Tomographic structure of East Asia: I. No fast (slab) anomalies beneath 660 km discontinuity*

Shunping Pei^{1,2} and Yongshun John Chen^{2,†}

¹ Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China

² Computational Geodynamics Laboratory, Department of Geophysics, School of Earth and Space Sciences, Peking University, Beijing 100871, China

Abstract This is the first of two papers that describes a regional tomography investigation, which combines P-wave arrival times of both regional and teleseismic earthquakes to obtain 3D mantle structures of East Asia up to 1 000 km depth. The most important findings of this tomography study are reported in this paper as follows. (1) No fast P-wave velocity anomalies can be related to subducted oceanic slabs beneath the 660 km discontinuity; instead the subducted oceanic slabs become flattened and stagnant within the transition zone. (2) The high velocity anomalies in the transition zone extend up to 1 500 km to the westward of the active trenches, which is a unique feature in the worldwide subduction systems. (3) Slow P-wave velocity anomalies are visible up to ~250 km underneath most of the East Asia on the east of 115°E, similar to the area of the stagnant slabs. These observations have important implications for the geodynamic process at depths beneath the East Asia, which might in turn control the widespread Cenozoic volcanism and associated extensional tectonics seen at the Earth's surface.

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 expressed by the development of large-scale strike-slip faults, rifts, volcanic fields, 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, 1978; 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, 2000; Ren et al., 2002; Hall, 2002).

Although the tectonics of North China (Figure 1) has been the focus of many studies over the past three

decades, most of these efforts have focused on crustal structures (e.g., Jin et al., 1980; Ma et al., 1983; Feng and Zheng, 1987; Ye et al., 1985, 1987; Tian et al., 1992; Yin and Nie, 1993, 1996; Zhu and Zheng, 1990; Zhang et al., 1996; Gao and Ma, 1993; Zhou and Graham, 1996; Hall, 1997; Zhang et al., 1998a, 1999; Li, 2000; Huang et al., 2002; Wang et al., 2003; Huang and Zhao, 2004, 2006; Sun et al., 2004; Yu et al., 2010). For example, although over more than twenty seismic reflection profiles had been surveyed in the North China region (e.g., Zhang et al., 1994, 1998; Li and Mooney, 1998; Sun et al., 1988; Li et al., 2001; Duan et al., 2002), little effort has been devoted to the study of the mantle structure beneath many of the well-known surface tectonic and geologic features. These include the NNE-striking Tanlu fault along the east side of North China, the N-trending Shanxi rift, and widespread Cenozoic volcanic fields in North China and its neighboring regions such as Mongolia and SE Siberia (Figure 1). Previous P-wave travel time tomographic studies (Liu et al., 1990; Liu and Jin, 1993) had obtained 3D velocity structure beneath the Chinese mainland, which is in general consistent with

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† Corresponding author. e-mail: johnyc@pku.edu.cn

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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. Volcanoes are also shown as triangles in red, and the solid triangles numbered is Wudalianci, Changbaishan, Huangyishan, Hannuoba, Datong, Penglai and Tengchong volcanoes in turn. North China is part of the Sino-Korean craton, which separates from the South China, known as the Yangtze craton, by the ESE trending Qinling-Dabie belt.

the inversion of lithospheric structures of China using surface waves data (Zhu et al., 2002). Similar to previous global tomographic studies, the coarse resolution of these (China) countrywide studies did not provide us enough information to examine the mantle structures beneath North China.

To illuminate the possible role of subduction in the western Pacific in Cenozoic deformation in East Asia, we examined three-dimensional (3D) mantle structures beneath East Asia by inverting P-wave arrival times. A similar attempt has been carried out recently for the western China (Xu et al., 2002). This is the first 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. This paper describes the data and inversion method with resolution tests, and presents important inversion results. A subsequent paper, hereafter referred to as paper 2 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). North China is part of the Sino-Korean craton, which is separated from the South China, known as the Yangtze craton, by the E-W trending Qinling-Dabie belt. In order to provide a general background for the study, we briefly review the Cenozoic geologic history of the region below.

Between 65 and 15 Ma B.P., deformation in East Asia is dominated by north-south contraction in Tibet and Tianshan (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 B.P., the eastern margin of Asia has become mostly contractional as expressed by the collapse of several back-arc

basins (e.g., Japan Sea and South China Sea) and development of contractional structures along their margins (Ren et al., 2002; Hall, 2002). Coeval with this late-phase continental-margin contraction is the occurrence of widespread east-west extension in the interior of Asian continent including the Tibetan plateau, North China (i.e., the Shanxi and Yinchuan rifts), and south-east Siberia (Baikal rift). This change in deformation pattern within and along the eastern margin may be explained by a change in the boundary conditions along the eastern margin of Asia that is related to the presence and absence of back-arc spreading (Yin, 2000; Chen, 2004).

North China experienced significant lithospheric thinning in the 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). 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 Riffits, 2002) and the formation of the Paleogene Huabei basin (Figure 1). The latter is covered mostly by post-rifting Neogene-Quaternary sediments. The Huabei 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 are first-order tectonic features in East Asia with multiple slip histories since the Late Permian (Yin and Nie, 1993, 1996; Li, 2000). Opening of the Huabei 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).

The South China block is located at the south of the Triassic Qinling-Dabie orogenic belt that was reactivated by left-slip faulting in the Cenozoic (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). In the 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 Asian continent beneath the Manila trench. This is fundamentally different from the tectonic setting of North China and the northeastern part of South China that lie in the over-riding plate above a subduction zone.

3 Data collection

We collected the P-wave arrival times that were recorded by 688 seismic stations of the International Seismological Center (ISC) and Chinese seismic networks (Figure 2a). Regional events used in this study consist of 8 002 shallow and intermediate-depth earthquakes within the study area of 20°N–55°N and 100°E–145°E. They were selected from three sources, including the ISC Bulletin of 1964–2001 compiled and published by ISC, the Annual Bulletin of Chinese Earthquakes (ABCE) of 1985–1998, and the temporary report of Chinese earthquakes of 1999 to 2001. These regional events are combined with 9 000 teleseismic events

Figure 2 (a) Distribution of stations (triangles) and earthquakes (circles) within the study area of East Asia. (b) Teleseismic events in a Lambert azimuthal equal-area projection, where the study area is also shown for reference.

between 1964 and 1999 occurred outside our study region with epicentral distances of 30° – 100° (Figure 2b). We also collected several thousands of P-wave arrival times recorded by Chinese regional networks in north-eastern China to improve the ray coverage there. The earthquakes occurred during 1964–1999 were relocated by Engdahl et al. (1998) and the locations of the rest events were extracted from catalogues in ABCE. In total, we had selected about 400 000 P-wave arrival times from 8 002 regional earthquakes and about 370 000 P-wave arrival times from 9 000 teleseismic events. The absolute residuals for regional earthquakes and the relative residuals for teleseismic events used in the inversion are less than 5 s and 2 s, respectively. Most of the events are located in subduction zone from 600 km to surface and the depth of earthquakes in Chinese mainland is usually less than 30 km.

Selection of teleseismic events was based on the criteria that an individual earthquake has to be recorded not only by at least 10 stations but also by at least one station of the Chinese seismic networks. The latter requirement is because the station distribution is highly uneven in the study area, sparse in China but much denser in Japan (Figure 2a).

4 Methods

4.1 Inversion method

We have applied the tomography method of Zhao et al. (1992, 1994) of combining residuals of regional earthquakes with relative travel time residuals of teleseismic events to invert for three-dimensional variations in P-wave velocity beneath East Asia.

Taking into account the distribution of seismic stations (Figure 2a), we discretized the model space with a grid spacing of 1° – 2° in horizontal direction and of 10–50 km in depth (Figure 3). A slightly modified IASP91 Earth model (Kennett and Engdahl, 1991) was used as the starting 1-D velocity model (Figure 4), then lateral variations in P-wave velocity structure at each grid depth were obtained by the tomographic inversion of Zhao et al. (1994).

The crust is modeled as one layer with a global mean velocity of 6.3 km/s (shown in Figure 4) since complete information about the variations of the Conrad discontinuity within the study region is not available. The uppermost mantle immediately beneath the Moho discontinuity is assigned a slightly lower P-wave velocity of 7.9 km/s than the IASP91 model (Figure 4) since

Figure 3 The model 3D grid with horizontal and vertical spacing. A geological map is also shown at the upper surface for reference.

Figure 4 Slightly modified- and unmodified-IASP91 Earth model for the P-wave velocity as a function of depth.

previous studies have shown that Pn velocity is generally low in East China (Wang et al., 2003; Pei et al., 2004a, b, 2007). Finally, Moho depth variations in the region obtained from deep seismic reflection studies (Teng et al., 2003) were incorporated in the tomographic inversion.

The residuals of regional earthquakes as a function of epicentral distance were derived according to the slightly modified IASP91 model. The average and standard deviation of travel time residuals are 0.006 s and 2.4 s, respectively. Only the data with residuals falling between -5 s and $+5$ s were used in the inversion, which resulted in about 400 000 P-wave arrival times from 8 002 regional earthquakes. The cutoff value of 5 s was chosen to be about twice of the standard deviation of 2.4 s of the data.

For the teleseismic events outside of the study region (Figure 2b), we adopted the approach of relative travel time residuals of Zhao et al. (1994) to minimize both the effect of uncertainties in source parameters such as errors in hypocentral locations and origin times, and the effect of velocity heterogeneities outside the model space. Theoretical travel times are calculated using the slightly modified- and unmodified-IASP91 Earth model inside and outside the model space, respectively. For each teleseismic event, a mean residual is first calculated as the average of the residuals of all stations in the study region. A relative travel time residual of this event at each station is then calculated by removing this mean residual from the residual at this station. In this way, we obtain the average and standard deviation of

relative residuals are 0.019 s and 1.44 s, respectively, and then we only choose the data with residuals falling between -2 s and $+2$ s in the inversion. This sub-data set consists of about 370 000 P-wave arrival times from 9 000 teleseismic events.

The combination of travel time residuals of regional earthquakes and relative travel time residuals of teleseismic events were used in the tomographic inversion to determine the 3D P-wave velocity structure inside the model space. The combination of these two sets of rays increases the total number of ray crossings and as a result, a significant improvement of the resolution of the inversion will be realized. The LSQR algorithm of Paige and Saunders (1982) was used to solve the large and sparse system of linear equations (Zhao et al., 1994).

We conducted a number of inversions with different values of the grid spacing and the damping parameter. We found that the overall pattern of the obtained tomographic images is quite stable for the grid spacing shown in Figure 3 and the optimal damping parameter is 150. The P-wave velocity perturbations are then calculated from the average 1-D velocity model at each grid depth. After the inversion the standard deviation of travel time residuals of regional and teleseismic events was decreased from 2.4 s to 1.9 s and from 1.44 s to 1.26 s, respectively.

4.2 Checkerboard tests

Conventional checkerboard tests (e.g., Zhao et al., 1992, 1994) were conducted to evaluate the effects of ray coverage and spatial resolution. An initial checkerboard velocity model was created by assigning positive and negative velocity anomalies to the 3D grid nodes of the model domain. Synthetic arrival times were calculated according to the initial model with the same number of earthquakes, stations, and ray paths as that used for the tomographic inversion of the real data. These synthetic arrival times were then inverted for the checkerboard 3D variations in the P-wave velocity using the same algorithm as that used for the inversion of the real data. The spatial resolution is considered to be good for the region where the checkerboard pattern is well recovered. Results of a checkerboard test are shown in Figure 5 for different depth layers.

As we have expected, the spatial resolution at shallow depth (~ 10 km) in the upper crust is rather poor (Figure 5a) throughout the study region because of the sparse distribution of stations (Figure 2), except along the Japan and the Nankai subduction zones where ex-

tensive seismic activity and a dense station coverage within Japan provided more ray paths at shallow depths. The spatial resolution was improved significantly with increasing depth of 60–120 km in the upper mantle (Figures 5b and 5c). The best resolution obtained in this study for the East Asia mantle structure is at the depth

range of 300–700 km, where the initial checkerboard velocity variations were well recovered as shown in Figures 5d–5f. The worst resolution at all depths is for the region to the north of 45°N because of fewer stations and fewer ray paths at these high latitude areas.

Figure 5 Lateral variation in the P-wave velocity for checkerboard tests for layer depths of 10–700 km.

5 Results

We obtained lateral variations of the P-wave velocity (Figures 6 and 7) relative to the reference 1-D veloc-

ity model (Figure 4) beneath East Asia. Huang and Zhao (2006) also obtained similar results. Horizontal and vertical resolutions of the P-wave velocity perturbations are about 80–200 km and 20–50 km, respectively, which

Figure 6 Two-dimensional images of lateral P-wave velocity perturbations at different depths from the tomographic inversion. Major geologic features and plate boundaries are shown as a reference. Earthquakes occurred either 50 km above or below the depth of each layer are shown as open circles and volcanoes are also shown in open triangles (pink). See text for detailed discussion.

Figure 7 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.

vary with depth because of the uneven grid spacing (Figure 3) and variable ray density. In general, 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 km and 700 km depth range. We next describe the results systematically, starting with 2-D images at different depths from surface downward and then moving to cross sections at different latitudes from south to north.

5.1 Horizontal slices

Although checkerboard tests indicate a rather poor resolution near the surface (Figure 5a) some correlations between inverted images and geological features seem to exist. Most of the prominent geological features in the North China region are associated with low P-velocity anomalies near the surface (Figure 6a). This is evident for the North China and Songliao basins, Shanxi rift, and the Tanlu fault zone. Most of the active volcanoes in North China are associated with low P-velocity anomalies. For example, both the prominent low velocity anomaly beneath the Datong volcano (40°N, 113.28°E) in the Shanxi province and the less prominent low velocity anomaly beneath the Penglai volcano (37°N, 121°E) in the eastern Shandong province could reflect a thermal anomaly or the presence of magma bodies in the upper crust beneath the volcanoes. Not to mention, the volcanic arcs along the Japan and Nankai subduction zones have low P-velocity anomalies in the upper crust.

At 60 km depth (Figure 6b), the dominant high P-velocity anomalies within the uppermost mantle reflect the continental lithosphere of East Asia, except at a few active volcanoes, such as the Penglai volcano and the Huangyishan volcano (41°N, 125°E) in the north-eastern China. The “rigid” Ordos block shows a prominent high P-velocity anomaly and so does the Sichuan basin. Overall, the high P-velocity anomalies in the eastern China are correlated with the mantle lithosphere of the Asian continent, which is believed to be at least 90 km thick in this region (Menzies et al., 1993; Griffin et al., 1998; Xu, 2001). The subducted Pacific plate and the Philippine Sea plate are well imaged to be associated with high P-velocity anomalies. An interesting feature is the apparent gap in the high P-velocity anomalies associated with the subducted plates in the central Japan, where the Philippine Sea plate was reported to be subducted at a very shallow angle (Ishida, 1992).

At 120 km depth (Figure 6c), the P-velocity anomalies are changed from predominantly high velocity anomalies at 60 km depth within the mantle litho-

sphere to predominantly low velocity anomalies beneath the thinned lithosphere of the Huabei basin. In contrast high velocity anomalies exist beneath the Ordos block and the region to the south of the Huabei basin, low velocity anomalies are also present beneath both the Yinchuan and Shanxi rifts on both sides of the Ordos block and below the Bohai bay (see Figure 1 for locations). The latter extends continuously eastward and links with low velocity anomalies beneath the Japan Sea and Japan arc (Figure 6c). The Bohai bay extensional system was reported to extend both southward to the East China Sea and westward to the Huabei basin (Zhao and Windley, 1990; Allen et al., 1997; Ren et al., 2002), which is correlated very well with the strong low velocity anomalies beneath the Bohai bay that is also extending both to the west and to the south. Low velocity anomalies also occur beneath the northern Philippine Sea plate, which is above the subducted Pacific plate along the Izu trench. The low velocity anomaly to the north of central Japan may be related to subduction of the Pacific plate along the Japan trench (Zhao et al., 1994). Apparently the subducted Philippine Sea plate does not have a signature at this depth beneath central Japan, which may be a result of subduction of the Philippine Sea plate at a very shallow angle there (Ishida, 1992). Recently, Zhao et al. (2004a) imaged the aseismic portion of the subducting Philippine Sea plate under southwest Japan, which can be traced down to at least 200 km depth.

The P-velocity anomalies at 210 km depth (Figure 6d) are very similar to those at 120 km depth. Most of East Asia, including the eastern China and the western Pacific marginal seas, exhibits low P-velocity anomalies. However, the region beneath the Ordos block and the South China block still shows high P-velocity anomalies. The subducted Pacific and Philippine Sea plates are both well imaged at this depth, which can be correlated with the earthquakes within the Wadati-Benioff zone (Engdahl et al., 1998). The Philippine Sea plate to the north of 26°N is underlied by a dominant low P-velocity anomaly. A strong low P-velocity anomaly also exists beneath most of the east coast of China.

At 300 km depth (Figure 6e) the subducted Philippine Sea plate is not well resolved (Could this depth be the lower limit for its subduction?), but the subducted Pacific plate is still clearly imaged to the west of the Japan and the Izu arcs. The dominant low P-velocity anomaly beneath the northern Philippine Sea plate remains visible. Most of southeastern China in the south-

ern South China block exhibits low P-velocity anomalies whereas similar low P-velocity anomalies are at shallower depths beneath the Huabei basin (Figure 6c). The high P-velocity anomalies beneath the Ordos block and the Qinling region to the south remain at this depth.

At depths of 450–600 km (Figures 6f and 6g) most of the low velocity anomalies at depths of 120–400 km in the eastern China, East China Sea, and the Japan Sea are changed to high velocity anomalies. There is a good correlation between the northeastern boundary of this prominent high velocity anomaly beneath East Asia at 600 km depth (Figure 6g) and the contour of 600 km depth of the subducted Pacific plate along the Japan trench, inferred from subduction earthquakes (Gudmundsson and Sambridge, 1998). The result shown here that the subducted Pacific and Philippine Sea plates have extended westward to 115°E–120°E beneath North China region is consistent with previous global tomography studies (e.g., Zhou and Clayton, 1990; Bijwaard et al., 1998; Zhao, 2001, 2004). Low P-velocity anomalies are mostly limited to the South China region and in the western and southwestern parts of the study area.

At 700 km depth just beneath the 660 km discontinuity (Figure 6h), which separates the upper and lower mantle, no clear high P-velocity anomalies are present. A NNE-trending low P-velocity anomaly zone extends from East China Sea at the latitude of Shanghai to the western Japan Sea at the latitude of North Korea where a cluster of deep earthquakes (~650 km) mark the tip of the Wadati-Benioff zone of earthquake seismicity (Engdahl et al., 1998). Within this zone there is a noticeable low P-velocity anomaly beneath the southwestern tip of Korean peninsula. Whether it is associated with a thermal anomaly with a lower mantle origin is beyond the scope of this study and needs to be further explored by global tomography (e.g., Montelli et al., 2004; Zhao, 2004).

The most striking and interesting result of the regional tomography shown in Figure 6 and in cross sections of Figure 7 is that there are no fast P-wave velocity anomalies that can be related to the subducted oceanic slabs beneath the 660 km discontinuity, which will be described next. 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 study with much improved resolution makes this interpretation a robust result.

5.2 Cross sections

While 2-D P-wave velocity perturbations at different depths provide us the map view of the lateral velocity variations, vertical cross sections help link surface geology directly to deep crustal and mantle structures. Six east-west cross sections are shown in Figure 7 at latitudes of 30°N, 33°N, 36°N, 38°N, 41°N, and 43°N, respectively. Also denoted at the surface are important tectonic features including marginal seas, major fault zones, and Cenozoic volcanoes (red triangles). Earthquakes (open circles) shown are those with their hypocenters within 20 km distance from the cross section.

All the cross sections of Figure 7 show a strong low P-wave velocity anomaly in the mantle wedge above the subducting slabs. This low velocity anomaly in general extends to the upper mantle above the 410 km transition zone, a result consistent with the high-quality tomography study of the Tonga subduction zone (Zhao et al., 1997).

Along the 30°N profile (Figure 7a), the Pacific and the Philippine Sea slabs are subducted westward to the depth of 410 km and become stagnant between 410 km and 660 km and extend westward up to 110°E. This is a robust result and is shown on all cross sections with different westward extension between 110°E and 120°E. The low velocity anomalies below the Japan and Ryukyu arcs at depths of 100–300 km can be extended westward beneath Japan Sea, East China Sea, and the eastern part of North China. This pattern suggests that the low velocity mantle wedge could have a horizontal extent over 1 000 km distance from the active arc.

While both Izu and Nankai arcs are related to the low velocity anomalies below (as shown clearly in local and regional tomography studies of Zhao et al. (1992, 1994)), the two volcanoes in the eastern China, the Xinchang volcano (Figure 7a) and the Jiashan volcano (Figure 7b), do not have a low velocity anomaly in the crustal region beneath them. The Sichuan basin and the North-South Seismic Belt, where a cluster of crustal earthquakes occurred (Figure 7a), are associated with high P-wave velocities in the crust and the upper mantle. While the South China block seems to have low velocity anomalies within the upper mantle above the mantle transition zone shown at the cross section of 30°N, it has a robust high velocity anomaly in the upper mantle at the cross section of 33°N, reflecting a complex geologi-

cal setting of the cratonic South China as shown in recent tomography images (Liu et al., 2000). Note the subducted Philippine Sea plate only reached to a depth of about 150 km at the cross section of 33°N (Figure 7b) although it could be traced down to the transition zone at the cross section of 30°N (Figure 7a).

The Ordos block and its eastern boundary, the Shanxi rift zone (Figure 1) are associated with fast and slow velocities extending to the depth of >200 km, respectively (Figure 7c). Except for large slow velocity anomaly above the subducted Pacific slab associated with the well-known flux melting, there are two strong slow velocity anomalies at the cross section of 36°N (Figure 7c): one is in the upper mantle of 150–450 km depth range near the western end of the cross section at 102°E beneath a strong fast velocity of the continental lithosphere, and the other is just beneath the subducted Pacific slab within the 250–450 km depth range at 140°E–143°E near the eastern end of the cross section. A similar slow velocity was found beneath the subducted slab under central Japan (Zhao et al., 1994; Zhao, 2004). As suggested by Zhao et al. (1994) and Zhao (2004) the slow velocity anomaly could be caused by a thermal anomaly associated with a small-scale mantle plume, which was capped at the top by the old and thick oceanic slab, preventing the plume from reaching the Earth's surface.

The cross section at 38°N (Figure 7d) is an important profile since it crosses many important tectonic features in East Asia. The subducted Pacific slab is well resolved, which correlates very well with the Wati-Benioff zone of earthquake seismicity. The deep earthquakes occurred above the 660 km discontinuity, where the slab pounded and remained but extended westward, which can be clearly traced up to 118°E, beneath the Tanlu fault zone, and possibly up to 114°E beneath the Jingxing volcano. At the western end of the cross section the strong continental lithosphere of both the Qilian mountain fault zone and the Ordos block are clearly resolved by the inversion. The Shanxi rift zone and the Penglai volcano region in the east of the Shandong peninsula are connected with both crustal and upper mantle slow velocities extending down to at least 250 km depth. The slow velocity anomalies above 300 km depth in the mantle wedge are clearly visible and are extended westward to the Shanxi rift zone at 112°E. An interesting feature is that the Huabei basin to the west of Tanlu fault zone has a fast velocity anomaly in the upper man-

tle shallower than 80 km, which probably marks a strong continental lithosphere beneath this part of the Huabei basin. Notice that two clusters of earthquakes are located at both the eastern and western boundaries of the Huabei basin.

The two high-latitude cross-sections at 41°N and 43°N of Figure 7 show a similar result as the rest of the cross sections, except that the stagnated Pacific slab above the 660 km discontinuity only extends westward up to Yanshan mountain at 118°E. The continental lithosphere of both the Ordos block and the Korean peninsula is shown as a fast velocity anomaly. Both the Hannuoba and the Huangyishan volcanoes are associated with slow velocity anomalies at shallow depth, which in turn seems to be connected to the slow anomalies in the mantle wedge at 200–300 km depths (Figure 7e). There is likely to be a large slow velocity anomaly beneath the Ordos block and the Yinshan mountain at 150–400 km depths (Figure 7e). Another slow velocity anomaly is seen beneath the subducted Pacific slab at 143°E, similar to the one at the 36°N cross section. Whether these slow velocity anomalies have a deep origin needs to be further explored with better resolutions.

5.3 Restoring resolution tests

To evaluate the reliability of the three most important results of our tomographic study, that is, the fast anomalies of the stagnant slabs above the 660 km discontinuity, the slow anomalies at depths of 100–250 km, and no fast (slab) anomalies beneath the 660 km discontinuity, we have performed synthetic tests for these three features.

Here an initial model with a subducting and stagnant slab and a slow anomaly above it (Figure 8a) is used to compute the synthetic “data” of the P-wave arrival times using the 3D ray tracing method. The synthetic data with random errors of 1 s added are then inverted using the same inversion algorithm and the same control parameters to obtain the “restoring images”. Although these are 3D synthetic tests Figure 8b only shows one cross section at 36°N.

As shown in Figure 8b both the subducted and stagnant slabs are well resolved by the inversion, which further indicates that this is a robust result of this study. The slow anomalies at shallow depths of upper mantle are reasonably recovered while some of them are smeared into the region below the initial model location. This test suggests that these two important features of this study are indeed reliable. We also test that if a sub-

ducted slab has penetrated the 660 km boundary into the lower mantle in this region, the fast (slab) anomaly can be resolved beneath 660 km depth. The fact that large fast anomalies were present within the transition zone in our study region (Figure 7) and there is no clear sign for

the fast (slab) anomalies beneath the 660 km discontinuity (Figure 7) is consistent with the conclusion that the subducted slab in East Asia did not penetrate into the lower mantle and instead, it remains stagnant above the 660 km discontinuity.

Figure 8 Initial model (a) and restoring image (b) of the synthetic tests of the two important features at latitude of 36°N. Random noises with a Gaussian distribution that has a standard deviation of 1.0 s and a zero mean, were added to the synthetic data. Both the subducted and the stagnant flat slab and the slow anomalies at shallow depths of upper mantle are reasonably recovered, indicating that these two important observations are indeed reliable.

6 Conclusions

The most important finding 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 fast 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 of this tectonic feature formed in the Cenozoic during Paleogene back-arc extension, P-wave velocity structures below

was 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).

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