Shear-wave velocity structure of the crust and uppermost mantle in the Shanxi rift zone

Meiqing Song · Yong Zheng · Chun Liu ·
Li Li · Xia Wang

Received: 19 November 2014 / Accepted: 21 March 2015 / Published online: 9 April 2015
© The Author(s) 2015. This article is published with open access at Springerlink.com

Abstract The Shanxi rift zone is one of the largest and active Cenozoic grabens in the world, studying the velocity structure of the crust and upper mantle in this region may help us to understand the mechanisms of rift processes and the seismogenic environment of active seismicity in continental rifts. In this work, using the broadband seismic data of Shanxi, Hebei, Henan, Shaanxi provinces, and the Inner Mongolia Autonomous Region from February 2009 to November 2011, we have picked out 350 high-quality phase velocity dispersion curves of fundamental mode Rayleigh waves at periods from 8 to 75 s, and Rayleigh wave phase velocity maps have been constructed from 8 to 75 s period with horizontal resolution ranging from 40 to 50 km by two-station surface-wave tomography. Then, using a genetic algorithm, a 3D shear-wave speed model of the crust and uppermost mantle have been derived from these maps with a spatial resolution of $0.4^\circ \times 0.4^\circ$. Four characteristics can be outlined from the results: (1) Except in the Datong volcanic zone, in the depth range of

11–30 km, the location of a transition zone between the high- and low-velocity regions is in agreement with the seismicity pattern in the study region, and the earthquakes are mostly concentrated near this transition zone; (2) In the depth range of 31–40 km, shear-wave velocities are higher to the south of the Taiyuan Basin and lower to the north, which is similar to the distribution pattern of Moho depth variations in the Shanxi region; (3) The shear-wave velocity pattern of higher velocities to the south of 38°N and lower velocities to the north is found to be consistent with that from the upper crustal levels to depth of 70 km. At the deeper depths, the spatial scale of the low-velocity anomalies zone in the north is gradually shrinking with depth increasing, the low-velocity anomalies are gradually disappearing beneath the Datong volcanic zone at the depth of 151–200 km. We proposed that the root of the Datong volcano may reach to a depth around 150 km; (4) Along the N–S vertical profile at 112.8°E , the 38°N latitude is the boundary between high and low velocities, arguing the tectonic difference between the Shanxi rift zone and its flanks, in the rift zone the seismic velocity is dominated by low-velocity anomalies while in the flanks it is high.

M. Song
Earthquake Prediction Center, Earthquake Administration of
Shanxi Province, Taiyuan 030021, China
e-mail: smq28@126.com

Y. Zheng (✉)
Institute of Geodesy and Geophysics, Chinese Academy of
Sciences, Wuhan 430077, China
e-mail: zhengyong@whigg.ac.cn

C. Liu
Earthquake Administration of Shaanxi Province, Xi'an 710068,
China

L. Li · X. Wang
Earthquake Administration of Shanxi Province, Taiyuan 030021,
China

Keywords Shanxi rift zone · Two-station method ·
Surface wave · Shear-wave velocity · Tomography

1 Introduction

The Shanxi rift zone is one of the second-order active tectonic zones in China (Zhang et al. 2003a, 2004), which absorbs the convergence rates between many tectonic blocks, such as the Ordos Block, the North China Block, and the South China Block (Liu 2008). Because of this kind of tectonic environment, a lot of active tectonic features

can be seen in this area. In the inner part of this rift zone, a series of Cenozoic rift basins distribute from north to south, including the Datong, the Xingding, the Taiyuan, the Linfen, the Yuncheng, and the Weihe rift basins (EAC 1988). Historical records show that there have been eight earthquakes with magnitudes equal to or larger than M 7.0 occurred in the Shanxi rift zone, which account for one quarter of the large-scale earthquakes that occurred in North China in the historical records (Li 1981). Due to the intensity and frequent occurrence of the strong earthquakes in this region, the Shanxi rift is presently identified as one of the most tectonically active Cenozoic rift zones in the world (Xing et al. 2005). The strong and unbalanced rifting may be closely related to geodynamic processes and deep structures within the rift as well as the surrounding tectonic environment. Thus, the Shanxi rift zone not only presents tectonic characteristics that are common to seismic environments but also exhibits uniquely tectonic processes (Yang et al. 1995). Moreover, the active tectonic environment also caused complex tectonic deformation in this area, and the Shanxi rift is spreading until now. In the north end of the Shanxi rift, there is Datong volcanic zone, which is a significant Quaternary volcanic zone in the North China Craton, and the tectonic evolution of the volcanic zone may play an important role for the rejuvenation of the North China Craton (Deng et al. 2007). Therefore, the Shanxi rift and the surrounding region are ideal regions for studying continental rift dynamics. A deep-going and systematic study of the velocity structure of the crust and upper mantle in this region would be of great importance. It would help to raise the location precision of Shanxi digital seismic network to determine the focal mechanisms of local earthquakes, to study the deep tectonic setting of the genesis of rift earthquakes and to reveal dynamic rift processes.

In the past two decades, a large number of geophysical studies have been done to image the velocity structure in Shanxi rift, including deep seismic sounding (DSS) (Zhu et al. 1994, 1999; Liu et al. 2000; Zhao et al. 1999, 2006; Zhang et al. 1997), waveform modeling (Zhang et al. 2003b), teleseismic receiver function (Ge et al. 2011; Wu et al. 2011; Tang et al. 2010), body-wave tomography (Wang 2005; Xu et al. 1997; Zhang et al. 2011), ambient seismic noise and two-station analysis (Zheng et al. 2011; Fang 2010; Tang et al. 2011), surface-wave tomography (Li et al. 2010, 2012), and magnetotelluric sounding (Wei et al. 2006; Zhao et al. 1997). These results have provided us the overall information of the crust and upper mantle in this region. However, due to the constraints from the datasets and the methods, the previous studies cannot provide detailed structure for the whole region of the Shanxi rift. For example, although DSS method can resolve the crustal structure well, only six unevenly distributed

sections have crossed this region. In addition, the magnetotelluric sounding work in this region only allows us to acquire the media properties under the Datong basin near Ying Xian. The resolution and reliability of the results from body-wave tomography (Wang 2005; Xu et al. 1997; Zhang et al. 2011), ambient noise tomography (Zheng et al. 2011; Fang 2010; Tang et al. 2011), and receiver function analysis (Ge et al. 2011; Wu et al. 2011; Tang et al. 2010) were not enough to comprehensively study the deformation mechanisms within the Shanxi rift zone. On the other hand, earthquake surface-wave tomography can reveal the velocity structure from the surface to a depth of 150 km, or even deeper, thus is free from the limitation of the ANT method that can only resolve the structure in shallow depth. Using this method, Li et al. (2012) obtained the Rayleigh-wave phase velocity structure as well as 3D shear-wave velocity images with period ranges from 12 to 125 s in the Ordos Block and its neighboring rift basin. However, due to the limitation of station coverage and azimuthal distribution of the earthquakes, the spatial resolution of these previous studies are worse than 100 km, which is unsatisfied for the requirement of deciphering the detailed tectonic features in the Shanxi rift zone whose spatial scale is only around 100 km.

In general, shear-wave velocity structure can provide better rheological images than that of the P-wave tomography, and surface-wave phase velocity is sensitive to the variation of shear-wave velocity, thus, surface-wave tomography is one of the most important tools to understand the rheological and tectonic structures in the crust and the upper mantle (Li and Burke 2006; Jia and Zhang 2008; Ding et al. 2008; Jobert et al. 1985; Toksoz and Anderson 1966; Kanamori 1970; Forsyth 1975; Zhang and Lay 1996; Zhang and Ma 1997). A number of studies have resolved the crustal and upper-mantle velocity structures using long-period surface-wave data (Zhu et al. 2007; Yanovskaya and Kozhevnikov 2003; Huang et al. 2003; He et al. 2002, 2009). However, due to the sparse station distribution, most of the previous studies used the single-station method to determine group velocity along mixed paths and further to obtain the crustal and upper-mantle velocity structures. Compared with traditional single-station surface-wave tomography (SWT), the precision of the phase dispersion curves measured by two-station method can be improved significantly because it is nearly free from the errors of epicenter location and the original time of the earthquake (Yanovskaya and Kozhevnikov 2003). With increasing Digital Seismic Network development in recent years, many scholars have been able to obtain very good local and regional crustal shear velocity structures with higher resolution by the use of two-station phase velocity dispersion (He et al. 2002, 2009; Prindle and Tanimoto 2006; Xu et al. 2000, 2007). For example, Yi et al. (2008)

obtained phase velocity images in mainland China and its adjacent regions using the Rayleigh-wave average phase velocity at periods from 20 to 120 s with 102 stations and 538 two-station paths.

Due to the characteristics of the two-station method, the two stations should be approximately on the same great-circle path along with the seismic source. Before 2008, the Shanxi Digital Seismic Network only contained 21 stations with uneven azimuthal distribution, and some of them were short-period seismographs, so the previous seismic network did not fulfill the requirements of the two-station method. Fortunately, with the development of the Shanxi Digital Seismic Network, the original 21 stations have been replaced with digital broadband seismometers, and 12 new broadband seismic stations were added into the network system. With the accumulation of data from the upgraded network, it is possible to study the high-resolution 3D fine structure of the crust and upper mantle in local regions by the use of the surface waves. In this paper, we try to study the fine structures of complex media in the crust and uppermost mantle by surface-wave tomographic images with the accumulated data from the upgraded seismic network.

2 Data

In this work, we collected the surface-wave data from 31 stations in Shanxi Digital Seismic Network. In order to increase the ray density at the boundaries of the studied area to ensure the reliability of the inversion, we also collected data from another six stations in adjacent provinces, including the Hebei, Henan, Shaanxi provinces, and the Inner Mongolia Autonomous Region (Fig. 1). Finally, we obtained seismic data with evenly distributed path coverage in the study area.

The data are selected to meet the following requirements: (1) the selected earthquake should be shallow events with focal depth less than 100 km, and the epicentral distance is between 30° and 90° and the magnitude is greater than 5.0 in order to obtain the fundamental mode Rayleigh waves; (2) the deviation angles between the path of the two stations to seismic source should be less than 3° ; (3) the distance between the two stations in a path should be larger than 100 km; and (4) the vertical waveform records should have high signal-to-noise ratios (SNR) without obvious disturbed signals, so that clear arrival times for wave-packet energy can be observed through the frequency time analysis (FTAN).

The seismic data were recorded from February 2009 to November 2011, and the number of earthquakes that satisfied the first requirement was greater than 100. Because there were five types of seismometers in the seismic network, we first removed the instrument responses for each station before choosing the pairs of the stations. Then, we

Fig. 1 The tectonic sketch map and distribution of stations and cross sections in the study region. The *solid triangles* are the broadband seismic stations used in this work, and the *solid lines* delineate the locations of the profiles shown in Fig. 9. The *stars (a) and (b)* denote the locations referred to in Fig. 6. The *rectangle* in the *inset* outlines the area of study region in the large-scale map

manually removed the low SNR data and chose fundamental mode Rayleigh-wave phases. After these procedures, long-period vertical surface-wave data from 37 earthquakes that satisfied conditions (2), (3), and (4) were selected (Fig. 2). Finally, we obtained 350 high-quality phase velocity dispersion curves of fundamental mode Rayleigh waves from all of the paths.

3 Method

In this work we first measured the surface-wave dispersion by two-station method, and built the phase velocity maps. Then, based on the dispersion curves, we further built the shear-wave velocity maps for the studied area by genetic algorithm, the methodologies are simply described in the follow sections:

3.1 Measurement of the dispersion curves

Picking Rayleigh-wave dispersion curves from the waveform data is critically important in surface-wave tomography. We measured the dispersion curves using the two-

Fig. 2 Epicenter distribution of the earthquakes used in this study. The *star* denotes the center of the Shanxi Digital Seismic Network, and *black dots* denote locations of earthquake epicenters

station method, which needs a large number of earthquakes with uniform distribution. Figure 1 shows the distribution of stations in the Shanxi region. We found that the azimuthal distribution is quite uniform. The narrow-band filtering cross-correlation method (Yao et al. 2004; Ditmar and Yanovskaya 1987) is used in this paper; the detailed description of the phase dispersion picking method can be found in Song et al. (2013).

Fig. 3 An example of phase velocity on the same path between two stations: **a** recorded waveforms and **b** phase velocity versus period. The *bold line* outlines the trajectory of the maximum value of cross correlation, it allows us to identify the phase velocity at the corresponding period

Figure 3 shows an example of measuring the phase velocity with narrow-band filtering cross-correlation method. Figure 3a shows high-quality vertical-component waveforms recorded by the XAX and YUY stations from the Sumatra earthquake that occurred on August 22, 2010. The waveforms have high signal-to-noise ratios, and contain abundant surface-wave frequency components. By tracking the maximum correlation coefficient value, we can identify the Rayleigh speed for the corresponding period by FTAN method, the maximum of the correlation coefficient can be easily tracked from 5 to 75 s periods (Fig. 3b). In general, the phase velocity errors are small and increase with period, for long-period range (e.g., from 65 to 75 s) the errors are relatively larger.

In this work, we obtained 350 phase velocity paths for all of the selected station pairs through FTAN (Fig. 4a), these paths have covered Shanxi region evenly at period range between 11 and 75 s. However, the paths are relatively poorer on the two sides of the rift region because the station spacing in the peripheral region is relatively sparse. At most periods, the numbers of the paths are near or greater than 300, except at some short periods (≤ 10 s, shown in Fig. 4b).

3.2 Inversion for the phase velocity maps

Using the methods of Ditmar and Yanovskaya (1987) and Yanovskaya and Ditmar (1990), we obtained phase velocity dispersion maps at 37 central periods from 5 to 75 s. Because the model basis function uses the integral form of the group arrival times, it does not require initial

Fig. 4 **a** Distribution of the paths for surface waves, **b** the measured number of raypaths at different periods

parameters or constraint conditions. The detailed method can be found in the literature (Xu et al. 1997). The fundamental concept is: if we input a phase velocity corresponding to the period T_n in the mixed L paths, we can obtain the phase velocity $[C(\phi, \lambda)]$ and the horizontal distribution of the resolution $[R(\phi, \lambda)]$ at this period. Here, ϕ is latitude, and λ is longitude at each node. The phase velocity contour outlines the lateral variation of the phase velocity distribution at a certain depth. Based on this method, we obtained phase velocity dispersion maps at 37 periods, ranging from 5 to 75 s with grid size of $0.2^\circ \times 0.2^\circ$. Figure 5 shows three path-density grade-resolution tests at periods 10, 33, and 62 s. The path

numbers are 288, 346, and 276, respectively. The resolution ranges from 40 to 50 km and reaches 70 km near the border of the study region.

3.3 Inversion for the SV structure

In this work, the genetic algorithm performed the inversion (Wu et al. 1997). Since the genetic algorithm is a kind of method of non-linear inversion, it requires a large amount of computation to find the suitable inversion result. In order to minimize the search space, improve the inversion efficiency, and diminish the non-uniqueness of the inversion, we constructed the reference model using a two-step

Fig. 5 Maps of phase velocity resolution in the studied area. The heavy lines are the 50 km marginal distribution resulting from the inversion of surface-wave phase velocities

procedure. In the first step, at all points we collected DSS results (Zhu et al. 1994, 1999; Liu et al. 2000; Zhao et al. 1999, 2006; Zhang et al. 1997), referred to the previous work on the Moho and lithosphere (Xing et al. 2002), the AK135 model (<http://rses.anu.edu.au/seismology/ak135/ak135f.html>) and the Moho thickness (Xing et al. 2002) and P/S velocity ratio determined by H–K stacking on teleseismic receiver functions (Tang et al. 2010). Considering that the longest period in the phase velocity dispersion curve is 75 s, the depth in the inversion was set from the Earth's surface to a depth of 200 km. In the second step, smoothing constraints were applied to the model parameterization, each layer thickness was fixed, and the shear-wave velocities were inverted in each horizontal layer. The smoothing coefficient was chosen based on the thickness of the layer. If the layer thickness is less than 3 km, the smoothing coefficient should be set between 0.2 and 0.4, and when the layer thickness is larger than 5 km, the smoothing coefficient is usually set in the range between 0.5 and 0.7. In shallow parts of the crust, the smoothing coefficient is about 0.6, and near the Moho discontinuity, the coefficient is set as 1.0.

Using these constraints, we first invert the shear-wave velocities on the grids which are close to the DSS profiles (the location shown in Fig. 1), and then we use these grid results as initial constraints to further invert the shear-wave velocities on the remaining grids. Overall, we have obtained the shear-wave velocities at each node with grid size of $0.4^\circ \times 0.4^\circ$ (165 grids) from 0 to 200 km, then, by assembling all the 1D v_s models for each grid point, we form the 3D model using the kriging gridding method (Jorge 2007). To clarify, because only Rayleigh waves are used in the inversion, the data are mainly sensitivity to S_v velocity (v_{sv}). Figure 6 shows an example of the v_{sv} inversion from phase velocity dispersion curves at locations (a) and (b) marked in Fig. 1. With the picked out dispersion curve with uncertainty (shown in the right column), the shear-wave velocity can be inverted within the upper and lower bounds.

4 Results and discussion

4.1 Phase velocity maps

Based on the horizontal distribution maps of phase velocities at six representative periods (Fig. 7), we analyzed the lateral heterogeneity of the crustal and upper-mantle velocity structures in the Shanxi region. Considering the shear velocity sensitivity kernels of Rayleigh-wave phase velocities (He et al. 2009; Zheng et al. 2010), the phase velocity maps can be used to analyze the shear-wave structure for different depths.

The distribution map of phase velocity at period 10 s is as shown in Fig. 7a. It mainly deciphers the features of velocity structure of the shallow crust (about 10 km). The distribution of low-velocity and high-velocity zones is closely related to the thickness of sedimentary layers and regional geological structures (He et al. 2004). The bedrock mountain areas and transverse uplift (Lingshi uplift) along the two sides of the Shanxi rift zone are high-velocity areas, while the basins in the central part of the Shanxi rift and the shallow depression in the two sides of the mountain area are low-velocity areas. These low-velocity areas include: Datong, Xinding, Taiyuan, Linfen basins, and Yuxian basin in the Taihang mountain uplift. Shanxi geological data (Xing and Ye 1991) and the results of DSS (Zhu et al. 1994, 1999; Liu et al. 2000; Zhao et al. 1999, 2006; Zhang et al. 1997) indicated that the thickness of sedimentary layers in these areas is between 1.4 and 5.1 km. The thicknesses of the Taiyuan basin and Datong basin are between 3.5 and 3.9 km, and the thickest sediment is located in the Yuncheng basin. The central areas of the subsided fault basins (e.g., Datong, Daixian, Qingxu, Hongtong, and Wuxiang) (Xu et al. 2007) show low-phase velocity anomalies that may be related to the thickness of sedimentary cover in the basins. Magnetotelluric sounding profiles from Yanggao in Datong to Rongcheng in the Shandong province show that there is a low-resistivity belt at the surface near Yanggao in Datong, suggesting that there is a Cenozoic sedimentary cover in this region (Zhao et al. 1997). In general, the Rayleigh-wave phase velocity map at 10 s clearly outlines the lateral variations of seismic-wave speed in the upper crust here, whereas depression basins display low-velocity anomalies, and uplifted mountains or bedrock outcrops show high-velocity anomalies.

The distribution map of phase velocities at period 15 s is as shown in Fig. 7b. This period range expresses the features of velocity structure in a range from the ground surface to about 20 km depth where the speed is still slightly affected by the presence of sedimentary. The low-velocity anomalies shown in the 10-s map also exist in the 15-s map, but their areas become smaller. This is due to an improvement in speed with increasing depth. In the northern Daixian and Datong region, there is an obvious low-velocity anomaly distributed in the middle-upper crust. The results of DSS and crustal electrical structure in the Datong and Yingxian–Fuping areas show low-speed anomalies (crustal high-conductive strata) near Yingxian at a depth range of 17–22 km (Zhang et al. 1997; Zhao et al. 1997; Fang et al. 1995; Liu et al. 1991), which is in good agreement with the phase velocity map pattern at 15 s in these areas.

The distribution map of phase velocities at periods 20 and 26 s are as shown in Fig. 7c, d. The influenced depth

Fig. 6 Examples of the v_{sv} inversion from phase velocity dispersion curves at locations (a) and (b) marked in Fig. 1 as stars, respectively. **a** and **c** The shear-wave velocity profile along the depth. The light gray curves represent the upper and lower bounds of the shear-wave velocity in the studied area, the black thick curve is the final inverted shear velocity profile by the genetic algorithm inversion. **b** and **d** The observed and computed Rayleigh-wave phase velocity curve at locations (a) and (b), the dots are observed as dispersion curve, and the line is fitted dispersion curve

range is about 30–40 km, this depth range is also close to the average depth of the Moho discontinuity in Shanxi. These maps reflect mainly the variation features of the upper-mantle and lowermost crust. Because the shear-wave velocity on the top of the upper mantle is usually about $4.5 \text{ km}\cdot\text{s}^{-1}$, which is much higher than that of the lowermost crust (about $3.9 \text{ km}\cdot\text{s}^{-1}$), thus the variation of Moho depth may have a large effect on the phase velocity (Tang et al. 2010). In Fig. 7c, d, phase velocities to the south of 38°N are higher than those to the north. Considering the

effect of the Moho variation, the high-velocity areas may be correspondent to shallower Moho depths, while the low-velocity area may reflect deeper Moho discontinuities. Figure 7e, f, are the phase velocity maps of Rayleigh waves at 36 and 54 s, which show the velocity structures at the top of the upper mantle. The phase velocity to the south of 38°N is higher than to the north, which is consistent with the surface-wave tomography results of Li et al. (2012). The scale and the range of low-velocity areas vary with period; the low-velocity area at 54 s is smaller than that at

Fig. 7 Phase velocity images from the Shanxi region: **a–f** are phase velocity maps at periods of 10, 15, 20, 26, 36, and 54 s, respectively. Solid black lines delineate the active faults in (a). Brown circles mark the locations of historical earthquakes $M_S \geq 6.0$. The black triangles are the locations of the cities in the region

36 s and is divided into two areas: one is near Taiyuan, and the other is in the Datong volcanic area.

Near Taiyuan, there is a persistent low-velocity anomaly from 8 to 75 s periods. Anomaly region extends from the Xishan fault of the Taiyuan basin to the west mountain area. There are many small earthquakes at the same region, however, no similar anomalies can be observed from studies of the geologic structure, magnetotelluric structure, or gravity field. Field surveys indicate that there are some hot springs distributed along the Xishan fault in this region (Liang et al. 2000). Since shear-wave velocities are more sensitive to the fluid content than P-wave velocities, fluids may be one cause of the low-velocity anomaly at the short-period interval. Another possible cause could be the existence of upwelling, asthenospheric material beneath the rift. It is needed to obtain the high-resolution velocity structure at greater depths to reveal this speed anomaly.

4.2 v_{SV} structure

The distribution pattern of the shear-wave velocities delineates the crustal and upper-mantle S-wave velocity structures quite well in Fig. 8. The shear-wave velocity varies with areas and depth, and is described in the following sections.

The upper crust model velocity structure depends on the quality of the phase dispersion curves at 5–10 s periods, however, the curve paths were poor in short periods in our work. Thus, we greatly focus on the deeper structures hereinafter.

In the crust, lateral heterogeneities can be observed in the horizontal S-wave velocity structures, and S-wave velocity ranges from 3.78 to 4.38 km s⁻¹. Shear velocity anomalies typically are similar with depth, except beneath Taiyuan, Wuxiang, Hongdong, as well as Jishan near basins. The shear-wave velocities in these areas exhibit significant low anomalies in the upper crust, which are mainly caused by the slow velocity in the sediments. The boundaries of basins cannot be clearly identified from velocity gradient, which is likely due to the horizontal span of the basins being smaller than the spatial resolution of this work. The most significant velocity variation feature in the middle to lower crust (10–40 km) (Fig. 8a–c) is that in general, high velocities zone mainly cover southern areas of Shanxi region, including Taiyuan, Yuncheng and Linfen basins, while low velocities areas concentrate in north areas of Shanxi region. These may be associated with the distribution of the Moho. As we know, the Moho is the discontinuity between the crust and the mantle; if the depth is shallower than the Moho discontinuity, the rocks still belong to crustal materials so that the velocity should be quite different from that in the mantle. Previous studies (Xing et al. 2005; Xing and Ye

1991) have shown that the Moho depth is about 38 km beneath Taiyuan basin and about from 35 to 37 km under the southern region (including the Yuncheng basin and the Linfen basin) and about 40–41 km below the northern region (including the Xinding basin and the Datong basin); at 40 km under Datong to north Taiyuan basin the rocks may still be the crustal materials, thus their velocity is shown in low anomalies. Furthermore, modest low velocities are observed throughout the Datong basin in the crust, maybe also caused by the elevated crust temperatures resulting from relatively thin lithosphere and young magmatism and extension.

The relocation of small to moderate earthquakes (Song et al. 2012) mostly occurred in the velocity anomalies gradient transition zone except in the Datong volcanic zone (Fig. 8a–c). This phenomenon is in agreement with the previous studies. For example, studies of traveltime tomography in North China (Wang 2005; Zhu et al. 1990; Yu et al. 2003) show that distribution of the strongest earthquakes also has similar pattern. During the process of tectonic movement, a large amount of strain energy can be accumulated in the relatively weak zones (near anomalies gradient areas), thereby potentially causing earthquakes (He et al. 2009). Therefore, this work may be the key to a better understanding of relative rift motion and patterns of seismicity.

One noteworthy observation is that the latitude of 38°N is one boundary that separates the Shanxi region into two different blocks. The northern block is relatively ‘soft’ with lower velocities, and the southern block is just the opposite. At the same time, there is a NW-trending velocity gradient belt along Lanxian–Qingxu–Wuxiang, which crosses the 38°N boundary in the northern tip of the Taiyuan basin (Figs. 7b, c, 8a, b). The gradient belt can also be found in the Bouguer gravity anomaly map of the Shanxi province (1:500,000 scale; Liu 2008). In addition, Wei et al. (2007) showed that there was a NNW P-wave velocity transitional areas at the depth of 10–20 km in the southwestern portion of the Shanxi province. The relocation of small to moderate earthquakes in the same area revealed one belt of sparse seismicity, suggesting that energy is able to easily accumulate and release suddenly under the structure strength long-term function.

In the uppermost mantle (Fig. 8d), the image revealed the shear-wave velocities ranges from 4.23 to 4.53 km s⁻¹ and the speeds are mostly larger than 4.45 km s⁻¹, except in the Datong region, which is probably due to being partially molten in the lower crust.

Velocity anomalies in the upper mantle (Fig. 8e, f) are distinct from those observed in the overlying crust and uppermost mantle. The shear wave increases with depth, on the other hand, the lateral variation gradually decreases with depth. With increasing depth, the spatial scale of the

Fig. 8 v_{vs} maps at depths of 11–19 km (a), 20–30 km (b), 31–40 km (c), 41–50 km (d), 51–70 km (e), 91–110 km (f), 111–150 km (g), and 151–200 km (h); the white spots indicate the small to moderate earthquakes versus depth ($M_L \geq 2.0$). The dashed lines denote the boundary between the Jinbei and Qinshui ancient block (the details described are given from Sun et al. 1992). The solid lines mark the thickness of Moho discontinuity in (c)

low-velocity anomalies in the north gradually shrank and finally concentrated in the Datong volcanic zone. Regional geological surveys (Xu et al. 2005; Zhang 1986) show that there are large-scale Cenozoic mantle-originated magmas, and the low-velocity anomalies are probably due to the elevated temperatures in the lower crust and uppermost mantle resulting from the upwelling of the hot mantle materials. Moreover, the low-velocity anomalies disappeared beneath the Datong volcanic zone at the depth of 151–200 km as shown in Fig. 8h. We propose that the root of the Datong volcano may reach a depth of around 150 km. Previous studies have indicated a large area of Cenozoic mantle-rooted magmatic rock covered in this area (Xu et al. 2005; Sun et al. 1992). Thus the Datong area is an active Cenozoic volcanic zone, which needs a relatively large and deep root magma chamber under the Datong volcanic area, the deep rooted low-velocity anomalies under the Datong revealed by this work is a good evidence for previous studies. As the Datong volcanic zone has a deep and broad root, it may be caused by the upwelling of hot asthenospheric materials under this region. As suggested by previous studies, the rejuvenation of the North China Craton may be caused by the upwelling materials under the central North China Craton (Deng et al. 2007); the Datong volcanic zone could be a result of this kind of tectonic movement. In order to make sure the reliability of the result, we also compare our result with that of Zheng et al. (2011), and both results exhibit deep root low-velocity anomalies under the Datong volcanic zone.

4.3 The maps along vertical profiles

Theoretical study indicates that the energy of Rayleigh waves is mainly concentrated towards the depth within the range of about half a wavelength (He et al. 2009). Thus, we can consider approximately that the phase velocity at a certain period is the average of S-wave velocities over a depth range of half a wavelength (in fact, the phase velocity is a little less than the S-wave velocity). Therefore, the variation of phase velocity when the period changes from short to long can be considered resulting from variation of materials from shallow to deep (He et al. 2009). Similarly, we can also find lateral material variation by comparing the phase velocities of different areas. In this work, we constructed the shear-wave velocity map for each grid in our study areas, and picked out three shear-wave vertical profiles ($A-A'$, $B-B'$, $C-C'$; locations shown in Fig. 1). Furthermore, in order to compare the velocity distribution between the surface-wave and shear-wave velocities, we also built phase velocity profiles along the same locations. The comparison is shown in Fig. 9.

The $A-A'$ profile traverses the Datong basin, Xinding basin, and Wutaishan uplift to the east, which belongs to the Yingxian–Fuping segment of Zibo–Yingxian DSS profile (Zhao et al. 2006). The phase- and shear-wave velocity variations are similar to the velocity structure revealed by the DSS profile. (Figure 9a, b, profile $A-A'$), and the contours of 3.8 km s^{-1} of phase velocity and 4.45 km s^{-1} of shear-wave velocity become shallower from west to east. This was consistent with the previous results about Moho discontinuity at the same locations. (Zhao et al. 2006).

The profile $B-B'$ that extends along longitude 113°E crosses the Qinshui block, Zhongtiaoshan block, and Jinbei block from south to north; it can express the velocity distribution features in N–S direction.

In the vicinity of latitude 38°N , there was a transition zone where the phase velocity changed rapidly. The phase velocity from 18 to 25 s varies gently on the south side of the transition zone, while sharply below the Xinding and Taiyuan basins on the north side. It is noteworthy that the phase velocity in the south is much higher than that in the north between 36 and 75 s periods (these periods reflect mainly the features of velocity structure of the top of upper mantle) (Fig. 9c). Sun et al. (1992) proposed that the Shanxi block could be divided into two different tectonic blocks at a boundary located at 38°N . In the northern part, the Jinbei block is ‘soft’ for asthenospheric material upwelling to the depths of $\sim 80 \text{ km}$; the Qinshui block in the southern portion is relatively ‘hard’, where the depth to the lithosphere is between 120 and 150 km. The phase velocities shown in Fig. 9c are very similar to the geological observations.

In Fig. 9d, the 38°N latitude is also the boundary between high and low velocities at depths between 40 and 100 km, and to the south of the 38°N latitude, shear-wave velocity is higher than to the north. Moreover, in Jinbei block between 39°N and 40°N , we can clearly observe prominent low-velocity anomalies, which provided the evidence that there is an upwelling asthenosphere channel in this region and that the Shanxi rift may be generated by this upwelling flow.

The profile $C-C'$ crosses the Lvliangshan uplift in the west and the Linfen basin in the central rift and Taihangshan uplift in the east, which belong to the Daning–Jincheng segment of DDS profile from Yinchuan to Zhengzhou (Zhu et al. 1994). The phase velocity structure revealed by this profile is very similar to the result of DDS. In Fig. 9e, due to the upwelling of materials from great depths below the Linfen Basin, the Moho interface and interfaces within the crust are uplifted, and the high-conductivity layer in the upper mantle shows a strong escalating trend (Zhu et al. 1994, Fig. 9f).

Fig. 9 Vertical cross sections of phase velocity and v_{sv} along the A–A', B–B', and C–C' profiles identified in Fig. 1. **a**, **c**, and **e** represent the phase speed versus depth. **b** and **d** display the shear-wave speed at corresponding depths. **f** The P-wave velocity section results taken from the DDS experiment by Zhu et al. (1994) at the same location along the C–C' profile

5 Conclusions

Based on teleseismic waveforms recorded by the Shanxi seismic network and networks of surrounding provinces, and removing instrument responses and applying the two-station (TS) method, we have obtained phase velocity distribution images from the inversion of phase velocity dispersion of Rayleigh waves. The horizontal resolution is between 40 and 50 km. Furthermore, the 1D S-wave velocity was inverted from the Earth's surface to 200 km beneath 165 nodes in the Shanxi region using a genetic algorithm, then, by assembling all the 1D v_s models for each grid point, we form the 3D model using kriging

gridding method (Jorge 2007). The main characteristics were as follows:

In the crust, the most significant difference between velocity anomalies in the middle/lower crusts (10–40 km (Moho)) (Fig. 8a–c) is that there are high velocities from Taiyuan basin to the Yuncheng basin in the southern parts of Shanxi region, while there are low speeds from the north of Taiyuan basin to the Datong basin. These may be associated with the distribution of the Moho discontinuity. Especially modest low velocities are observed throughout the Datong basin in the crust, probably due to the elevated crust temperatures resulting from relatively thin lithosphere and young magmatism and extension.

In the uppermost mantle, the image revealed that the shear-wave velocities are mostly larger than $4.45 \text{ km} \cdot \text{s}^{-1}$, except in the Datong region, which is probably due to the partial melting in the lower crust. Moreover, in the upper mantle (Fig. 8e–h), shear-wave velocity increased with depth and the lateral heterogeneity gradually decreased. With increasing depth, the spatial scale of the low-velocity anomalies in the north gradually shrank, and the low-velocity anomalies disappeared beneath the Datong volcanic zone at the depth of 151–200 km. We proposed that the root of the Datong volcano may be a depth of around 150 km.

Except in the Datong volcanic zone, most of the relocated events on the north of the Taiyuan basin were located in the transition zone between high and low velocities at depths between 11 and 19 km, while the ones on the south were closer to the velocity gradient belt at depths between 11 and 30 km (Fig. 8a–b). The findings are in agreement with the results of some researchers who showed that the earthquakes mainly concentrated in the velocity anomalies gradient transition zone, therefore the seismicity is mainly controlled by the upper crustal structures.

The latitude of 38°N is one boundary that separates the Shanxi region into two different blocks. The northern block is relatively ‘soft’ with lower velocities, and the southern block is just the opposite. Same pattern can be observed in the depth from 40 to 100 km that 38°N is the boundary of high velocity and low velocity and the shear-wave velocity increases from north to south. Moreover, in Jinbei block between 39°N and 40°N , we can clearly observe prominent low-velocity anomalies, which provided the evidence that there is an upwelling asthenosphere channel in this region.

Although our study has characterized the crust–mantle velocity structure of the Shanxi region, better seismic velocity structure can be expected in the future. In our work, we already collected seismic data in 45 stations, which are more than any previous studies in this region, however, there are 56 stations running in the Shanxi rift zone, and in recent days, additional 12 stations have been deployed, so that the ray paths in the studied area are much more evenly distributed. So, in the near future, we will collect more data and apply new methods other than only two-station methods, such as ambient noise tomography (Zheng et al. 2011) and two-plane wave tomography (Li et al. 2012) to build better resolution crustal and uppermost mantle shear-wave velocity structure model for the Shanxi rift zone, so that we can understand more clearly about the tectonic settings in this region.

Acknowledgments The authors thank three anonymous reviewers and editors for constructive critical reviews that improved this manuscript. This work was financially supported by Open Grant from State key Laboratory of Geodesy and Earth’s Dynamics (Grant No. SKLGED2014-4-4-E), and Office of Science and Technology in

Shanxi province based on research Projects (2012011029), and Scientific and Technological Research Projects in Shanxi province (20100311129-2, 20090311084), and the China Earthquake Administration spark Project (XH15007).

Open Access This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

References

- Deng JF, Su SG, Niu YL, Liu C, Zhao GC, Zhao XG, Zhou S, Wu ZX (2007) A possible model for the lithospheric thinning of North China Craton: evidence from the Yanshanian (Jura-Cretaceous) magmatism and tectonism. *Lithos* 96:22–35
- Ding ZF, He ZQ, Sun WG (2008) 3-D crust and upper mantle velocity structure in eastern Tibetan plateau and its surrounding areas. *Chin J Geophys* 51(5):1431–1443 (in Chinese with English Abstract)
- Ditmar PG, Yanovskaya TB (1987) Generalization of Backus–Gilbert method for estimation lateral variations of surface wave velocities. *Phys Solid Earth Izvestia Acad Sci USSR* 23(6):470–477
- Fang LH (2010) Rayleigh surface wave ambient noise tomographic imaging of the North China. *Natl Earthq Dyn* 4:40–42 (in Chinese with English Abstract)
- Fang SM, Yu QF, Lou H, Xing JS (1995) Study of gravity anomaly in crustal low velocity zone in the WUTAI region. *Seismol Geol* 17(2):109–113 (in Chinese with English Abstract)
- Forsyth DW (1975) The early structural evolution and anisotropy of the oceanic upper mantle. *Geophys J R Astron Soc* 43:103–162
- Ge C, Zheng Y, Xiong X (2011) Study of crustal thickness and Poisson ratio of the North China Craton. *Chin J Geophys* 54(10):2538–2548 (in Chinese with English Abstract)
- He ZQ, Ding ZF, Ye TL, Sun WG, Zhang NL (2002) Group velocity distribution of Rayleigh waves and crustal and upper mantle velocity structure of the Chinese mainland and its vicinity. *Acta Seismol Sin* 24(3):252–259 (in Chinese with English Abstract)
- He ZQ, Su W, Ye TL (2004) Seismic tomography of Yunnan region using short-period surface wave phase velocity. *Acta Seismol Sin* 26(6):583–590 (in Chinese with English Abstract)
- He ZQ, Yie DL, Ding ZF (2009) Surface wave tomography for the phase velocity in the northeastern part of North China. *Chin J Geophys* 52(5):1233–1242 (in Chinese with English Abstract)
- Huang ZX, Su W, Peng YJ, Zheng YJ, Li HY (2003) Rayleigh wave tomography of China and adjacent regions. *J Geophys Res* 108(B2):2073 (in Chinese with English Abstract)
- Jia SX, Zhang XK (2008) Study on the crust phases of deep seismic sounding experiments and fine crust structures in the northeast margin of Tibetan plateau. *Chin J Geophys* 51(5):1431–1443 (in Chinese with English Abstract)
- Jobert N, Jomet B, Him A, Zhong SK (1985) Deep structure of southern Tibet inferred from the dispersion of Rayleigh waves through a long-period seismic network. *Nature* 313:386–388
- Jorge KY (2007) On unbiased backtransform of lognormal kriging estimates. *Computat Geosci* 11(3):219–234
- Kanamori H (1970) Velocity and Q of mantle waves. *Phys Earth Planet Inter* 2:259–275
- Li SB (1981) Earthquake Research in China. Seismological Press, Beijing, pp 120–121 (in Chinese with English Abstract)
- Li A, Burke K (2006) Upper mantle structure of southern Africa from Rayleigh wave tomography. *J Geophys Res* 111:10303–10318
- Li P, Zhou SY, Chen YS, Feng YG, Jiang MM, Tang YC (2010) 3D velocity structure in Shanxi graben and Ordos from two plane

- waves method. *CT Theory Appl* 19(3):47–60 (in Chinese with English Abstract) (54(5):1233–1242)
- Li D, Zhou SY, Chen YS, Feng YG, Li P (2012) 3-D lithospheric structure of upper mantle beneath Ordos region from Rayleigh wave tomography. *Chin J Geophys* 55(5):1613–1623 (in Chinese with English Abstract)
- Liang WB, Li HJ, Yang CY (2000) Edge geomorphology and neotectonic movement in Taiyuan basin and their meanings. *J Shanxi Univ (Nat Sci Ed)* 23(2):178–181 (in Chinese with English Abstract)
- Liu JL (2008) Recognite division tectonic by using the new technology of gravity and magnetic potential field in Shanxi fault basin. Changan University, Xian
- Liu CQ, Qia SX, Du GH (1991) Result of seismic refraction sounding along the transect from Xiangshui Jiangsu, to Mondula, Nei Monggol. *Seismol Geol* 13(3):193–203 (in Chinese with English Abstract)
- Liu BF, Zhang XK, Zhang CK, Song SY, Zhou XS (2000) Geological interpretation of S wave data along the Wen'an-Yuxian-Cahay-ouzhongqi profile in north China. *Seismol Geol* 22(1):81–88 (in Chinese with English Abstract)
- Prindle K, Tanimoto T (2006) Teleseismic surface wave study for S-wave velocity structure under an array: Southern California. *Geophys J Int* 166:601–621
- Song MQ, Zheng Y, Ge C, Li B (2012) Relocation of small to moderate earthquakes in Shanxi Province and its relation to the seismogenic structures. *Chin J Geophys* 55(2):513–525 (in Chinese with English Abstract)
- Song MQ, He ZQ, Zheng Y, Lv F, Liu C, Liang XJ, Su Y, Li L (2013) Rayleigh-wave phase velocity distributions in Shanxi region. *Prog Geophys* 28(4):1836–1848 (in Chinese with English Abstract)
- Sun JY, Xing JS, Ye ZG, Chen CW (1992) The research of intraplate tectonics and deep process in North China. *Geol Sci Technol Inf* 11(1):1–12 (in Chinese with English Abstract)
- Tang YC, Feng YG, Chen YS, Zhou SY, Ning JY, Wei SQ, Li P, Yu CQ, Fan WY, Wang HY (2010) Receiver function analysis at Shanxi Rift. *Chin J Geophys* 53(9):2102–2109 (in Chinese with English Abstract)
- Tang YC, Chen YS, Yang YJ, Ding ZF, Liu RF, Feng YG, Li P, Yu CQ, Wei SQ, Fan WY, Wang HY, Zhou SY, Ning JY (2011) Ambient noise tomography in north China craton. *Chin J Geophys* 54(8):2011–2022 (in Chinese with English Abstract)
- The active fault system in Erdos block and its margins subject group (1988) The active fault system in Erdos block and its margins. Seismological Press, Beijing
- Toksoz MN, Anderson DL (1966) Phase velocity of long-period surface waves and structure of the upper Mantle. *J Geophys Res* 71:1649–1658
- Wang ZS (2005) Tomographic imaging of the 3-D Crust and upper mantle velocity structures beneath North China and its vicinity. Institute of Geophysics, China Earthquake Administration, Beijing
- Wei WB, Jin S, Ye GF, Deng M, Jing JE (2006) MT sounding and lithosphere thickness in North China. *Geol China* 33(4):762–772 (in Chinese with English Abstract)
- Wei WB, Ye GF, Jin S, Deng M, Jing JE (2007) Three dimensional p-wave velocity structure of the crust of North China. *Earth Sci J China Univ Geosci* 32(4):441–452 (in Chinese with English Abstract)
- Wu JP, Ming YH, Tang Y (1997) The application in uppermost mantle velocity structure study using the genetic algorithm. *Seismol Geomagn Obs Res* 18(2):11–25 (in Chinese with English Abstract)
- Wu Y, Ding ZF, Zhu LP (2011) Crustal structure of the North China Craton from teleseismic receiver function by the Common Conversion Point stacking method. *Chin J Geophys* 54(10):2528–2537 (in Chinese with English Abstract)
- Xing JS, Ye ZG (1991) Preliminary discussions on interpolate structural features and their evolution in Shanxi Province. *Shanxi Geol* 6(1):3–15 (in Chinese with English Abstract)
- Xing JS, Liu JH, Zhao JQ (2002) Deep-seated Tectonics in the North China intraplate. *Earthq Res Shanxi* 4:3–12 (in Chinese with English Abstract)
- Xing ZY, Zhao B, Tu MY, Xing JS (2005) The information of the Fenwei rift valley. *Earth Sci Front* 12(2):247–262 (in Chinese with English Abstract)
- Xu Y, Tian Y, Chuo YQ, Wang J, Wu L (1997) The P wave velocity structure of cruster in Datong-Yanggao 6.1 seismic area and its surrounding regions. *Earthq Res Shanxi* 1–2:24–29
- Xu GM, Li GP, Wang SE, Chen H, Zhou HS (2000) The 3-D structure of shear waves in the crust and mantle of east continental China inverted by Rayleigh wave data. *Chin J Geophys* 43(3):366–376 (in Chinese with English Abstract)
- Xu YG, Ma JL, Frey FA, Feigenson MD, Liu JF (2005) Role of lithosphere-asthenosphere interaction in the genesis of Quaternary alkali and tholeiitic basalts from Datong, western North China Craton. *Chem Geol* 224(4):247–271
- Xu GM, Yao HJ, Zhu LB, Shen YS (2007) Shear wave velocity structure of the crust and upper mantle in western China and its adjacent area. *Chin J Geophys* 50(1):193–208 (in Chinese with English Abstract)
- Yang WR, Sun JY, Ji KC, Xing JS (1995) The contrast of continental rift—the analysis between the Fen_Wei rift and Baikal rift. China University of Geoscience Press, Wuhan
- Yanovskaya TB, Ditmar PG (1990) Smoothness criteria in surface wave tomography. *Geophys J Int* 102(1):63–72
- Yanovskaya TB, Kozhevnikov VM (2003) 3D S-wave velocity pattern in the upper mantle beneath the continent of Asia from Rayleigh wave data. *Phys Earth Planet Inter* 138:263–278
- Yao HJ, Xu GM, Xiao X, Zhu LB (2004) A quick tracing method based determination of dual stations surface wave on image analysis technique for the phase velocities dispersion curve of surface wave. *Seismol Geomagn Obs Res* 25(1):1–8 (in Chinese with English Abstract)
- Yi GX, Yao HJ, Zhu JS, van der Hilst RD (2008) Rayleigh-wave phase velocity distribution in China continent and adjacent regions. *Chin J Geophys* 51(2):402–411 (in Chinese with English Abstract)
- Yu XW, Chen YT, Wang PD (2003) Three dimensional P wave velocity structure in Beijing Tianjin-Tangshan area. *Acta Seismol Sin* 25(1):1–14 (in Chinese with English Abstract)
- Zhang YB (1986) Characteristics of petrology of the Datong Basalts. *Seismol Geol* 8(1):59–67 (in Chinese with English Abstract)
- Zhang YS, Lay T (1996) GlobM surface wave phase velocity variations. *J Geophys Res* 101:8415–8436
- Zhang YS, Ma SZ (1997) Global surface wave phase velocity variations and their tectonic implications. *Chin J Geophys* 40(2):181–192 (in Chinese with English Abstract)
- Zhang JS, Zhu ZP, Zhang XK, Zhang CK, Gai YJ, Nie WY (1997) The seismic velocity structure of cruster and upper mantle and deep structure feature in north Shanxi plateau. *Seismol Geol* 19(2):220–226 (in Chinese with English Abstract)
- Zhang PZ, Deng QD, Zhang GM, Ma J, Gan WJ, Min W, Mao FY, Wang Q (2003a) The strong earthquakes mainland and activity blocks. *Sci China Earth Sci (Ser D)* 33:12–19 (in Chinese with English Abstract)
- Zhang XM, Shu PY, Diao GL (2003b) Study on S wave velocity structure under part stations in Shanxi province. *Acta Seismol Sin* 25(4):341–350 (in Chinese with English Abstract)
- Zhang GM, Ma HS, Wang H, Li L (2004) Relations between the active blocks mainland and the strong seismic activity. *Sci China Earth Sci (Ser D)* 34(7):591–599 (in Chinese with English Abstract)

- Zhang FX, Li YH, Wu QJ, Ding ZF (2011) The P wave velocity structure of upper mantle beneath the North China and surrounding regions from FMTT. *Chin J Geophys* 54:1233–1242 (in Chinese with English Abstract)
- Zhao GZ, Liu TS, Jiang Z, Tang J, Xu CF, Zhan Y, Bai DH, Liu GD (1997) Investigation on MT data along Yanggao-Rongcheng profile by two-dimensional inversion. *Chin J Geophys* 40(1):38–46 (in Chinese with English Abstract)
- Zhao JR, Zhang XK, Zhang CK, Ren QF, Zhu ZP, Wu T (1999) The structure features of deep crustal structure in seismic area of Linxian, Henan Province. *Earthq Res China* 15(3):229–236 (in Chinese with English Abstract)
- Zhao JR, Zhang XK, Zhang CK, Zhang JS, Liu BF, Pan SZ (2006) Features of deep crustal structure beneath the Wutai mountain area of Shanxi province. *Chin J Geophys* 49(1):123–129 (in Chinese with English Abstract)
- Zheng Y, Yang YJ, Ritzwoller MH, Zheng XF, Xiong X, Li ZN (2010) Crustal structure of the northeastern Tibetan plateau, the Ordos block and the Sichuan basin from ambient noise tomography. *Earthq Sci* 23:465–476
- Zheng Y, Shen WS, Zhou LQ, Yang YJ, Xie ZJ, Michael H (2011) Crust and upper most mantle beneath the North China Craton, northeastern China, and the Sea of Japan from ambient noise tomography. *J Geophys Res* 116:B12312. doi:[10.1029/2011JB008637](https://doi.org/10.1029/2011JB008637)
- Zhu LP, Zeng RS, Liu FT (1990) Three-dimensional P-wave velocity structure under the Beijing network area. *Chin J Geophys* 30(3):267–277 (in Chinese with English Abstract)
- Zhu ZP, Zhang JS, Zhou XS, Zhu WX (1994) Study on the structure of crust and upper mantle in Linfen earthquake region in Shanxi. *Earthq Sci North China* 12(1):77–84 (in Chinese with English Abstract)
- Zhu ZP, Zhang JS, Zhang CK, Zhao JR, Liu MQ, Tang ZQ, Gai YJ, Ren QF, Nie WY, Yang Q (1999) Study of crust mantle structure in central and southern Shanxi. *Acta Seismol Sin* 21(1):42–49 (in Chinese with English Abstract)
- Zhu JS, Cao JM, Yan ZQ (2007) High-resolution Rayleigh surface wave tomographic imaging of China and adjacent regions and its geodynamic implications. *Geol China* 34(5):759–767 (in Chinese with English Abstract)