profiles NSw, EW1, O1, EW2, O2, and O3, respectively, from north to south (the first two almost overlap). The Tanlu Fault Zone and the NSGL are also marked.

Figure 1. The study region, showing seismic stations, data coverage, and RF imaging profiles. Seismic data were recorded at 212 temporary NCISP stations (black triangles) and 47 permanent CSN stations (inverted triangles). Piercing points at 410- and 660-km depths for P-to-S converted phases are shown as yellow and blue dots, respectively. The mantle transition zone structure was imaged along 10 profiles (red lines), including 4 E–W (EWn1, EWn2, EWs1, EWs2), 3 N–S (NSe, NSm, NSw), and 3 NW–SE (O1–O3) profiles. The shaded rectangular blocks mark the areas of the stacked RFs shown in Figure 2. Thick gray line represents the north-south gravity lineament (NSGL). The top inset shows the location of the study region and the distribution of teleseismic events used. The bottom inset is a topographic map of the study region showing the threefold division of the NCC; thick dashed lines mark boundaries within the NCC, i.e., the eastern NCC (ENCC), central NCC (CNCC) and western NCC (WNCC). Yellow circles give the locations where sharp changes in the 660 structure and mostly also in the mantle-mantle transition zone thickness are detected along profiles NSm, EW1, O1, EW2, O2, and O3, respectively, from north to south (the first two almost overlap). The Tanlu Fault Zone and the NSGL are also marked.
components, such as the strongly temperature-dependent transformation of majorite garnet to perovskite between about 660 and 750 km depth [Weidner and Wang, 2000; Hirose, 2002]. Therefore the 660 structure often appears more complex especially in cold environments, and is probably more temperature sensitive than that of the 410 [Vacher et al., 1998; Akaogi et al., 2002; Andrews and Deuss, 2008]. The broader context of the presence of the 660 is its effect on mantle dynamics [Anderson, 1989; Benz and Vidale, 1993; Weidner and Wang, 1998]. The buoyant force exerted by the dissociation of ringwoodite at the 660 may inhibit, but in some cases may be too small to prevent, subducting slabs from penetrating into the lower mantle [Benz and Vidale, 1993], as has been reported in localized areas of the NW Pacific subduction zone region [Ai et al., 2003; X. Li and Yuan, 2003; D. Zhao, 2004]. In this regard, detailed knowledge about the discontinuity structure of the mantle transition zone beneath the NCC can help us to gain deeper insights into both the Phanerozoic reactivation of the overlying craton and the deep subduction and fate of the oceanic Pacific plate, and particularly the correlation between the two processes.

[5] Recent receiver function imaging results have revealed a thicker mantle transition zone under the basin and coastal areas of the eastern NCC [Ai and Zheng, 2003; Chen et al., 2006b], implying a cold lower-upper-mantle environment of the region. This is consistent with the cooling caused by a flat-lying slab at the bottom of the upper mantle beneath East Asia as imaged by both global and regional tomography [Fukao et al., 2001; D. Zhao, 2004; J. Huang and Zhao, 2006]. In addition, the high-resolution regional tomographic image shows that the western edge of the stagnant slab roughly coincides with the NSGL and the sudden change in surface topography [J. Huang and Zhao, 2006]. To date, subducted slabs have not been detected seismologically in the region to the west of the NSGL. These observations, combined with mineral physics data, led D. Zhao et al. [2007] to propose a big mantle wedge model, in which the active tectonics and mantle dynamics in East Asia are attributed mainly to deep dehydration of the subducting Pacific slab and associated convective circulation processes above the stagnant slab [D. Zhao et al., 2007]. Although slab flattening appears prevalent to the east of the NSGL beneath eastern China, local penetration of the slab into the lower mantle has also been documented under this region using high-density receiver function data [Ai et al., 2003; X. Li and Yuan, 2003], and is hinted at by the regional tomographic images [J. Huang and Zhao, 2006], indicating that the subduction of the Pacific slab is more complex than previously thought.

[6] However, because of the insensitivity of seismic tomography to sharp velocity discontinuities, and the limited data coverage of previous receiver function studies, the structure of the 410 and the 660 in the NCC have not been studied sufficiently, especially from a regional point of view. The lateral variations in the discontinuity structure and thickness of the mantle transition zone in response to the complex Pacific subduction process beneath the eastern NCC are not well constrained. The ways in which the mantle transition zone west of the stagnant slab beneath the central and western NCC differs structurally from that under the eastern NCC also are unclear. These structural differences are important for constraining the thermal regime in the deep upper mantle and deciphering the factors that have controlled the tectonic evolution in both regions.

[7] In this study, we contribute to this issue by presenting a detailed study on the mantle transition zone discontinuities beneath the NCC. We have applied the wave equation-based poststack migration technique to a combined receiver function (RF) data set collected at both dense temporary seismic arrays and a permanent station network in the region. We have investigated the topography and image features of the 410 and the 660, and particularly focused on the lateral variation in the thickness of the mantle transition zone under the craton. On the basis of our migrated receiver function images and comparisons with tomography results, we discuss the structural differences between the eastern NCC and the central and western NCC, variations in the morphology of the subducting Pacific slab under the eastern NCC, and possible influences of the deep Pacific subduction and the India-Eurasia collision on the tectonic reactivation and destruction of the craton.

2. Data and Method

[8] Teleseismic waveform data collected at more than 250 broadband seismic stations in the NCC (Figure 1) were combined to image the mantle transition zone structure of the NCC in this study. Among these stations, 212 are temporary North China Interior Structure Project (NCISP) stations forming four linear arrays across the region (black triangles in Figure 1a). These seismic arrays operated sequentially from late 2000 with a period of about 1 year for each array and an average interstation spacing of about 10 km [Zheng et al., 2005]. The remaining 47 stations (inverted triangles in Figure 1a) belong to the permanent Capital Seismic Network (CSN) with a 30 ~ 40-km station separation. We analyzed data from over 1800 events with body wave magnitude ≥5.5 and epicentral distance between 28° and 92°. A time window of 20 s before and 100 s after the P wave arrival was selected and RFs which isolate
The time domain RFs (0.03–0.3 Hz) display obviously different timing and waveform features in different areas (Figure 2), suggesting considerable structural variation in the deep upper mantle beneath the study region. Although the Ps conversion signals from the mantle transition zones discontinuities generally could not be identified from individual RFs because of their low amplitudes and possible noise contamination, they were visible in most cases when proper stacking was performed on the RFs with close piercing points at depth. In the study region, these signals appear to be the most clearly identified signals in the stacked RFs, in addition to the strong Moho Ps phase and its multiples, as exemplified in Figure 2 for three rectangular blocks in the southeastern, northeastern and middle-to-western parts of the NCC, respectively (see Figure 1 for block locations). The Ps conversions from the 410 and the 660 vary distinctly from one area to another. The RF for the southeastern block shows the largest phase separation and the most complicated 660 signals, while that for the western block gives a delayed 410 phase and the closest phase pair from the 410 and the 660. The Ps conversion from the 410 in the northeastern block arrives as early as that in the southeastern one, but the separation between the 410 and the 660 conversions appears only slightly larger than that of the western block. These signals together with the shallow crustal phases, which show large variations in delay time relative to the direct Moho (Pms), the 410 (P_{410}s) and the 660 (P_{660}s), and the Moho multiple (PpPms) are marked on top.

Considering the complexity of the structure under the region associated with the stagnancy and possible local penetration of the Pacific slab, migration is therefore necessary for more reliably retrieving the structural features of the mantle transition zone beneath the NCC.

We processed the RFs in two steps following the migration procedure described by Chen et al. (2005): common conversion point (CCP) stacking and backward wavefield extrapolation. The CCP stacking was conducted in the time domain to produce RF stacks at the points along the profiles similarly to those shown in Figure 2 but on the higher-frequency data up to 1 Hz. Rectangular bins with a fixed half length of 80–120 km (mostly 100 km) perpendicular to the profiles, but with variable bin widths parallel to the profiles, were adopted in the stacking to account for the uneven data sampling. The backward wavefield extrapolation was performed in the frequency domain on the basis of the one-way wave equation and the final image was created by superposing the contributions from the migrated frequency contents of the RFs [Chen et al., 2005], if not specified, in the range of 0.03–0.4 Hz. We adopted different velocity models in stacking and migration. We either only employed the average 1-D crustal model for east China as we did to image the lithospheric structure of the region previously [Chen et al., 2006a, 2008] or took into account the lateral variations in crustal structure [e.g., Zheng et al., 2006; Sun and Toksoz, 2006; Sun et al., 2008], lithospheric thickness [e.g., Zhu et al., 2004; Chen et al., 2008] and upper mantle velocities of the region [e.g., Z Huang et al., 2003; J. Huang and Zhao, 2006; Pei et al., 2007; Sun et al., 2008].

To gain a more detailed and accurate picture of the structure of the mantle transition zone beneath the study region, we selected ten imaging profiles (red lines in Figure 1) according to the data coverage and the tectonic division of the NCC and applied the wave equation-based poststack migration method [Chen et al., 2005] to the RF data set to construct the structural image for each profile individually. This migration method has proven to be more efficient in recovering heterogeneous structural features than the commonly used stacking-based method [Chen et al., 2005, 2006a]. To gain a more detailed and accurate picture of the structure of the mantle transition zone beneath the study region, we selected ten imaging profiles (red lines in Figure 1) according to the data coverage and the tectonic division of the NCC and applied the wave equation-based poststack migration method [Chen et al., 2005] to the RF data set to construct the structural image for each profile individually. This migration method has proven to be more efficient in recovering heterogeneous structural features than the commonly used stacking-based method [Chen et al., 2005, 2006a].
profiles, velocity models used in migration were constructed by considering the available P and S wave velocity models either separately or jointly with different combinations. The maximum difference in the depth-averaged Vp/Vs ratio above the mantle transition zone among different migration velocity models varied spatially within the range of 0~2.0%, resulting in a maximum depth variation of the imaged 410 not exceeding 20 km.

3. Structural Images
[12] The migrated RF images constructed in the way given above show strong Ps conversion signals from the 410 and the 660 in the most parts of all the profiles (Figure 3),
indicating that these two discontinuities are generally well defined beneath the NCC. The image features, including both topography and amplitudes of the 410 and the 660, vary noticeably with different velocity models and different shallow structure corrections considered in RF migration, as exemplified in Figures 4–6 for profiles EW, O1, and profile O1, respectively. Nevertheless, by properly accounting for the shallow structural heterogeneities and by largely removing the correlated topography between the 410 and the 660, our imaging results suggest substantial structural differences, both laterally and vertically, in the mantle transition zone under the study region.

[13] The 410 and the 660 exhibit contrasting image features along most of the profiles. The 410 is imaged as a relatively simple and flat-lying discontinuity in the depth range of 408–420 km; it is slightly (~3 km on average) shallower in the eastern NCC than in the central and western NCC when the shallow structure corrections were included in the migration (Figure 3, more clearly in Figures 4b, 5b, and 6d). If the 1-D average velocity model is used, the image of the 410 does show noticeable topography that is obviously correlated with that of the 660 (e.g., Figures 4a, 5a, 6a, and 6c). These observations suggest that the imaged topography of the 410 probably is an artifact induced by inappropriate compensation of the structural heterogeneity above the mantle transition zone, and the real structure of the 410 is probably much less variable beneath the region.

[14] The 660 presents more complex images with significant undulations, multiple signals and strong variations in amplitude, no matter which velocity model was incorporated.
In the migration (Figures 3–6). In addition, the image features of the 660 display distinct regional variations that are not obviously observed for the 410. For instance, complex images of the 660, including double discontinuities and significant depressions up to 40 km from the global average at 660 km, appear in areas beneath the southern part of the eastern NCC, while the northern, central and western parts of the craton show a relatively smooth 660 image with depth variations mostly less than 10 km along each profile (Figures 3–6).

We believe that the double image of the 660 in both the southeastern part of profile EWs2 and the southern end of profile NSm (solid arrow in Figures 3d and 3f) and the significant depression of the 660 along profiles EWs1, EWs2, and O1–O3 (open arrow in Figures 3c, 3d, and 3j, also see Figures 5 and 6) may reflect real structural features underneath the southern part of the eastern NCC, for the following reasons. First, such complicated features are always present in the RF images constructed with various binning schemes in CCP stacking or using different velocity models in the migration, and apparently do not result from unsuppressed noise contamination due to the paucity of data (see the RF numbers and bin sizes in the upper panel for each profile in Figure 3). Second, the locations of both the double discontinuities and the depressed 660 imaged along different profiles are spatially coincident and the estimated depths of the two discontinuity branches and the magnitude of the depression, and thus the mantle transition zone thickness agree (within uncertainties) among different profiles (Figure 7). Finally, the double discontinuity structure and
localized depression of the 660 with a comparable magnitude have been observed previously beneath the same area using a smaller set of data and a different imaging technique [Ai and Zheng, 2003]. Therefore, the 660 under the southern part of the eastern NCC probably has the most complicated structure within the entire study region. The marked difference between the 410 and the 660 images in this part of the craton is consistent with previous seismic observations [Ai and Zheng, 2003; Chen et al., 2006b], and contrasts with other parts of the craton where a less variable 660 and similar appearances of the 410 and the 660 were observed.

[16] Although the above mentioned double-discontinuity images of the 660 for profiles EW and NS are probably real, the interpretation of other multiple signals at about the similar depths may require caution. In particular, at the edges of some profiles the image may be distorted or contaminated by unsuppressed noise because of the insufficient data available. For example, some weak signals appear at ~700-km depth and deeper below the strongest and most continuous 660 image at the northern edge of profile NS (Figure 3f). Considering the sparse data there (upper panel in Figure 3f) compared with those at the southern edge where double discontinuities were observed and considered to be real, the nature of these signals cannot be determined with confidence. They could either represent true Ps conversion or scattered energies associated with small-scale heterogeneities.

Figure 4. Migrated RF images for profile EW, (a) using the 1-D average velocity model and (b) taking into account the crustal and upper mantle structure to remove the correlated depth variations between the 410 and the 660 (enlarged from Figure 3a). (c) Variations in the discontinuity depths (estimated for bins that contain at least 200 RF samples in the depth range of the mantle transition zone and smoothed over 100 km laterally) relative to 410- and 660-km depths, respectively, and the corresponding mantle transition zone thickness relative to the global average of 250 km estimated from the images shown in Figure 4a (dashed lines) and Figure 4b (solid lines). Blue, pink, and gray shaded areas represent the possible ranges of the discontinuity depths and the mantle transition zone thickness, considering the uncertainties in the velocity model above the 410. The boundaries between the eastern, central, and western NCC and the NSGL are marked at the top of Figure 4c.
near the upper-lower-mantle boundary or reverberations from shallow structures that may not be fully suppressed by migrating a small amount of data. While the lack of data also may be responsible for the weak and erratic 410 image at the similar portion of the profile (Figure 3f), more detailed analysis and comparisons with other observations are needed to reach a definite conclusion. Even where the data sampling is dense, complex signals may also appear around the depth of the 660, such as the double ones in the southeastern part of profile O\textsubscript{1} (Figure 3h). However, when the highest migration frequency was lowered from 0.4 Hz to 0.3 Hz only the much stronger deeper signals were still visible and the 660 image became more continuous (compare Figures 6c and 6d with Figures 6a and 6b). This observation suggests that the deeper signal may be representative of the general structural feature of the 660 in this area whereas the weaker shallower signal may result from more localized scattering. This is further confirmed by the concordance of the mantle transition zone thickness estimated from the deeper signal with that from the image of profile NS\textsubscript{e} which intersects with profile O\textsubscript{1} at around this location, and by the lack of a shallower signal along profile NS\textsubscript{e} (purple lines and purple bars in Figure 7, Figure 3e). We therefore interpret the 660 beneath this area as a single discontinuity. From these comparisons and analyses, only the double discontinuities detected along profiles EW\textsubscript{n1} and NS\textsubscript{m} beneath the southern part of the eastern NCC are considered real and further integrated in mapping the regional thickness of the mantle transition zone.

[17] Rapid changes in the depth and in some cases in the image strength of the 660 were observed in areas a little further west or northwest of the complex 660 area along almost all the profiles that traverse at least two of the three constituent parts of the NCC (EW\textsubscript{n1}, distance \~750 km in Figures 3a and 4; EW\textsubscript{n2}, distance \~820 km in Figure 3b; NS\textsubscript{m}, distance \~850 km in Figure 3g; O\textsubscript{1}, distance \~660 km in Figures 3h and 6; O\textsubscript{2}, distance \~750 km in Figure 3i; O\textsubscript{3}, distance \~850 km in Figures 3j and 5). Taking profile EW\textsubscript{n1} as example, an gap in the image of the 660 appears at around distance 750 km, accompanying an apparent uplift of the discontinuity from east to west on the order of \~10 km over a lateral distance of 50 km (Figures 3a, 4a, and 4b). This is a robust image feature, as it was consistently observed both with and without lateral structural corrections included in the

![Figure 5](image-url)

Figure 5. Same as Figure 4 except for profile O\textsubscript{3}. Figure 5b is the image enlarged from Figure 3j.
Figure 6. Migrated RF images for profile O$_1$, (a and c) constructed by adopting the 1-D average velocity model and (b and d) taking into account the sedimentary, crustal, and upper mantle structure, respectively. Different frequency contents of RFs were considered in the migration, i.e., 0.03–0.4 Hz (Figures 6a and 6b) and 0.03–0.3 Hz (Figures 6c and 6d). Figure 6b is the image enlarged from Figure 3h. (e) Same as Figure 4c except for profile O$_1$. 
migration (compare Figure 4a with Figure 4b). It also contrasts with the artificial depression of the 660 some 300 km to the west along the same profile; this depression is induced by incorrect velocity corrections, and shows an apparent correlation with the depression of the 410 when using the 1-D average velocity model (Figure 4a), but disappears when the shallow structural heterogeneity was properly taken into account (Figure 4b). On the basis of these observations, we therefore regard the imaged discontinuous feature of the 660 on profile EW\textsubscript{n1} as a real structural feature. Similarly, the image gap or rapid change in either the depth or the image strength (or both) of the 660 in profiles that traverse different parts of the NCC (except for profile NS\textsubscript{m}) are probably also real. Given the relatively flat feature of the 410, most of these sharp structural variations at the base of the upper mantle therefore also result in rapid changes in the thickness of the mantle transition zone (e.g., Figures 4c, 5c, and 6e). Geographically, these changes all roughly coincide with the NSGL and the boundary between the eastern and central NCC (as marked by yellow circles in the bottom inset of Figure 1 and Figure 8), demonstrating distinct structural differences between the two sides of the craton.

4. Mantle Transition Zone Thickness

[18] As shown in Figures 4–6, the estimated absolute depths and the image strengths of the 410 and the 660 can vary significantly and depend strongly on the velocity structure adopted in RF migration. However, the resulting thickness of the mantle transition zone appears much less variable, with uncertainties mostly on the order of 5 km (except at some edge areas of the profiles) which is 2 to 4 times smaller than those of the depth estimated for individual discontinuities (e.g., Figures 4c, 5c, and 6e). This indicates that the mantle transition zone thickness can be constrained fairly well from the RF data even without knowing the exact velocity structure of the overlying mantle, in agreement with previous studies [e.g., X. Li et al., 2000; Owens et al., 2000]. Therefore, in this study we mainly focus on the regional variation in the thickness of the mantle tran-
transition zone and the nature of its lateral variation without much discussion of the absolute depths of the 410 and the 660.

By integrating the results of our RF migration (Figures 3–6), we produced a map of the thickness of the mantle transition zone across the study region (Figure 8). This map, covering most of the eastern NCC and the northern part of the central and western NCC (with at least 200 RFs sampling the transition zone depths in each stacking bin), illustrates the distinct structural variations of the deep upper mantle under the NCC. It shows a general thinning of the mantle transition zone from >280 km in the southeast coastal areas to about 240 km in the northwest highland and continental interior. The most significant change in the mantle transition zone thickness is on the order of ~30 km and occurs over a distance of several hundred kilometers laterally around the Tanlu Fault Zone in the southern part of the eastern NCC and coastal to offshore areas further to the east, where the thickest mantle transition zone and the most complex structure of the 660 are consistently imaged (Figures 3–8).

In contrast to this SE zone, the northern part of the eastern NCC and the central and western parts of the craton all feature relatively gradual variations with the eastern part having thicknesses mostly >250 km, the central part varying around 250 km and the western part generally <250 km, respectively (Figure 8). However, rapid changes in either mantle transition zone thickness or the image features of the 660 (usually both) are observed in the individual profiles (Figure 3) at locations roughly along the boundary between the eastern and central NCC and close to the NSGL (yellow circles in Figure 8 and in the bottom inset in Figure 1); the most distinct cases appear in profiles EW1, O1, and O3 (Figures 4–6). The mantle transition zone beneath the northern part of the western NCC also shows some obvious variations in thickness, from ~250 km in the interior of the craton to ~240 km and even as low as ~235 km in the marginal area, which has the thinnest mantle transition zone within the study region (Figure 8). All these pronounced changes in the thickness of the mantle transition zone coincide with obvious variations in surface topography (compare Figure 8 with the bottom inset in Figure 1), suggesting a close correlation between deep mantle structure and the surface tectonics of the study region.

Note that we did not take into account possible lateral variations in the velocity structure of the mantle transition zone beneath the study region in our RF migration and the subsequent image integration to construct the map of the mantle transition zone thickness. Both global and regional tomographic studies [e.g., D. Zhao, 2004; J. Huang and Zhao, 2006; C. Li et al., 2006] have revealed relatively high velocities in the mantle transition zone under eastern China compared with those to the west. Such a velocity variation would produce an even thicker mantle transition zone image beneath the eastern NCC and would have the opposite effect beneath the central and western NCC. Therefore, our migrated RF images may provide a lower and upper bound, respectively, for the thickness of the mantle transition zone in the two regions. Synthethic calculations suggest that adopting a more realistic velocity model may enhance the estimated thickness difference between the two regions by several to 10 km at the most. On the whole, lateral heterogeneities in the mantle transition zone would not affect the general features shown in Figure 8.

5. Discussion

The strongly varying thickness of the mantle transition zone (Figure 8) probably reflects marked differences in the thermal state of the deep upper mantle on the opposite sides of the NSGL in the NCC. Combined with mineral physics data, our migrated RF images of a thick mantle transition zone beneath the eastern side (eastern NCC) and a normal-to-thin mantle transition zone beneath the western side (central and western NCC) indicate a relatively cool thermal regime to the east, and a normal-to-hot one to the west. This is consistent with recent tomographic results that show a high-velocity slab trapped in the mantle transition zone mainly under areas east of the NSGL [D. Zhao, 2004; J. Huang and Zhao, 2006]. In addition, detailed analyses of the dense seismic array data also suggest contrasting crustal and lithospheric structure across the NSGL [e.g., Zheng et al., 2006; Chen, 2009]. The close correspondence between the slab morphology, the variation in the mantle transition zone thickness, and changes in the shallow lithospheric structure, gravity field and surface topography (bottom inset in Figure 1 and Figure 8) lends further support to the previous speculations that the Phanerozoic mantle dynamics and tectonic evolution of the NCC are predominantly controlled by the deep subduction and flattening of the Pacific plate [Ye et al., 1987; Griffin et al., 1998; F. Y. Wu et al., 2003; D. Zhao et al., 2007].

To the east of the NSGL, distinctly different structural features of the mantle transition zone discontinuities, particularly the 660, probably are related to the complex morphology and subduction pattern of the Pacific slab beneath the eastern NCC. The complicated structure characterized by double discontinuities and significant topography of the 660 appears at around the thickest (and therefore coldest) portion of the mantle transition zone in the southeastern part of the study region in both our RF images (Figures 3 and 8) and those obtained previously [Ai and Zheng, 2003]. We interpret the double-discontinuity image as representing the structural feature of the 660 itself in a cold environment, rather than reflecting an additional velocity interface associated with the presence of the flat-flying Pacific slab. Any possible impedance contrast near the base of the upper mantle due to the lithological stratification of a slab would result largely from a density change rather than a velocity variation [Schutt and Lesher, 2006; Ganguly et al., 2009] and therefore could not produce Ps signals (which are insensitive to density contrasts [Julià, 2007]) strong enough to have comparable amplitudes to that produced by the phase change at ~660-km depth, as observed in our RF images (Figures 3d and 3f). Moreover, 2-D synthetic modeling results suggest that, by waveform-based migration, significant topography or locally steeply dipping geometry of the 660 could be recovered quite well even with much sparser sampling or strong noise contamination of the RF data [Chen et al., 2005]. Therefore, the imaged double-discontinuity structure is also unlikely to be a scattering-induced artifact because of an abnormal geometry of the 660, although the effect of 3-D heterogeneity cannot be fully ruled out.
The double-discontinuity structure is limited to the presumably cold area, suggesting that it could be attributed to the multiple phase transformations that occur in both olivine and non-olivine systems under the low-temperature regime [Vacher et al., 1998; Akaogi et al., 2002; Andrews and Deuss, 2008]. Assuming that the topography of the 660 is caused solely by a temperature effect and only considering the phase transformations in olivine, then the observed ~30 km of the 660 depression under the region (Figure 8) would require a thermal variation of 300–600 K laterally, given a range in the Clapeyron slope from 2.0 to 4.0 MPa/K for the 660 [Ito and Takahashi, 1989; Ito et al., 1990; Bina and Helffrich, 1994]. Taking into account the influence of phase transformations of non-olivine components, the required temperature difference would be even larger [Vacher et al., 1998; Weidner and Wang, 1998, 2000]. Collectively, the significant

Figure 9. Comparisons between RF images obtained in this study and tomographic images of $P$ wave velocity variation (at similar latitudes) from J. Huang and Zhao [2006]. Profiles of (a) $EW_{11}$ (107.5°E–122.9°E), (b) $EW_{12}$ (105.4°E–122.8°E), (c) $EW_{13}$ (114.8°E–122.0°E), and (d) $EW_{14}$ (114.8°E–122.0°E).
depression of the 660 and the presence of the double discontinuities probably indicate that this part of the slab is the coldest within the study region. The high density and viscosity associated with low temperature may lead to rapid descent and local collapse of the slab into the lower mantle, as reported under some areas in northeast China where multiple discontinuities and anomalous 660 topography were also imaged near the base of the upper mantle [Niu and Kawakatsu, 1996; Ai et al., 2003; X. Li and Yuan, 2003].

[25] Local penetration of the slab under the southern part of the eastern NCC was also hinted at in the regional P wave tomographic images [J. Huang and Zhao, 2006] (Figures 9c and 9d), although it is uncertain because of the relatively low resolution of tomography in the lower mantle [J. Huang and Zhao, 2006]. On the other hand, our imaging results show that the structure of the mantle transition zone varies strongly from south to north in the eastern NCC, and exhibits much smoother and less pronounced thickness variations beneath the northern part of the region (Figures 3 and 8), in agreement with the change in the structural feature revealed by the regional P wave tomography [J. Huang and Zhao, 2006] (compare Figures 9a and 9b with Figures 9c and 9d). These observations may reflect a smoother temperature distribution in the north than in the south, indicating that the descent of the slab may be slower and that the slab probably has not penetrated the upper-lower-mantle boundary under the northern part of the eastern NCC. Therefore, if slab penetration is the main cause of the imaged complicated structural features of the 660, our RF images combined with the high-resolution tomography results argue for a localized collapse of the Pacific slab into the lower mantle. Moreover, the observed rapid structural variations near the NSGL (yellow circles in Figures 1 and 8) which may represent the transition from the stagnant slab to the surrounding mantle probably result from a mineralogical change with possible compositional variation superimposed on the temperature effect.

[26] The relatively simple structural feature of the imaged 410 implies a less significant influence of the Pacific slab on the shallow structure of the mantle transition zone beneath the region. This is because the slab may have not piled up to occupy the entire depth range between the 410 and the 660 as imaged by tomography (e.g., Figure 9b) but rests only in the lower part of the mantle transition zone. Alternatively, the slab-induced anomalies may fade away more rapidly at near the top surface of the stagnant slab than at the bottom, perhaps aided by slab-dehydration-induced convective circulation in the overlying mantle wedge which has been suggested as the main cause of the active tectonics and craton destruction in eastern China [D. Zhao et al., 2007].

[27] The influence of the deep subduction and stagnancy of the Pacific slab is undetectably small in the central and western NCC, as shown by the considerably reduced thickness (even less than the global average) and the simpler structure of the mantle transition zone beneath these regions (Figures 3–8). The contrasting structural features suggest different properties and deep mantle dynamics from their eastern counterpart, which may have been directly associated with the Pacific subduction. Previous geological and geochemical observations have suggested that the Cenozoic surface tectonics and lithospheric processes of the central and western NCC reflect the Early Cenozoic collision between the Indian and Eurasian plates [e.g., Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Zhang et al., 1998, 2003]. This agrees with the recent seismic tomography and geodynamic modeling results that show low-velocity anomalies in the shallow upper mantle beneath the Cenozoic tectonically active zones in these regions [e.g., Liu et al., 2004; J. Huang and Zhao, 2006; Pei et al., 2007]; the slow anomalies may represent a lateral asthenospheric mantle flow driven by the India-Eurasia collision [Liu et al., 2004]. A hotter mantle transition zone beneath areas in the central NCC and near the northern margin of the western part of the craton, as inferred from our RF images (Figure 8), corresponds well with the tomographically observed low-velocity structures in the shallow upper mantle and suggests that the influence of the India-Eurasia collision may have extended to the deep upper mantle.

[28] A systematic comparison between the mantle transition zone structure, the deformation pattern of the upper mantle and the lithospheric structure and surface tectonics of these regions are beyond of the scope of this paper, and will be addressed in detail elsewhere (L. Chen, Concordant structural variations from the surface to the base of the upper mantle in the North China Craton and its tectonic implications, submitted to Lithos, 2009). Nevertheless, it seems clear that the simpler discontinuity structural features and relatively small mantle transition zone thickness anomalies under the central and western NCC suggest a less significant effect of the India-Eurasia collision on these parts of the craton compared with the effect of the Pacific slab on the eastern NCC. This interpretation is consistent with the absence of widespread extension west of the NSGL and the presence of intensive extension with development of large-scale rifted basins on the eastern side of the NSGL, in the Mesozoic-Cenozoic time [Ye et al., 1987; Zhang et al., 1998, 2003; Ren et al., 2002].

[29] The marked difference in the structure of the mantle transition zone across the NSGL, which is concordant with the sudden change in the surface topography, gravity field and crustal and lithospheric structural features, and roughly coincides with the western limit of the stagnant Pacific slab, corroborates the previous suggestion that the north-south gravity lineament is not merely a near-surface feature, but acts as a deep intracontinental boundary between two tectonically different domains [Xu, 2007]. It appears to be the geophysical expression of large-scale mantle dynamics during the Mesozoic-Cenozoic reactivation and destruction of the NCC.

6. Conclusions

[30] We have studied the structures of the 410 and the 660 and the variation in the thickness of mantle transition zone across the NCC by applying the wave equation-based migration to a large body of teleseismic RFs that densely sample the region. Our imaging results show contrasting structural features of the mantle transition zone on the opposite sides of the NSGL. To the east, the NCC is characterized by a generally depressed 660 and a thickened mantle transition zone, consistent with the deep subduction and stagnancy of the cold Pacific plate above the bottom of the upper mantle under this region. In particular, double discontinuities and a significant depression of the 660 by up to 30~40 km were observed locally in the southern part of the region. These may suggest that the cold slab has overcome the positive buoy-
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