Tomographic structure of East Asia: II. Stagnant slab above 660 km discontinuity and its geodynamic implications*

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Abstract P-wave arrival times of both regional and teleseismic earthquakes were inverted to obtain mantle structures of East Asia. No fast (slab) velocity anomalies were found beneath the 660-km discontinuity through tomography besides a stagnant slab within the transition zone. Slow P-wave velocity anomalies are present at depths of 100–250 km below the active volcanic arc and East Asia. The western end of the flat stagnant slab is about 1 500 km west to active trench and may also be correlated with prominent surface topographic break in eastern China. We suggested that active mantle convection might be operating within this horizontally expanded “mantle wedge” above both the active subducting slabs and the stagnant flat slabs beneath much of the North China plain. Both the widespread Cenozoic volcanism and associated extensional basins in East Asia could be the manifestation of this vigorous upper mantle convection. Cold or thermal anomalies associated with the stagnant slabs above the 660-km discontinuity have not only caused a broad depression of the boundary due to its negative Clapeyron slope but also effectively shielded the asthenosphere and continental lithosphere above from any possible influence of mantle plumes in the lower mantle.

Key words: tomography; stagnant slab; mantle wedge

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1 Introduction

Cenozoic tectonics of East Asia, including east China, Mongolia, and the western Pacific marginal seas, is characterized by large-scale strike-slip faults, rifts, volcanic fields, and intracontinental and marginal sea basins (Figure 1). Researches in the past three decades have attributed the development of these features exclusively to plate boundary forces such as Indo-Asian collision (Dewey and Burke, 1973; Molnar and Tapponnier, 1975; Dewey et al., 1989; Houseman and England, 1996; Kosarev et al., 1999) and subduction of the Pacific and Philippine Sea plates in the western Pacific (van der Hilst et al., 1991, 1993; Northrup et al., 1995; Yin and Harrison, 2000; Ren et al., 2002; Hall, 2002). In the

above tectonic and dynamic models, the mantle beneath the Asian continental lithosphere has been treated as a passive and resistant free continuum. As a result, the role of mantle dynamics in Cenozoic deformation of East Asia has never been systematically evaluated. This is partly due to the fact that we know little about detailed structures in the mantle beneath the East Asian lithosphere.

To illuminate the possible role of subduction in the western Pacific in Cenozoic deformation in East Asia, we obtained a three-dimensional (3-D) mantle structures beneath East Asia by means of a tomography study of this region. A similar attempt has been carried out recently for the western China (Xu et al., 2002). This is the second of two papers that describes this regional tomography investigation, which combines P-wave arrival times of both regional and teleseismic earthquakes to obtain mantle structures of East Asia. The first paper hereafter referred to as Paper 1 describes the data and

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Figure 1 Topography map of East Asia with plate boundaries (yellow lines) and major geological features and provinces. Cenozoic deformation in East Asia has mostly been dominated by north-south contraction in Tibet and westward subduction in the western Pacific. The study area is marked by dashed lines in red. Our study area, marked by dashed red lines, is in eastern China, which covers most of North China between the Dabie Shan to the south and the Sino-Russia border to the north and eastern part of South China between the Dabie Shan to the north and the South China Sea to the south. Volcanoes are also shown as open triangles in red. North China is part of the Sino-Korean Craton, which separates from the South China, known as the Yangtze Craton, by the ESE trending Qingling-Dabie belt.

inversion method with resolution tests and presents important inversion results. This second paper will focus on the geodynamic implications of this study, that is, use these inversion results to explore the possible links between Cenozoic tectonic deformation and intra-plate volcanism in East Asia to the deep processes in the mantle related to the subduction process in the western Pacific.

2 Tectonic setting

The main interest of our study area is in eastern China, which covers most of North China between the Dabie Mountain to the south and the Sino-Russia border to the north and eastern part of South China between the Dabie Mountain to the north and the South China Sea to the south (Figure 1). Deformation in East Asia was dominated by north-south contraction in Tibet and Tian Shan between 65 and 15 Ma (e.g., Rowley, 1996; Yin and Harrison, 2000; Tapponnier et al., 2001; Vinnik et al., 2002). During the same period, back-arc extension along the eastern margin of East Asia occurred as a result of rapid eastward migration of the western Pacific trench system (e.g., Ren et al., 2002; Hall, 2002). Since

~15 Ma, with the collapse of several back-arc basins, the eastern margin of Asia has become mostly contractional (e.g., Japan Sea and South China Sea) (Ren et al., 2002; Hall, 2002), meanwhile widespread east-west extension in the interior of mainland Asia occurred including the Tibetan plateau, North China (i.e., the Shanxi and Yinchun rifts), and southeast Siberia (Baikal rift). This above mentioned changes may be explained by boundary condition variation related to the presence and absence of back-arc spreading along the eastern margin of Asia (Yin, 2000; Yin and Chen, 2004).

Lithosphere below North China thinned significantly in Paleogene as a result of back-arc extension (e.g., Ye et al., 1985; 1987; Menzies et al., 1993; Griffin et al., 1998; Xu, 2001; Wang et al., 2001). The extension was associated with widespread eruption of basalts along the eastern margin of the North China craton (e.g., Zhou et al., 1988; Darby and Ritts, 2002) and the formation of the Paleogene North China basin (Figure 1). The North China basin is covered mostly by post-rifting Neogene-Quaternary sediments. The North China basin is bounded to the west by the NNE-trending Taihang Mountain and to the east by the NNE-trending Tanlu

fault zone (Figure 1), which is a first-order tectonic block in East Asia with multiple slip histories since the Late Permian (Yin and Nie, 1993, 1996; Li, 2000). Opening of the North China basin was coeval with extension in the Bohai Bay resulting from the same back-arc extensional process (e.g., Allen et al., 1997; Ren et al., 2002). GPS survey shows that the Tanlu fault is also currently extensional, accommodating mostly east-west extension (Shen et al., 2000).

The South China block is located south of the Triassic Qinling-Dabie orogenic belt. This belt was reactivated in the Cenozoic by left-slip faulting (Zhang et al., 1998a; 1999; Ratschbacher et al., 2000). The northern part of the South China is located in a back-arc setting behind the Ryukyu trench along which the Philippine Sea plate is subducting westward (Figure 1). South of the Ryukyu trench, the convergence between Asia and the Philippine Sea is accommodated by eastward subduction of the South China Sea and the mainland Asia beneath the Manila trench. As a result, the southern part of the South China is located within a down-going plate. This is fundamentally different from the tectonic setting of the North China and the northeastern part of South China that lie in the over-riding plate above a subduction zone.

3 Data and seismic tomography results

In the regional tomography study described in details in Paper 1, we had used 400 000 P-wave arrival times from 8 002 regional earthquakes and 370 000 P-wave arrival times from 9 000 teleseismic events (see Figure 2, Paper 1) to invert for the 3-D mantle structures within the study area of 20°N–55°N and 100°E–145°E marked by the red dashed box in Figure 1. We have applied the tomography method of Zhao et al. (1992; 1994) to both the travel time residuals of regional earthquakes and relative travel time residuals of teleseismic events to improve the resolution of the inversion. With the optimal damping parameter of 150, the standard deviation of travel time residuals was decreased from 2.4 s to 1.9 s after the inversion. Conventional checkerboard tests indicated that the spatial resolution at shallow depth (~10 km) in the upper crust is rather poor because of the sparse distribution of stations and the spatial resolution can be improved significantly with increasing depth and reached the best resolution at the depth range of 120–700 km.

We obtained lateral variations of the P-wave velocity (Figures 2 and 3; also Figures 6 and 7, Paper 1) rela-

tive to the reference 1-D velocity model, which is a slightly modified Iasp91 Earth model (see Figure 4, Paper 1) beneath East Asia. Because of the uneven grid spacing (see Figure 3, Paper 1) and variable ray density the resolution is poor at the surface and near the bottom (1 000 km depth) of the model space and is the best between 100 and 700 km depth range. While the inversion results are presented in details in Paper 1, next we are going to focus on several important results of these tomography images and their geodynamic implications for the tectonics of East Asia.

4 Discussion

The most striking and interesting result of the tomography shown in cross sections of Figure 2 is that there are no fast P-wave velocity anomalies that can be related to the subducted oceanic slabs beneath the 660-km discontinuity. There is also no evidence for any penetration of subducted slabs into the lower mantle within the study area of East Asia. Although previous global tomography studies indicate that the subducted oceanic slabs are stagnant atop of the 660-km discontinuity beneath East Asia (e.g., Zhou and Clayton, 1990; Vinnik et al., 1996; Bijwaard et al., 1998; Karason and van der Hilst, 2000; Zhao, 2004), this regional study with much improved resolution makes this interpretation a robust result.

4.1 Western extent of the stagnant oceanic slabs

Tomographic results show clearly that the subducted oceanic plates (the Pacific and the Philippine Sea plates) in the western Pacific did not penetrate the 660-km discontinuity into the lower mantle (Figure 2). Instead, they become stagnant within the mantle transition zone and extend westward beneath East Asia as previously imaged by global tomography (e.g., Zhou, 1996; Zhao, 2004). The stagnant oceanic slabs extended westward up to 112°E at latitudes of 30°N–33°N (Figure 2a; also see Figures 7a and 7b, Paper 1) and 118°E at latitudes of 36°E–38°E (Figure 2b; Figures 7c and 7d of Paper 1), respectively. This western end of the stagnant slabs within the mantle transition zone is located at 122°E–125°E for the higher latitudes of 40°N–45°N (Figure 2c; Figures 7e–7f of Paper 1) in the northeast of China.

To correlate surface deformation of East Asia with our tomographic images of the stagnant slabs, we plot the velocity variations at 600-km depth against topography of east China in Figure 3. A sharp change in elevation of

Figure 2 Vertical cross-sections of lateral P-wave velocity perturbations at six different latitudes from the tomographic inversion. Major geologic features and volcanoes are marked at the top surface as a reference. Open circles are the earthquakes within 50 km distance from each cross section. The two major mantle discontinuities at 410 km and 660 km are also shown as two horizontal dashed lines. See text for detailed discussion.

larger than 1 500 m (shown as a thick black line) from the NNE trending Taihang Mountains and the Ordos block in the west to the low and flat topography of the North China basin in the east [that is, between the point of $\sim (30^\circ\text{N}, 112^\circ\text{E})$ and $(45^\circ\text{N}, 122^\circ\text{E})$, Figure 3a], correlates well with the western termination of the stagnant subducted Pacific and Philippine Sea slabs beneath eastern North China. This topographic break is coincident with a rapid change in both gravity anomalies and crustal thickness, and is often referred in the Chinese literature as the Great Gradient Line that separates the East China from the West China. It is interesting to note that the topographic break shows a right-step offset of about five longi-

tudinal degrees at 40°N and there seems to exist a similar right-step offset of the western end of the stagnant oceanic slabs at this latitude (Figure 3b). This NNE trending topographic boundary is in general parallel to the plate boundaries between Asian continent and the Pacific-Philippine Sea plates, and the right-step offset of the topographic front at 40°N seems to follow the shape of the trenches at the southwest of Japan (Figure 1).

4.2 410-km and 660-km discontinuities

The seismic discontinuities at a global average depth of 410-km and 660-km in the Earth's mantle have been generally attributed to the transformation of olivine into wadsleyite (β -phase of olivine) and ringwoodite

Figure 3 Topography map of East Asia (a) and tomographic image at 600 km depth (b), which shows the stagnant slabs. Note that the NNE trending topographic boundary is in general parallel to the plate boundaries between Asian continent and the Pacific-Philippine Sea plates, including a right-step offset at 40°N. The triangles denote seismic stations.

Figure 4 Stacked receiver functions along an east-west profile at 36°N in east China (From Ai and Zheng, 2003).

(γ phase of olivine) into perovskite and magnesiowustite, respectively (Ringwood, 1969; Ringwood and Irifune, 1988; Ito and Takahashi, 1989; Shearer and Masters, 1992; Flanagan and Shearer, 1998; Simmins and Gurrola, 2000; Lebedev et al., 2002; Jing et al., 2002). Mineral physics studies have shown that the 410-km phase boundary has a positive Clapeyron slope (dT/dP) whereas the postspinel phase boundary at 660-km has a negative Clapeyron slope (e.g., Ito and Takahashi, 1989; Ito et al., 1990). Therefore, the effect of a cold slab at a subduction zone could lead to elevating the 410-km boundary and depressing the 660-km boundary within the slab, respectively. The amplitude of the deviation of these discontinuities within the slab is proportional to the temperature difference between the cold slab and the ambient mantle at these depths. Combination of the 410-km and 660-km variations leads to a thicker mantle transition zone within a subducted slab with a steep dip angle.

The temperature anomalies associated with the stagnant oceanic slabs beneath most of East Asia as shown in Figure 3b should cause variations in these seismic discontinuities, such as deepening of the 660-km boundary over large areas of East Asia. Such variations have been reported in seismic studies using the P-to-S converted phases from temporary portable seismic networks at two different locations of East Asia (Ai and Zheng, 2003; Ai et al., 2003; Li and Yuan, 2003).

A temporary PASSCAL seismic network experiment was conducted from June 1998 to April 1999 in northeast China. The network had 18 broadband seismic stations and it covered an area of about 400 km in diameter centered at (42°N, 128°E), shown as a dashed line box in Figure 3b. This area is about a few hundreds

of kilometers west of the 600-km depth contour of the subducted Pacific slab. Receiver functions calculated from these broadband stations have revealed large variations in the seismic discontinuities (Ai et al., 2003; Li and Yuan, 2003). The stacked receiver functions across the network showed clear evidence for the deepening of the 660-km discontinuity by 20 km over the study area and by as much as 35 km at a small area at (43°N, 129°E). It also showed a deepening of the 410-km discontinuity with reduced magnitude relative to that of the 660-km discontinuity. The thickness of the mantle transition zone, which is the difference between the depths of the 660-km and the 410-km discontinuities, is large by more than 10 km in most of the area than the global average (Li and Yuan, 2003).

The deepening of the 660-km discontinuity across this local network could be explained by the presence of the stagnant Pacific slab above this boundary (Figure 3b) and the over 20-km change in 660-km depth would require a temperature anomaly of about 300°C of the stagnant cold slab relative to the normal mantle temperature at this depth. It seems possible since this area is only a few hundreds of kilometers west of the tip of the subducted Pacific slab, it should have a larger temperature anomaly than the stagnant slabs to the west.

The deepening of the 410-km discontinuity here was rather a puzzle since the subducted Pacific slab passed through this boundary a few hundreds of kilometers to the east of this network. Furthermore, any effect of the subducted slab should raise this boundary and not to depress it as seen in the stacked receiver functions (Li and Yuan, 2003). In a separate study by stacking SS precursors, Flanagan and Shearer (1998) also found that the 410-km discontinuity in this region was at > 430 km depths.

Using the data from the same PASSCAL seismic network plus four CNDN broadband stations, Ai et al. (2003) conducted a similar receiver function study of this area with slightly different approach. The high density of the seismic data allowed them to stack many receiver functions that have close piercing points (within a stacking bin) at the 660-km boundary. The stacked receiver functions showed a similar result of a depression of the 660-km discontinuity in the region but the data also indicate a multiple discontinuity structure of the 660-km boundary at the tip of the subducted slab. They interpreted this narrow region of the complex structure of 660-km boundary was caused by the slab penetrating into the lower mantle (Ai et al., 2003), which not only

leads to the breakdown of the γ -spinel but also involves non-olivine components such as reactions from garnet to ilmenite or from ilmenite to perovskite as suggested from mineral physics study (Vacher et al., 1998).

Here we offer an explanation to this significant deepening of the 410-km discontinuity at this region based on our tomography results of this study. This temporary PASSCAL seismic network is centered at 128°E near the Mishan-Dunhua fault zone, where tomography results show slow P-wave velocity anomalies in the crust and the upper mantle as shown in Figure 2b. These slow anomalies could be seen throughout the upper mantle and can be traced eastward up to the volcanic arc. These slow anomalies in the upper mantle could be related to the melting in the mantle wedge caused by the slab-derived volatiles at the subducting slab. More importantly, there is a slow anomaly at 410-km discontinuity just below the area of this network from 128°E to 132°E. We would like to suggest that the observed deepening of the 410-km discontinuity over this relatively large region (~400 km) is caused by the accumulated effects of these slow velocities within the upper mantle above the 410-km boundary. In particular, the maximum depression of the 410-km discontinuity by 30 km at 43°N and 130°E is enhanced by the positive temperature anomaly associated with the slow P-wave velocity anomaly at the 410-km discontinuity directly beneath it.

From November 2000 to August 2001, 54 portable broadband seismic stations were deployed in Shandong Province of eastern China as the North China Interior Structure Project (NCISP). The stacking of dense receiver functions along an east-west profile at 36°N reported by Ai and Zheng (2003) revealed strong signals from both the 410-km and the 660-km discontinuities as shown in Figure 4. The location of this stack profile is shown as an east-west line labeled as TT' in Figure 3a. The sharp 410-km discontinuity is flat with little evidence of perturbations. In contrast, the 660-km discontinuity shows a complex structure. From west to east, it changes from a single sharp boundary into a two-boundary structure at 117.5°E and then the two boundaries merge into one broad boundary east of 119.2°E. Phase transformations of non-olivine components at lower temperatures were suggested to be the cause for the multiple 660-km discontinuities (Ai and Zheng, 2003).

Our tomography results support this interpretation. As shown in Figure 2b for the profile at 36°N, the stag-

nant Pacific slab clearly extends westward up to 117.5°E, where the stacked receiver functions indicate a boundary between a single sharp 660-km discontinuity to the west and a multiple 660-km discontinuities to the east. Therefore, the region where a multiple 660-km discontinuities were detected by receiver functions (Ai and Zheng, 2003) correlates very well with the region of the stagnant cold slab revealed by our tomography. The negative thermal anomaly associated with the stagnant cold slab has not only depressed the average depth of the complex 660-km boundary but also made it possible for non-olivine reactions, which were suggested as the cause for multiple 660-km discontinuities by mineral physics study (Vacher et al., 1998).

We conclude that while the 410-km discontinuity may not be affected by the stagnant cold slab within the transition zone, the negative temperature anomaly associated with the stagnant cold slab could depress the 660-km discontinuity over a broad region of the East Asia. Previous receiver function studies in Asia seem to be consistent with this notion that the 660-km discontinuity in East Asia is depressed (e.g., Ai and Zheng, 2003; Ai et al., 2003; Li and Yuan, 2003) whereas there is little evidence for the depression of the 660-km boundary in western China (e.g., Kind et al., 2002). In a manuscript under preparation, Ai (personal communication) has stacked many receiver functions along two NNE trending profiles with a similar approach as in Ai and Zheng (2003). Both profiles are roughly parallel to the NNE trending boundary of surface elevation and tectonics shown in Figure 3a. One profile is about 400 km to the west of this boundary and the other profile is in the East China region connecting the two portable networks reported in Ai et al. (2003) and Ai and Zheng (2003), respectively. The stacked receiver functions along the east profile show clear evidence for the depression of the 660-km discontinuity for most of the region, an indication of the effect of the stagnant cold slab revealed by our tomography in this study. In contrast, the west profile shows little evidence for any broad depression of the 660-km discontinuity. These unpublished results (Ai, personal communication) support our conclusion based on the west extent of the stagnant oceanic slabs detected by seismic tomography in this study.

4.3 Penetrating the 660-km in northeast China?

One of the extensively debated issues in the past few decades is whether a subducting oceanic slab could penetrate the 660-km discontinuity into the lower mantle (e.g., Creager and Jordan, 1988; Anderson, 2000; Wen

and Anderson, 1995; 1997). Significant efforts have been focused on the convergent boundary along several subduction zones in the west Pacific, where seismic studies of the subducting oceanic plates have suggested contrary scenarios (Zhou and Clayton, 1990; van der Hilst et al., 1991; 1993; van der Hilst and Seno, 1993; van der Voo et al., 1999; Fukao et al., 2001; Zhao, 2004).

The above-mentioned receiver function studies of a similar data set collected from a portable seismic network in the northeast China have found a narrow zone (Ai et al., 2003) or a small area (Li and Yuan, 2003) at or near the tip of the subducted oceanic slab where the 660-km discontinuity was depressed as much as 35 km and the mantle transition zone was thickened by more than 20 km. Both studies had suggested that this local depression of 660-km boundary and the thickening of the mantle transition zone were evidence for the local penetration of the slab into the lower mantle.

We disagree with this interpretation. First, the rapid subduction (10 cm/a; DeMets et al., 1990) of the old (~130 Ma) Pacific plate along the Japan trench could have kept a cold and rigid core of the slab down to the 660-km depth, which is consistent with the well developed Wadati-Benioff zone of earthquake seismicity along the Japan subduction zone and a cluster of deep earthquakes at tip of the subducted slab. This cold and rigid subducting slab is well resolved in both previous global tomography studies (e.g., Zhou, 1996; Fukao et al., 2001; Zhao, 2004) and the regional tomography in this study (Figure 2c; also see Figures 7e and 7f of Paper 1). From the perspective of mechanics, it is unlikely that the rigid slab could exhibit such drastic different deformation style along the strike after it reaches the 660-km boundary, that is, most of the slab is piled up above the boundary whereas a small portion of the slab is continuing its journey into the lower mantle.

Second, the tomography results of this study show little evidence for any penetration of the subducted slab into the lower mantle in East Asia. All the slab-related fast velocity anomalies are above the 660-km boundary and there are no fast P-wave velocity anomalies that can be related to the subducted oceanic slabs beneath the 660-km discontinuity (Figure 2; also see Figures 6 and 7 of Paper 1). This observation is consistent with previous global tomography studies (e.g., Zhou and Clayton, 1990; Fukao et al., 1992; Zhou, 1996; Bijwaard et al., 1998; Zhao, 2004). Therefore, we conclude that the subducting Pacific and Philippine Sea plates along the

Japan and Nankai trenches did not penetrate into the lower mantle and instead, the stagnant slabs have extended subhorizontally above the 660-km discontinuity westward beneath the continent of East Asia although oceanic plates could penetrate into the lower mantle at other subduction zones such as at the northern Kurile (van der Voo et al., 1999) and at the Mariana (van der Hilst et al., 1991; van der Hilst and Seno, 1993).

4.4 Origin of the Cenozoic volcanisms in East Asia

The widespread volcanism since the Late Mesozoic in East Asia (Liu, 1999; Yin, 2000; Yin and Chen, 2004) is unique since it happened under an intra-plate setting without a clearly defined thermal structure as the source in the upper mantle. Some of the volcanoes are currently active such as the Changbaishan volcano and the Wudalianchi volcano in northeast China. There is no clear evidence from either geochemical or tomographic studies for any mantle plumes beneath this reactivated cratonic region (Basu et al., 1991; Liu et al., 1995; Xu et al., 2004).

Most common sources proposed for intra-plate volcanism are mantle plumes from lower mantle such as the Hawaii-Empire volcanic chains in middle of the north Pacific and the volcanism in South Africa within the interior of the African continental plate (Morgan, 1971). The tomography results of this study (Figures 2) show clearly the presence of the stagnant slabs within the mantle transition zone beneath most of the East Asian continent. These cold stagnant slabs could shield the northeast Asian continent from influence of a lower mantle plume. Therefore, it could be concluded from this study that the widespread intra-plate volcanism in East Asia is not originated from melting within a rising mantle plume from the lower mantle. In a recent study, although it only covered three localities and is far from conclusion, analysis of He isotopic data by Chen et al. (personal communication) showed Helium isotopic ratio in mantle xenoliths in NE China volcanics is relatively uniform and its value was close to the tight range of MORB, and lack of high- $^3\text{He}/^4\text{He}$ plume signature. We call for more geochemical studies that systematically examine different hypotheses for the origin of the geographically abundant Cenozoic volcanisms in East Asia.

The second type of volcanism at a continental margin is the arc volcanism above a subduction zone such as the Cascadia arc of volcanoes in the northwest of North America and the Andes arc of volcanoes along the west coast of the South America, where the oceanic Juan de Fuca and Nazca plates are subducting beneath the

North and South American continents, respectively. The volcanic arcs are usually located about a few hundreds of kilometers behind the trench and about 80–200 km above the subducting oceanic slab (e.g., Gill, 1981; Tatsumi et al., 1983; Tatsumi and Eggins, 1995).

The volcanic activities in East Asia are about 1 000–2 000 km from the trenches in the western Pacific. Is this intraplate volcanism related to the subduction of oceanic plates in the western Pacific? The answer is possible according to our tomography results, which show clear evidence for the connection of the slow velocity anomalies beneath these intraplate volcanic regions and the slow velocity anomalies beneath the volcanic arcs above the subducted oceanic slabs (Figures 2 and 3b; also see Figures 6 and 7 of Paper 1). Tomography has revealed slow P-wave velocity anomalies everywhere from the volcanic arc to the East Asia at depths of 100–250 km within the asthenosphere beneath the continental lithosphere of East Asia (Figure 6 of Paper 1). Cross section images of Figure 2 show these slow anomalies are well connected at depths of 200–300 km and they are all associated with the melting processes within the mantle wedge beneath the volcanic arcs.

Recently Zhao et al. (2004) obtained a detailed tomographic image under the active Changbai volcano in northeast China using teleseismic data recorded by a local network of 19 portable seismic stations. They detected a low-velocity anomaly of about 200 km wide extending down to 400 km depth right beneath the Changbai volcano. A high-velocity anomaly was observed in the mantle transition zone (410–660 km depth), which was considered to represent the stagnant Pacific slab under northeast China (Zhao et al., 2004), consistent with the tomographic results of this study. Both studies indicate that the intra-plate volcanoes in northeast China are not originated from a deep mantle plume like Hawaii, but a kind of back-arc volcanoes associated with the deep subduction of the oceanic slab and its stagnancy in the mantle transition zone under northeast Asia.

It is possible that the slab-derived aqueous fluid could be released continuously from the dehydration of the subducted oceanic sediments and crust up to 300–400 km depths as suggested for the Tonga subduction zone (Zhao et al., 1997), which has caused the melting of a large portion of the mantle wedge above the subducting slab, shown as strong slow velocity anomalies (Figure 2). The complex tectonic history of the plate boundary in the western Pacific, such as retreating of the

trench system and the rapid subduction here, could have invoked a vigorous convection in the mantle wedge. It is likely that this vigorous convection in the mantle wedge could extend westward, that is, including the asthenosphere beneath the East Asia, which could either effectively transport the melt generated in the mantle wedge above the slab laterally to the region beneath the East Asia or caused local asthenospheric melting to feed the volcanism on the surface of East Asia. Alternatively, the convection could transport the aqueous fluid laterally to the region beneath the East Asia, which then leads to melting of the continental mantle to feed the widespread volcanism in East Asia.

4.5 A “extended mantle wedge” model

These major results discussed above are summarized in a cartoon (Figure 5), which shows an “extended mantle wedge” model for the volcanism at both the volcanic arcs and the East Asia, and for the large-scale tectonics within the upper mantle of this region as well. The term of “extended” is relative to the horizontal extent of a typical mantle wedge, which is usually referred to the mantle above the subducting slab (e.g., Stern, 2002; van Keken, 2003). Here we suggest that vigorous mantle convection is operating within this horizontally expanded “mantle wedge” above both the active subducting slab in the western Pacific and the stagnant slab beneath much of the North China plain.

The large horizontal dimension of the convection is unique among the worldwide subduction zones, which is probably resulted from the combined effects of the large horizontal extent of the stagnant oceanic slabs above the 660-km boundary and the tertiary extension in East Asia associated with the eastward migration of the trench system. The northward intrusion of the Indian mantle beneath the Asian continent has caused both southward extrusion of the mantle toward the South China Sea and eastward flow of the mantle in central and north China (e.g., Flower et al., 1998; Cui et al., 2004), which might have further encouraged this rather large-scale convection above the subducted and stagnant flat oceanic slabs beneath East Asia.

We postulate that the stagnant flat slab above the 660-km discontinuity was the consequence of the rapid eastward migration of the trench system in the western Pacific since the beginning of the Cenozoic. The trench retreat has effectively slowed the sinking velocity of the slab; the slab becomes warmer and weaker, and thus may not penetrate the 660-km boundary. As a consequence, the slab was piled up at the 660-km boundary

Figure 5 Cartoon of a “Bigger Mantle Wedge” model that summarizes all the major features of East Asia and possible correlations between the regional tectonics on the surface and seismic velocity anomalies at depth, particularly the subduction processes in the western Pacific. The gray shaded area indicates a typical mantle wedge, that is, the mantle above a subducting slab. The shaded areas show the bigger mantle wedge, a horizontally extended mantle wedge that includes mantle above both the subducting slab and the stagnant flat slab. The cold stagnant slab caused a broad depression of the 660 km boundary and the convective flow within the large mantle wedge would be responsible for the low and flat elevation at the surface relative to the high and rough topography to the west. The bigger mantle wedge could also be responsible for both the arc volcano and the intra-plate volcanoes in the low land of East Asia.

instead. Thus we suggest that the stagnant flat slabs beneath the East China seen in our tomography images were Cenozoic subducted oceanic slabs that did not penetrate into the lower mantle. On the other hand, the sinking of the Cenozoic subducted oceanic slabs caused asthenospheric upwelling within this horizontally expanded mantle wedge, resulting in partial melting beneath the lithosphere seen as low velocity anomalies in our tomography images, which was in turn responsible for the Cenozoic volcanism in East Asia. That is, our model suggests that the Cenozoic volcanism in East Asia was originated from asthenospheric melting that is consistent with published geochemical studies (e.g., Xu et al., 2004).

The west end of this big-mantle-wedge convection is probably located above the western end of the stagnant flat oceanic slab (Figure 5). This western boundary is correlated with the NNE trending topographic boundary that separates the surface elevation and tectonic features of the east China from the west China. We postulate that both the widespread volcanism associated with Cenozoic extensional basins and the general low and flat elevations in East Asia are the surface manifestation of this vigorous convection within this horizontally extended mantle wedge beneath the continental lithosphere. The negative thermal anomaly associated with the stagnant flat slabs above the 660-km discontinuity has not only caused a broad depression of this boundary due to its negative Clapeyron slope but also effectively shielded the asthenosphere and the continental lithosphere in East Asia from any possible influence of mantle plumes in the lower mantle, if there is any (see, for

example, Zhao, 2004).

The NNE trending topographic boundary is also known as the Daxing'anling-Taihang Gravity Lineament (DTGL) among the Chinese literatures, which was named after the first-order linear feature in the gravity anomaly map of China. Along the DTGL, the Bouguer gravity anomaly has a large gradient (Ma, 1989), indicating a significant change in crustal thickness and mantle densities from western provinces to eastern region of China. While Cenozoic basalts from both sides of the DTGL have compositions that are consistent with a dominant asthenospheric source, their temporal variations in depths and degrees of melting have shown a large difference across this boundary (Xu et al., 2004). In the region west of DTGL, magmas evolved from xenolith-bearing alkali basalts during late Eocene-Oligocene to (subalkaline) tholeiitic basalts of late Miocene-Quaternary age, and the opposite trend is observed for Cenozoic basalts from the region east of DTGL. This contrasting trend seen in the Cenozoic basalts across the DTGL was taken as the evidence for diachronous extension (or delayed extension from east to west), with an initial extension in the region east of DTGL and subsequent extension in the region west of DTGL (Xu et al., 2004). These geochemical observations are in general consistent with our model presented here. The observed increase in alkalinity with time in the Cenozoic basalts from the eastern China could be related to the extensive extension in Paleogene along the continental margin as well as back-arc spreading due to the eastward migration of the trench system in the western Pacific and the subsequent cooling in Neogene as

the back-arc extension associated with the trench retreat stopped about 15 Ma ago. The thermal structure could have been strongly influenced by the variations of extension activities, which leads to a decrease in the degree of partial melting and an increase in the depth of melting from Paleogene to Neogene as seen in the basalt samples in the region.

China has recently rapidly expanded its seismic networks with both permanent and portable broadband seismic stations. Data with good coverage in the much-needed areas of the north and northeast of China will become available within the next few years. China has also made significant progress in data sharing and we are in a process of expanding our database to include data recorded from several local networks (permanent and portable) in the North China, which became accessible to us recently. Therefore, future improvement is to expand our database to increase the coverage in the north and northeast of China, where the current resolution is rather poor. Important effort should also be focused on how to better resolve the western extent of the stagnant slabs beneath the East Asia and its correlation with the surface NNE trending boundary, which is the first order feature (and it is so obvious) in the surface topography map of Asia.

5 Conclusions

The most important result of this regional tomography is that there are no fast P-wave velocity anomalies that can be related to the subducted oceanic slabs beneath the 660-km discontinuity. All the slab-related high velocity anomalies are above the 660-km boundary and there is no evidence for any penetration of the subducted slabs into the lower mantle beneath the East Asia. Tomographic results show the subducted oceanic slabs have become stagnant within the mantle transition zone and extended subhorizontally westward beneath the East Asian continent. While this result was suggested by previous global tomography studies, the improved resolution of this regional tomography has made it as a robust conclusion.

The western end of the stagnant oceanic slabs above the 660-km discontinuity correlates well with the NNE trending topographic boundary that separates the high altitude Ordos plateau to the west and the low elevation Huabei basin in the east. Because this tectonic feature formed in the Cenozoic during Paleogene back-arc extension, P-wave velocity structures below likely formed in the Cenozoic. Our tomographic results

have also revealed low P-wave velocity anomalies at depths of 100–250 km within the asthenosphere from the volcanic arc to the East Asia and more importantly, these slow anomalies are well connected and can be traced back to the slow anomalies beneath the volcanic arcs, where they are associated with the well-known flux melting due to the slab-derived aqueous fluid from dehydration of the subducted oceanic sediments and crust (e.g., Iwamori, 1998; Iwamori and Zhao, 2000; van Keken, 2003).

A simple model, the big mantle wedge model, is postulated based on all these observations and the complex tectonic history of the East Asia. In the model, a vigorous convection is occurring within this horizontally expanded “mantle wedge” above both the subducting and stagnant slabs. This horizontally expanded convection was probably resulted from both the eastward migration of the trench system and the large horizontal dimension of the stagnant slabs within the transition zone beneath the East Asia. The west boundary of this big-mantle-wedge convection is probably located above the western end of the stagnant oceanic slabs, which is also correlated well with the NNE trending surface boundary of the East China. Both the widespread volcanism associated with Cenozoic extensional basins and the low, flat average elevations in East Asia are probably the surface manifestation of this vigorous convection beneath the continental lithosphere. The negative thermal anomaly associated with the stagnant slabs above the 660-km discontinuity has probably not only caused a broad depression of this boundary due to its negative Clapeyron slope but also effectively shielded the asthenosphere and the continental lithosphere in East Asia from any possible influence of mantle plumes in the lower mantle.

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