Preliminary study of lateral variation in crustal structure of Northeast China from teleseismic receiver functions*

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Abstract We conducted comprehensive receiver function analyses for a large amount of high-quality broad-band teleseismic waveforms data recorded at 19 China National Digital Seismic Network (CNDSN) stations deployed in Northeast China. An advanced H - κ domain search method was adopted to accurately estimate the crustal thickness and v_P/v_S ratio. The crust has an average thickness of about 34.4 km. The thinnest crust occurs in the central region of Northeast China, while the thickest crust is beneath the Yanshan belt. The v_P/v_S ratio is relatively uniform with an average of about 1.733. The highest v_P/v_S ratio is found beneath the Changbaishan, likely associated with its volcanic activities. We found significant lateral heterogeneity beneath three stations CN2, MDJ, and MIH located along the Suolon suture from the back-azimuthal dependence of Moho depth. The velocity modeling from receiver functions indicated complicated Earth structure beneath these stations with large crust-mantle transition zone, noticeable velocity jump in upper mantle, and low velocity zone in middle crust. Dipping velocity interface in the crust with strike approximately parallel to the Suolon suture and down-dip to the south or southeast might explain the observed lateral heterogeneity.

Key words: Moho; crust; receiver function; lateral heterogeneity

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1 Introduction

Northeast China consists of tectonic collages of accreted late Paleozoic terranes, which include a series of fold belts and sedimentary basins. It is delimited to the south by the Permo-Triassic Suolon suture and to the north by the Cretaceous Mongolo-Okhotsk suture (Figure 1). Northeast China is comprised of part of the Sino-Korean Craton and part of the Mongolian accretionary fold belt. During the late Permian and early Triassic, the Mongolian arc terrane was finally welded together with Sino-Korean Craton along the Suolon suture (Yin and Nie, 1996; Davis et al., 2001; Graham et al., 2001). The Suolon suture was reactivated of its southern part in the Mesozoic to form the Yanshan

fold belt. During the same geologic period, large sedimentary Basins, such as the Hailar and Songliao Basins, formed. This region was also influenced by the important subduction processes during most of its history of evolution, such as the Mongolo-Okhotsk ocean subduction to the both north and south during the late Triassic (Vermeesch, 2003).

The importance of the evolutionary history of Northeast China results in relatively complicated crustal and upper mantle structure beneath this region. As a preliminary result, we studied lateral heterogeneity of the crust by applying teleseismic receiver function technique on the China National Digital Seismic Network (CNDSN) deployed in Northeast China in this paper. Since the later 1990s, the China Earthquake Administration (CEA) has spent tremendous efforts on building modern digital seismic networks. The CNDSN has been accumulating a large amount of high-quality waveform data applied in all sorts of geophysical studies for China (e.g., Huang et al., 2003; Ma and Zhou,

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2007; Zheng et al., 2008). Chen et al. (2010) measured the crustal thickness (defined as Moho depth), and average crustal v_P/v_S ratio (also the better known crustal elastic property Poisson's ratio) through a comprehensive receiver function analysis on teleseismic waveforms recorded at 48 first-order CNDSN stations to investigate the crustal structure and properties across China. The receiver function models provided complementary constraints for the Earth structure and properties from independent perspective comparable to other geophysical models derived from travel-time tomography and deep seismic sounding (DSS) experiments conducted across China (e.g., Cui et al., 1995; Li and Mooney, 1998; Wang et al., 2000; Vergne et al., 2002; Wang et al., 2003, 2007; Liang et al., 2004; Pei et al., 2004; Sun et al., 2004;

Zhang et al., 2005; Sun and Töksöz, 2006; Li et al., 2006; Liu et al., 2006; Zhao et al., 2006; Sun et al., 2008). In this study, we performed comprehensive receiver function analyses on nine first-order CNDSN stations and ten regional stations deployed in the region of Northeast China (Figure 1). All first-order stations were collected more than 230 receiver function traces with high quality, while most regional stations had 70–110 receiver function traces. The ample number of recordings enables excellent back-azimuthal coverage of each station. We first measure the crustal thickness and v_P/v_S ratio beneath each station, and then investigate the possible lateral variations of the crustal structure from the variation of the receiver functions dependent on back azimuths.

Figure 1 Distribution of 19 CNDSN stations (triangles) used in this study. The red triangles represent the first-order CNDSN stations, while the magenta triangles represent the regional stations. The topographic map also shows major tectonic blocks and faults in this region. Abbreviations on the map are Mongol-Okhotsk fold belt (M-O FB); Sino-Korean Craton (S-K Craton); Suolon suture (1); Mongolo-Okhotsk suture (2).

2 Measurements for crustal thickness and v_P/v_S ratio

The information of Earth's structure near the receiver site contained in teleseismic P-waveforms can

be isolated by deconvolving the vertical from the horizontal components to remove the source and distant path effects, which are in common in both vertical and horizontal components (e.g., Langston, 1979; Ammon, 1991). The resultant receiver function is most sensi-

tive to the velocity discontinuities beneath the recording site that generates P-to-S conversions. Therefore, the receiver function technique provides a stable way to determine the crustal thickness, the v_P/v_S ratio, the density contrast across the Moho, as well as shear-wave velocity structure in the crust and upper mantle.

In this study, we adopted an advanced H - κ (crustal thickness - v_P/v_S ratio) domain stacking and search procedure to estimate crustal thickness and v_P/v_S ratio simultaneously. The stacking for amplitudes of the primary P-to-S converted phase and crustal multiples usually results in relatively strong trade-off between H and κ (e.g. Nair et al., 2006). We calculated the coherence between P-to-S converted phase and crustal multiples at different κ values, and applied their semblance as an additional weighting factor in stacking. This new technique has been proven efficiently to eliminate the trade-off between H and κ (refer Niu et al. (2007) and Chen et al. (2010) for details). We utilized teleseismic waveforms coming from all back-azimuthal directions in order to obtain average crustal thickness and v_P/v_S

ratio beneath each station.

We show our results on all used stations in Northeast China in Figure 2 and Table 1. Table 1 also lists the actual number of receiver functions used by each station, measurement errors, as well as comparison with a tomographic model for China (Sun and Toksöz, 2006; Sun et al., 2008) and Crust2.0 model (Bassin et al., 2000). The average crustal P-wave velocity used in H - κ stacking is taken from Sun and Toksöz (2006) tomographic model (Table 1). Among the results of these stations, YIL presents a thick crust and very low v_P/v_S ratio. However, considering the fact that it has only eight receiver functions used for computation (Table 1), the measurements on this station are not as reliable as other stations. Excluding YIL, the crustal thickness of this region ranges from 29 km to 39 km with an average of 34.4 km, while the v_P/v_S ratio ranges from 1.65 to 1.79 with an average of 1.733 ($\sigma=0.251$).

We generate 2D relief maps for crustal thickness and v_P/v_S ratio (Figure 3) by inverting values at meshed grids of $0.5^\circ \times 0.5^\circ$ from 18 (excluding YIL) reliable

Figure 2 Stacked receiver functions are mapped to depth (a) and to v_P/v_S ratio (b). The squares denote the maximum peak corresponding to the depth of Moho (a) and appropriate crustal v_P/v_S ratio (b). The vertical lines indicate the average values across our study region.

Table 1 Results of the Moho depth, v_P/v_S ratio, the average crustal v_P used in H - κ search, and comparison to tomographic model and Crust2.0

Station code	Number of RFs	Moho depth /km	v_P/v_S	v_P /($\text{km}\cdot\text{s}^{-1}$)	Moho/km (Tomo)	v_P/v_S (Tomo)	Moho/km (Crust2.0)	v_P/v_S (Crust2.0)
BJT	536	39.3 ± 0.3	1.788 ± 0.009	6.4799	31.0	1.77	30.0	1.78
ZJK	87	40.0 ± 0.2	1.716 ± 0.005	6.5080	36.6	1.76	31.0	1.76
DL2	231	35.1 ± 0.4	1.702 ± 0.016	6.2400	31.8	1.80	30.0	1.81
THA	73	32.8 ± 0.3	1.754 ± 0.008	6.4508	38.9	1.78	37.0	1.76
SNY	246	31.2 ± 0.5	1.774 ± 0.015	6.4194	39.3	1.75	37.0	1.76
YNB	83	33.0 ± 0.1	1.764 ± 0.003	6.5813	39.5	1.77	32.0	1.79
CIF	113	34.1 ± 0.2	1.725 ± 0.003	6.3704	33.8	1.72	31.0	1.76
XLT	277	35.6 ± 0.4	1.752 ± 0.016	6.2367	39.1	1.75	37.0	1.76
HIA	505	35.1 ± 0.7	1.648 ± 0.027	6.4010	39.0	1.80	36.5	1.78
MDJ	696	37.5 ± 0.3	1.730 ± 0.016	6.4514	39.5	1.78	32.0	1.79
MIH	8	34.2 ± 0.4	1.791 ± 0.014	6.5451	38.7	1.83	37.0	1.76
CN2	26	29.3 ± 0.4	1.754 ± 0.010	6.5453	43.2	1.88	37.0	1.76
YIL	8	40.4 ± 0.3	1.573 ± 0.007	6.5532	38.8	1.78	37.0	1.76
HEG	110	36.7 ± 0.2	1.630 ± 0.005	6.5019	38.9	1.82	36.5	1.78
WHT	90	35.4 ± 0.3	1.737 ± 0.006	6.3270	38.7	1.73	39.0	1.77
NZN	78	34.0 ± 0.4	1.794 ± 0.015	6.4437	39.1	1.78	37.0	1.78
WDL	99	32.2 ± 0.3	1.697 ± 0.011	6.4412	38.9	1.75	36.5	1.78
HEH	278	32.6 ± 0.3	1.732 ± 0.009	6.5361	40.7	1.84	36.5	1.78
BNX	243	31.2 ± 0.3	1.712 ± 0.015	6.5254	39.5	1.80	37.0	1.76

Figure 3 Moho relief map inverted from observations on stations shown as solid triangles. The stations in open triangles are not used for inversion. (b) Relief map of lateral variations for v_P/v_S ratio. The inversion method is the same as that used for the Moho relief map.

observations (Niu et al., 2007). The main purpose of the relief maps is to demonstrate lateral variations of crustal thickness and v_P/v_S ratio across Northeast China. We must note that the maps have no resolution in the corner regions, nor in the tectonic units short of observations, such as the Songliao Basin. The crust is less than 34

km thick beneath the middle and eastern part of North-east China, and it gradually thickens towards the North China Block (Figure 3a). The thickest crust occurs beneath the Yanshan fold belt, where the crustal structure could probably be complicated comparing to the rest of regions (Zheng et al., 2007). The apparent dis-

tinct crustal thickness might be attributed to the multiple phases of contraction and possible occurrence of crustal delamination beneath the Yanshan belt, which is in large contrast to other regions in Northeast China where tectonic extension likely dominated the crustal deformation since the late Mesozoic (e.g., Tian et al., 1992; Davis et al., 2001; Ren et al., 2002; Meng, 2003). The distribution of crustal v_P/v_S ratio has no apparent correlation with the thickness. It presents a low value zone to the northeastern part of our study area, while a high value zone beneath the Changbaishan (Figure 3b). This relatively high v_P/v_S ratio (above 1.85) very likely related to the back-arc volcanic activities in the Changbaishan (Lei and Zhao, 2005).

3 Lateral heterogeneity beneath stations CN2, MDJ and MIH

While estimating the crustal thickness and v_P/v_S ratio of Northeast China, we found interesting phenomena beneath stations CN2, MDJ and MIH that reveal strong lateral heterogeneous structure along the Suolon suture. Especially on CN2 and MIH, the crustal lateral heterogeneity is so strong that we could not find an optimal crustal thickness and v_P/v_S ratio by reconciling receiver functions from all back azimuthal directions. The measurements of these two stations are thus the results of a subset of teleseismic events in the direction

of northeast (30° – 60° in back azimuth) since what they generate estimates well agree with nearby stations. The advanced H - κ domain search method sufficiently gives accurate measurements if the crust is of minor lateral heterogeneities. In the case of strong lateral heterogeneities in the crust, the arrivals of P-to-S conversion and crustal multiples are not only the functions of epicentral distances, but also depend on back azimuths. It thus prevents us from reconciling the phases of observed P-to-S conversion and crustal multiples from all back azimuths to the predicted arrivals calculated on homogenous model in H - κ domain search.

In order to examine azimuthal dependence of crustal structure around CN2, MDJ and MIH, we binned receiver functions in 30° back azimuth windows and moved the window at step of 10° . The receiver functions gathered at all back azimuthal bins were applied in our advanced H - κ domain search method and mapped to depth profile (Figure 4). All three stations present noticeable variation in Moho depth with back azimuths. However, we also note the fact that although our data sets have all back-azimuthal coverage, more than half of seismicity occurs in the directions of the southeast and southwest given the geographical location of Northeast China. Therefore, the results derived from back azimuths between 110° and 250° have higher resolution than from other back azimuth ranges. At CN2 (Figure 4a), the Moho is found at depth of 29 km from back azimuths 20° to 50° , and it turns to increase with back

Figure 4 Depth stacked receiver functions generated at back-azimuth bins for stations CN2 (a), MDJ (b), and MIH (c), respectively.

azimuths. At 100° to 150° , the Moho depth reaches its maximum, and shows two peaks with different amplitudes in the stacked receiver functions. We adopted a multi-step receiver function modeling method including multiple constraints from grid search, H - κ domain search, and Pn and Sn wave velocities from previous tomography models to invert for 1-D shear-wave velocity model beneath CN2 (refer Tkalić et al. (2010) for details). The final model is simplified from the inversion by combining the layers with small velocity differences (Figure 5a). The model displays a low velocity zone in the middle crust at about 25 km following by gradually increasing of velocity down to about 38 km. A relatively sharp velocity jump occurs at depth of about 47 km. The velocity model well supports our observation in the depth mapping of receiver functions. Our model suggests very complicated structure of crust-mantle transition zone ranging over 10 km from 30 km to 47 km in depth.

From about 150° to 250° , the back-azimuthal dependence of Moho on station MDJ (Figure 4b) mani-

festes an apparent variation in depth. The crust reaches its deepest value of about 41 km at 200° . A number of controversial estimates of crustal thickness near MDJ indicated the complexity of local structure from different techniques and data sets. For instance, the Moho depth varies from 27 km from regional P and PP waveform modeling (Beckers et al., 1994), 34–36 km by active source seismic refraction experiment (Yuan et al., 1986), 42–43 km by surface wave modeling (Feng et al., 1981), to 36–42 km by very few receiver functions measurements (Mangino et al., 1999; Ma and Zhou, 2007). The H - κ domain search in this study gives an average thickness of 37.5 km. The shear-wave velocity model inverted from receiver functions (Figure 5b) might partly explain the difference between these results. The model also has a low velocity zone in the lower crust. The crust-mantle transition zone occurs between about 30 km and 43 km with gradually increased velocity. Another apparent velocity jump occurs at depth of about 51 km in upper mantle as gradually increased zone. The crustal velocity model for station MIH is similar to CN2 and

Figure 5 Shear-wave velocity models obtained from linearized inversion of receiver functions for stations CN2 (a), MDJ (b), and MIH (c), respectively. The best fitting models are shown in thin black lines. All iterations with different smoothness weight are shown in gray. The thick black lines indicate simplified models obtained from best fitting models by combining layers with similar velocity values.

MDJ, but with noticeable difference. Due to relative less number of teleseismic waveforms collected for MIH, we did not have enough observations to conduct H - κ domain search for back azimuths above 200° . The available back-azimuthal observations show the variation in Moho depth from 120° to 230° (Figure 4c), and the crust-mantle transition zone probably occurs from about 34 km to about 41 km, which is also revealed in the velocity model (Figure 5c). Comparing to CN2 and MDJ, our receiver function modeling of MIH indicates that it might not have low velocity zone in the middle/lower crust, but might have a low velocity zone in upper mantle.

4 A hypothesis of lateral heterogeneity: Dipping interfaces in the crust

We further investigate the lateral heterogeneity beneath the three stations by checking their tangential receiver functions. The tangential receiver function is complete zero when teleseismic P-wave propagates through an ideal lateral homogenous medium. However, if the tangential receiver function is comparable in amplitude to the radial receiver function, it indicates strong lateral heterogeneity beneath the site. One possibility of lateral heterogeneity is a dipping planar velocity interface, in which both the radial and tangential receiver functions vary with back azimuth in a predictable pattern (e.g., Langston, 1977; Cassidy, 1992; Zhu et al., 1995; Frederikson and Bostock, 2000). The numerical simulation for a model with dipping layers illustrates that the incident P-wave traveling towards the up-dip direction generates the largest and latest arrival of P-to-S phase on the radial receiver function, while the wave traveling towards the down-dip direction generates the smallest and earliest arrival of P-to-S phase. The radial receiver functions are thus symmetric across a line parallel to the dip direction. The tangential receiver functions are anti-symmetric about this direction and have zero amplitude, and the largest amplitudes of arrivals occur on the strike direction of the dipping interface.

For each of these three stations, we grouped and stacked both radial and tangential receiver functions in back azimuth range of 10° , and then aligned and plotted stacked waveforms according to the central values of all back-azimuth ranges (Figures 6–8). Since a lowpass Gaussian filter ($a=1.0$) was used to generate receiver functions, the arrivals of P-to-S converted phase and

crustal multiples as functions of epicentral distances did not cause important move-out in the stacking. At CN2, we found that the largest and latest P-to-S phase arrived at back azimuth 170° on the radial receiver function, while the tangential receiver function has minimum amplitude on this direction. This direction can be assumed as the down-dip of interface in the crust. At MDJ and MIH, we determined the down-dip direction at 170° and 190° respectively.

We calculated synthetics using an anisotropic ray theory code developed by Frederikson and Bostock (2000). The Earth models were taken from the simplified receiver function models shown in Figure 5 for these three stations, plus a crustal dip interface with strike at 80° , 80° and 100° for CN2, MDJ and MIH

Figure 6 The radial (a) and tangential (b) receiver functions at station CN2 stacked and aligned according to back azimuth. (c) and (d) are synthetic radial and tangential receiver functions at this station.

Figure 7 The radial (a) and tangential (b) receiver functions at station MDJ stacked and aligned according to back azimuth. (c) and (d) are synthetic radial and tangential receiver functions at this station.

Figure 8 The radial (a) and tangential (b) receiver functions at station MIH stacked and aligned according to back azimuth. (c) and (d) are synthetic radial and tangential receiver functions at this station.

respectively, and uniform dip angle at 30° . Synthetic receiver functions are plotted in Figures 6–8 to compare with observations on these three stations. In general, the pattern of the arrivals of P-to-S phase varying with back-azimuth revealed in synthetics is roughly consistent with observed data. The tangential receiver function stacks did not present apparent anti-symmetry as shown in synthetics probably because tangential waveforms are noisier than radial waveforms, as well as large epicentral distances stacking.

5 Discussion and conclusions

In this paper, we first estimated the crustal thickness and average v_P/v_S ratio for 19 CNDN stations

in Northeast China, and then studied crustal lateral heterogeneous structure beneath stations CN2, MDJ and MIH along the Suolun suture. The average crustal thickness of Northeast China is about 34.4 km with a variation of 10 km across the entire region. The central part of the study region has thinner crust than the average value, probably associated with the widespread extensional Mesozoic deformation in Northeast China (Cope and Graham, 2007). The thickest crust is found beneath the Sino-Korean Craton, which could be the result of contraction and possible crustal delamination of the Yanshan belt (Meng, 2003). The average crustal v_P/v_S ratio is about 1.733 ($\sigma=0.251$), lower than the global average of 1.78 for the bulk continental crust

(Zandt and Ammon, 1995). The only region with high v_P/v_S ratio (above 1.85) is beneath the Changbai volcano. However, it is difficult to relate the variations in crustal thickness and v_P/v_S ratio with the difference of tectonic blocks in Northeast China from basins and Cratons to fold belts and uplifts based on the results of only 19 stations.

As one of the oldest collision zones in the Asian tectonic collage, the Suolon suture is a ~ 3000 km long boundary between Paleozoic arc and accretionary complexes of southern Mongolia and Precambrian microcontinental blocks to the south (Sengor et al., 1993). It welded the Mongolian arc terranes and the Sino-Korean Craton together during the late Permian and early Triassic, and underwent reactivation during the Jurassic and Cretaceous as the Yanshan fold and thrust belt associated with the extension that formed the Hailar Basin and the Songliao Basin in the Mongolian arc terranes (Davis et al., 2001; Graham et al., 2001). The complicated tectonic history, as well as the existence of several known and inferred faults near stations, makes possible the existing of strong lateral heterogeneity in the crust of this region. We found the Moho depth beneath three stations, CN2, MDJ and MIH, along the Suolon suture strongly depend on back azimuth. On the other hand, we did find back-azimuth dependence for another station near the Suolon suture, CIF, which has a normal and flat Moho. This is probably because CIF is located on the Sino-Korean Craton, and the beneath crustal structure is largely dominated by the contraction of the Yanshan belt, instead of tectonic extension of Northeast China (Zheng et al., 2007). CN2, MDJ and MIH are all located at the most northeastern end of the Suolon suture. The strike runs from about 20° to about 80° from the northeast to the west in the region of Northeast China (Figure 1). The back-azimuthal dependent measurements for Moho depth on CN2, MDJ and MIH indicated the deepest Moho at 180° , 200° and 140° , respectively. If the model of dipping interfaces in the crust is able to explain the observed lateral heterogeneity, the dipping direction must concentrate on the direction roughly perpendicular to the Suolon suture, very likely towards the south or southeast side of the Suolon suture under the Changbaishan.

The preliminary results discussed in this paper mainly focus on the discovery of the strong lateral heterogeneous structure in the crust along the Suolon suture. The dipping interface in the crust might not be the only model to explain the observations because we also note the large dissimilarity between synthetic

and observed waveforms (Figures 6–8). The modeling of lateral heterogeneity or dipping interface structure in details involves the determination of many parameters, such as geometry of the dipping interface, possible anisotropy on the interface, as well as a priori knowledge of the Suolon suture. In the future studies for this problem, we will quantitatively determine these parameters in order to improve the waveforms match. Moreover, with more regional seismic stations available and more seismograms accumulated, we will achieve more clear image of crustal and upper mantle structure in this region.

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