Crustal thickness and v_P/v_S ratio in Shanxi Graben, China

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Received: 22 September 2014 / Accepted: 24 October 2014 / Published online: 30 November 2014

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Abstract Shanxi Graben is in the middle part of the North China Craton, from south to north. With the teleseismic data recorded by Regional Seismograph Networks and the temporary ZBnet-W Seismic Array around east part of Shanxi Graben, we measured the crustal thickness and v_P/v_S ratio beneath each station using the H - κ stack of receiver functions. The observed crustal thickness shows obvious lateral variation, increasing gradually from east to west in the Shanxi Graben. Beneath the Shanxi Graben the crust is relatively thicker than both sides of the south and the north. In addition, the v_P/v_S ratio in the north of study zone is higher than that in the south. The highest v_P/v_S ratio exists in the crust of the Xinding basin and the Datong basin. Our study also suggests that high velocity ratio might result from the strong activities of the magmatism and volcanism.

Keywords Shanxi Graben · North China Craton (NCC) · Receiver function · Crustal thickness · Crustal v_P/v_S ratio

1 Introduction

Under the push from the Qinghai–Tibet Plateau and the pull of the westward subduction of Pacific Plate and Philippine Plate, the lithosphere of the North China Craton (NCC) is suffering from destruction at different levels (Zhang et al. 2003; Liu et al. 2004; Zhu and Zheng 2009). Many studies have shown that there are regional variations of rock compositions and velocity structure in the crust and

the upper mantle in the North China Craton (Gao et al. 2010; Xu et al. 2011). At present, there are two controversial hypotheses about what leads to the destruction in the NCC: one is plate edge effect caused by plate movement (Gao et al. 2002; Wu et al. 2005), and the other is driven primarily by plate basal force associated with small-scale mantle convection (Xu 2001).

The Shanxi Graben divides the North China Craton into eastern and western segments (Kusky and Li 2003; Chen et al. 2009) (Fig. 1). The Ordos block became very stable during the Archean era, with negligible destruction (Qiu et al. 2005). From the Mesozoic to the Cenozoic Era, the eastern region of the North China Craton was not a typical Craton due to reconstruction and disruption (Zhai and Liu 2003). Therefore, the lithosphere of the North China Craton presents a feature of “East West Thin Thick.” However, the crustal structure in the Shanxi Graben displays complicated characteristics of spatial distribution (Jia et al. 2005; Tian et al. 2009; Chen et al. 2009). Previous studies suggest that there is a large lateral variations on the crustal thickness and the constituents of the Shanxi Graben (Liu et al. 2011). The crustal Poisson’s ratio in north of Shanxi Graben increases as the crustal thickness reduces, and this indicates that the stretching of lithosphere resulted in a reduction of crustal thickness, together with magmatic underplating in this area (Ji et al. 2009). The spatial variation of crustal structure in the Shanxi Graben shows not only the overall stability of the heritage Craton but also regional transformation and thickness reduction.

Shanxi Graben, located in the east side of the Ordos block and the west side of the North China Basin, consists of the Xuanhua basin, Yanhuai basin, Datong basin, Xinding basin, Taiyuan basin, Linfen basin, and Yuncheng basin from north to south (Fig. 1). There were many strong

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Fig. 1 The structure map of Shanxi Graben area, the distribution of seismic stations around Shanxi Graben area, and the temporary seismic stations of ZBnet-W used in this study. XH, YH, DT, XD, TY, LF, and YC are Xuanhua Basin, Yanhuai Basin, Datong Basin, Xiding Basin, Taiyuan Basin, Linfen Basin, and Yuncheng Basin, respectively

earthquakes in the region of the Shanxi Graben, such as the Hongdong $M8.0$ earthquake in 1303. Thus, Shanxi Graben is one of the most important seismic active belts in east China. The renowned Datong volcano is a quaternary volcanic cluster, which is mainly distributed around the eastern part of Datong basin in Shanxi Graben. Volcanic activities not only modify the crustal structure, but also provide mineral resources, such as coal and oil. Therefore, research on the crustal structure under the Shanxi Graben will help in illuminating the mechanism and characteristics of the earthquakes which occurred in the region, and providing deep geophysical information for earthquake forecasting in the Central Orogenic belt.

Receiver function is one of the most effective approaches to study crustal deformation and dynamic modification (Gao and Zhou 1998; Liu et al. 1997; Owens and Zandt 1997; Tian et al. 2005a, 2005b; Wu and Zeng 1998; Zhang et al. 2013). Our study of the crustal structure of the

Fig. 2 The epicentral distribution of teleseismic events (red dots) used in this study

Shanxi Graben was based on the teleseismic data recorded by Shanxi Regional Seismograph Network and ZBnet-W seismic array. From the data on crustal thickness and average velocity ratio (v_p/v_s) from the receiver function beneath each seismic station, we infer the geologic structure of Shanxi Graben, which significantly helps us get more information of the evolution of the Central Orogenic belt and the NCC, and provides useful information on the Datong volcano and its resources.

2 Data and method

In order to increase the distribution density of seismic stations, the Shanxi Regional Seismograph Network was expanded to 32 broadband seismic stations (Red triangles, Fig. 1). These stations have provided a variety of waveform data for the study on crustal structure. In July 2008, the Institute of Earthquake Science, China Earthquake Administration set up ZBnet-W seismic array with 12 temporary seismic stations to observe for 14 months in the west of Zhangjiakou-Bohai Seismic belt (ZB-belt) (Blue triangles, Fig. 1), and got plenty of teleseismic data. The types of seismographs are CMG-3ESP and BKD, with 100 Hz and 62.5 Hz sample frequencies in Regional Seismograph Network and ZBnet-W seismic array, respectively.

We utilized the teleseismic events from Shanxi Regional Seismograph Network and the part of Hebei Regional Seismograph Network during August 2007–July 2010 and the teleseismic events recorded by ZBnet-W seismic array. All clear teleseismic events with phases in the epicenter distance range between 30° and 90° with magnitude of 5.5 or greater were selected.

Fig. 3 The $H-\kappa$ stacking results of the temporary seismic station Z01 and local seismic stations DAX and LIF (*the left*). The stacking of receiver functions based on ray parameter (*the right*)

Data selection and processing are crucial points in seismologic research. Therefore, in this study, seismic waves were adopted with high signal-to-noise ratios for each station and filtered every waveform with 0.02–0.5 Hz bandwidth with Gaussian filter for receiver function study by the frequency-domain deconvolution. Most of the events were distributed on the south of the study region (Fig. 2). Finally, 6204 receiver functions for estimation of crustal thickness (H) and the velocity ratio (v_p/v_s) were calculated from 40 seismic stations.

$H-\kappa$ stacking of receiver function, based on the arrival times and amplitudes of the conversion phase (Pms) and multiple conversion phases (PpPms, PpSms + PsPmsPs) on Moho with weight 0.7, 0.2, and 0.1, has been employed to measure velocity discontinuity in the crust and its properties. In general, the crustal thickness and average Poisson's ratio through $H-\kappa$ stacking are crucial information for the research of local geologic structure and the variation of physical properties in the rock (Zandt and Ammon 1995; Li et al. 2006a, b; Luo et al. 2008; Zhang et al. 2009).

In this research, the crustal thickness and average Poisson's ratio of the Shanxi Graben were obtained by $H-\kappa$ stacking of receiver function (Zhu and Kanamori 2000). According to the previous study in the Shanxi Graben, we used an average crustal P-wave velocity of 6.2 km/s (Chen 1983; Sun and Xu 2007). We varied crustal thickness and v_p/v_s ratio in the ranges between 30 km and 50 km and 1.6 and 1.9, respectively, with an increment of 1 km and 0.005. Finally, the optimal crustal thickness and average velocity ratio beneath each station were obtained in this study.

Figure 3 shows the $H-\kappa$ stacking results for v_p/v_s ratio and crustal thickness beneath the temporary seismic station Z01 and local seismic station DAX and LIFs.

Variance of the $H-\kappa$ stacking can be estimated as follows:

$$\sigma_H^2 = 2\sigma_s / \frac{\partial^2 s}{\partial H^2}; \quad \sigma_\kappa^2 = 2\sigma_s / \frac{\partial^2 s}{\partial \kappa^2}$$

where, σ_s is the estimated variance of $H-\kappa$ stacking, σ_H and σ_κ are the estimated variances of the crustal thickness and velocity ratio, respectively.

Table 1 Crustal thickness and Poisson's ratio under the researched stations

Station	Crustal thickness H (km)	v_P/v_S ratio	Number of earthquakes	Station	Crustal thickness H (km)	v_P/v_S ratio	Number of earthquakes
ANZ	36 ± 1.10	1.85 ± 0.04	171	XIX	45 ± 0.71	1.79 ± 0.03	93
BOD	43 ± 0.72	1.71 ± 0.03	104	XIY	40 ± 0.94	1.72 ± 0.03	115
CHZ	40 ± 0.64	1.69 ± 0.14	108	YAC	39 ± 0.65	1.72 ± 0.02	140
DAX	43 ± 0.51	1.77 ± 0.02	309	YAY	42 ± 0.65	1.72 ± 0.02	166
DOS	39 ± 0.52	1.79 ± 0.02	183	YMG	39 ± 0.10	1.83 ± 0.05	115
HMA	36 ± 0.81	1.72 ± 0.04	157	ZCH	43 ± 0.99	1.81 ± 0.03	282
HSB	42 ± 1.08	1.81 ± 0.04	130	ZOQ	41 ± 0.90	1.72 ± 0.03	159
HZH	41 ± 0.75	1.70 ± 0.03	155	ZHB	41 ± 1.48	1.79 ± 0.03	43
KEL	42 ± 0.63	1.84 ± 0.03	180	KAB	40 ± 1.07	1.79 ± 0.03	159
LIC	41 ± 0.77	1.69 ± 0.68	243	ZJK	40 ± 1.22	1.78 ± 0.04	186
LIF	45 ± 0.60	1.73 ± 0.05	161	YAY	41 ± 1.08	1.73 ± 0.02	398
LIS	43 ± 0.60	1.73 ± 0.05	230	CHC	40 ± 1.04	1.75 ± 0.05	148
LNQ	41 ± 0.65	1.77 ± 0.02	44	Z01	41 ± 0.93	1.73 ± 0.03	237
LOF	41 ± 0.91	1.72 ± 0.04	175	Z03	42 ± 0.99	1.71 ± 0.04	126
NIW	43 ± 0.54	1.85 ± 0.02	92	Z05	41 ± 0.89	1.72 ± 0.03	132
PIG	44 ± 0.78	1.77 ± 0.03	118	Z06	42 ± 0.85	1.71 ± 0.03	178
SZZ	42 ± 0.71	1.84 ± 0.03	365	Z07	43 ± 1.34	1.74 ± 0.04	85
TAG	42 ± 0.82	1.71 ± 0.37	79	Z09	42 ± 0.88	1.73 ± 0.68	126
TIY	43 ± 0.83	1.78 ± 0.02	37	Z10	41 ± 1.33	1.75 ± 0.04	71
XAY	41 ± 0.90	1.71 ± 0.03	162	Z11	40 ± 0.82	1.75 ± 0.03	65

3 Moho interfacial morphology and the distribution of crustal velocity ratio

In this study, the obtained receiver functions beneath each station were stacked by using H - κ stacking method, and then the distributions of crustal thickness and the v_P/v_S ratio were estimated in the Shanxi Graben (Table 1; Fig. 4), which were basically consistent with other relative studies (Wang et al. 2009; Li et al. 2010a; Tang et al. 2010; Liu et al. 2011; Tian et al. 2011). However, the v_P/v_S ratios still present some differences, mainly around the Xinding basin of the Shanxi Graben. In some areas, the v_P/v_S ratios beneath the stations ZCH and SZZ, located around the Datong volcanoes, exhibit obviously different results compared with other studies.

Other studies have shown that the crustal thickness of the Shanxi Graben ranges around 37–45 km (Li et al. 2010b), and the crustal thickness increases westward at the North China from 32 km to 38 km (Wang et al. 2014), which is characterized by the coexistence of both preserved thick and destructive thinned lithosphere (Chen et al. 2010a). We also found agreement with results from receiver function by 124 earthquakes recorded between July 2007 and early August 2008 (Pan and Niu 2011). Likewise, in the present study, crustal thickness of the Shanxi Graben ranges around 36–45 km and gradually

increases from east to west, presenting a lateral variation (Figs. 4, 5b). Moreover, in the Shanxi Graben, the crustal thickness distribution indicates thicker crust in the center than in the north and south sides (Table 1; Fig. 4), and the thickest area is located in the Wutai uplift. Specifically, the northern part of our study region, the part of the west side of the ZB-belt ranging from 40 km to 43 km in crustal thickness, was investigated by stations (ZHB, KAB, ZJK, YAY, CHC, Z01, Z03, Z05, Z06, Z07, Z09, Z10, Z11) in this area. The Taihang uplift, near the west side of North China Basin where the crustal thicknesses range from 39 km to 41 km, was investigated by several stations (XIY, ZOQ, XAY, CHZ, LIC). In the Shanxi Graben, the crustal thicknesses, beneath some stations (YAY, SZZ, ZCH, LNQ, YMG, DAX, TIY, DOS, TAG, HZH, LIF, ANZ, HMA) ranging from 36 km to 45 km, indicate that there is an off-shift of Moho in this area. Meanwhile, the average crustal thickness of Xuanhua basin, Yanhuai basin, and north of Datong basin, belonging to Shanxi Graben, is about 41.1 km. The crustal thickness in the Xinding basin and its vicinity, based on the results of stations (YMG, DAX, NIW, TIY) in this area, is about 42 km. Geologically, the Wutai uplift which is observed by the NIW and DAX stations is along the northern and southern boundaries of the Xinding basin. Previous studies which have shown that the geologic structure of the Wutai uplift is complicated with thickened 43 km

Fig. 4 The distributions of crustal thickness (*the left*) and the v_p/v_s ratio (*the right*) in the Shanxi Graben obtained from the H - κ stack of receiver function. The *black triangle* indicates the locations of seismic station

crust (Zhao et al. 2006), and even thicker crust in the vicinity, are consistent with this study. The crustal thickness displays large variation from some stations (HMA, HZH, LIF, ANZ) located in the Linfen basin and the northern Yuncheng Basin. The crustal thickness in the western area we observed at several stations (PIG, BOD, KEL, LOF, LIS, XIX), namely the Luliang uplift belonging to the Ordos block, is about 43 km. Wu et al. (2011) found that the Luliang uplift was the dividing point between the western side and the central subterranean section of the NCC. In addition, we observed that the crustal thickness of the Ordos block is about 44–46 km, which is higher than that of the Luliang uplift (Fig. 3). Thus, the distinctive discontinuity of crustal thickness which exists in Luliang uplift might be caused by the differential crustal structure between the western side and the central section of the NCC.

The Poisson's ratio indicates the variations of the crustal constituent and physical property (Ji et al. 2009; Tian and Zhang 2013). The v_p/v_s ratios in the Shanxi Graben and the surrounding region range from 1.69 to 1.85 (Table 1; Fig. 4) and the corresponding Poisson's ratio from 0.23 to 0.29. On the whole, the v_p/v_s ratio constantly increases while the crustal thickness decreases based on the results from the stations located in the Shanxi Graben (Fig. 5a). Thus, we conclude that the lithospheric stretching results in the reduction of crustal thickness under the effect of the

mafic magma in Shanxi Graben. Taking the junction of the Xinding basin and the Taiyuan basin as the boundary in the Shanxi Graben, the v_p/v_s ratio in the north is higher than that in the south (Figs. 4, 5a). However, there are little variations of v_p/v_s ratio along the longitude direction in this area (Figs. 4, 5b). In the Taiyuan basin and its southern region, small variations of v_p/v_s ratio indicate a heterogeneous crust. There is a variation with latitude in v_p/v_s ratio in the north of Shanxi Graben, which ranges from 1.71 to 1.75 beneath several stations (Z01, Z03, Z05, Z06, Z07, Z09, Z10, Z11). The ratio increases as the crustal thickness reduces (Fig. 5d). Previous study indicates that the average v_p/v_s ratio and Poisson's ratio in China Mainland are 1.73 and 0.25, respectively (Chen et al. 2010b). The v_p/v_s ratios in the Xinding basin and its surrounding area are obviously high, which were measured by several stations (DAX, NIW, TIY, YMG) with values of 1.77, 1.85, 1.78, and 1.83, respectively. In addition, large-scaled low-velocity anomalies exist in the upper crust with strong reflection waves beneath the Wutai uplift from the active seismic study in the area (Zhao et al. 2006). Therefore, we suggest there are intense activities of magmatism under the Wutai uplift. Because magmatism causes richer mafic materials in surrounding crust (Ji et al. 2009), the v_p/v_s ratio is higher in the Xinding basin and its surroundings than those in the other areas. The v_p/v_s ratios measured by Station ANZ and

Fig. 5 The latitude versus v_p/v_s ratio (a) and the longitude versus crustal thickness (b) for all stations considered in this study. The v_p/v_s ratio versus crustal thickness in the Shanxi Graben (c) and Zhangjiakou area (d)

XIX located at the Linfen basin were also high with values of 1.85 and 1.79, respectively. This is probably related to an especial geologic structure and complicated dynamics in Shanxi Graben, which is caused by the effect of the tension-shear, mantle material upwelling (Tang et al. 2010).

The v_p/v_s ratios measured by several stations (SZZ, ZCH, HSH, YMG) in Datong basin are higher than those in the other areas. These results indicate there are rich mafic materials or particle melting in the Datong basin. Especially, the crustal v_p/v_s ratios beneath station SZZ (1.84) and ZCH (1.85) in this research (Fig. 6) are different from the corresponding results of Li et al. (2010), which are 1.72 (SZZ) and 1.75 (ZCH). In addition, the Ps amplitudes of

receiver function beneath the stations SZZ and ZCH are not clear, and display various characteristics with the changes in azimuth, even which are indistinct (Fig. 6).

Datong volcano, where the stations SZZ and ZCH are located, is an active quaternary volcano caused by subduction of the western Pacific plate and lateral compression of the India Plate (Chen et al. 1997; Chen et al. 2010a). The high v_p/v_s ratio exists in Datong volcanic rock in this research. Therefore, we suggest that the high v_p/v_s ratios in Datong volcano and its surrounding area are caused by volcanic activity, because alkali basalts and tholeiitic basalts separately dominate the mineral in northeast and southeast areas in Datong basin and Xiding basin (Zhang

Fig. 6 The receiver functions from SZZ and ZCH stations. The top is the summation of all receiver functions (*dash black line*) and the individual receiver functions (*gray line*)

Fig. 7 The variations of thickness and v_p/v_s ratio with azimuths of earthquake at stations of SZZ and ZCH

et al. 1997). These rocks were generated by magmatism of the Datong volcano and changed the surface and internal crustal constitution.

The v_p/v_s ratios from these two stations show obvious azimuthal variation. Its value obtained from the

earthquakes in northwest direction is smaller than that from earthquakes in other directions (Fig. 7). This may suggest that the amount of mafic material or partial melting is low in northwest direction compared to those in other azimuths.

4 Conclusions

The Shanxi Graben, one of the main rifts forming in the North China Craton, results from material flowing from the Tibetan Plateau (Tapponnier and Molnar 1977). Under the effect of the large extension by the subduction of the Pacific plate, material flows up from the eastern Asthenosphere and is blocked by the Ordos block. These mantle materials are leading to upwelling in the Shanxi Graben, together with volcanic activity and earthquakes. All of these present as a thinner crust and a higher Poisson's ratio (Ge et al. 2011).

In this study, 6204 receiver functions were obtained from teleseismic events recorded at 40 digital seismic stations in Shanxi Regional Seismograph Network and temporary seismic stations (ZBnet-W) that were deployed by the Institute of Earthquake Science, China Earthquake Administration. The crustal thickness and v_p/v_s ratio under the Shanxi Graben and its surroundings were inverted. Our result shows the crustal thickness in Shanxi Graben ranging from 36 km to 45 km, and the v_p/v_s ratio ranging from 1.68 to 1.85. In addition, the result reveals obvious lateral variation in crustal thickness, which increases gradually from the east to the west. Along the NS direction across the Graben, crust changes from thin to thick, and then to thin again, with the deepest Moho located beneath the central part. Specifically, the crustal thickness of Xinding basin, in the middle of the orogenic belt, is 43 km, which is higher than that of northern and southern regions. In the north of the confluence of the Xinding basin and Taiyuan basin, the average v_p/v_s ratio is higher than that in the south. Furthermore, the highest v_p/v_s ratio exists in the crust of the Xinding basin and Datong basin.

According to this study, due to the fierce activities of the magmatism under the Wutai uplift, the crustal thickness of Xinding basin and its vicinity area is greater, as is the v_p/v_s ratio, compared to those in other areas of the Shanxi Graben. In addition, due to the magmatism of the Datong volcano caused by subduction of the western Pacific plate and lateral compression of the India Plate, we note a high v_p/v_s ratio which indicates richer mafic materials or higher partial melting in the crust, and that the amount of mafic material or partial melting is low in the northwest direction compared to those in other azimuths.

In general, P wave velocity is positively correlated with crustal depth, and negatively correlated with the velocity ratio. There is some influence for the crustal depth in complex crustal structure with the variation of P wave (Li et al. 2010). The sediment layer in Shanxi Graben is thinner, and the influence is smaller for the receiver function result. Therefore, we did not take into account the effect of sediment structure on the top crust in this

research, and the suggested velocity P wave was 6.2 km/s from the some previous study.

Acknowledgments Waveform data for this study were provided by the Data Management Center of China National Seismic Network at Institute of Geophysics, China Earthquake Administration (Zheng et al. 2010). We thank Prof. Fenglin Niu for constructive comments and helpful revision. This research is supported by the National Natural Science Foundation of China (No. 41230210), the Projects of International Cooperation and Exchanges from the Ministry of Science and Technology of China (Grant No. 2010DFB20190), and the Fundamental Research Funds for the Institute of Earthquake Science, China Earthquake Administration. We sincerely thank two anonymous referees for their constructive comments and suggestions which helped improving the manuscript.

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