P-wave tomography and relation between shallow and deep structures beneath the Songliao basin

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Abstract We selected relative travel-time residuals from teleseismic waveform data using the waveform correction method and imaged the P wave velocity structure beneath Northeast China. In combination with other geophysical data, we discussed the relation between the shallow and deep structures of the area. The results show that there is a primary high-velocity zone with some high- and low-velocity distribution characters beneath the Songliao basin. The low-velocity anomalies may extend down to the upper mantle, and may be the result of material upwelling. The low-velocity anomaly beneath the southern part of the Songliao basin is connected to those beneath the Changbaishan and A'ershan volcanic areas. It may be an upwelling channel from the mantle beneath the Songliao basin and adjacent area. This finding indicates the Songliao basin was a result of asthenospheric upwelling caused by subduction of the Pacific plate under the Eurasian plate.

Keywords Tomography · Northeast China · Ray · Relation between shallow-deep structures

1 Introduction

The Songliao basin is in the center of the Northeast China region, with the Central Asian fold belt (the Great Xing'an Range) to the west, the uplifted Changbaishan volcanic region to the east, and the Sino-Korean Craton to the south. The Songliao basin is commonly believed to be formed due to rifting in the Mesozoic Era (Hu et al. 1998; Ren et al. 2001; Liu and Niu 2011). In recent years, some studies have used tomography (P wave, Pn wave, S wave, and ambient noise), receiver functions, and S wave attenuation to reveal deep dynamic characteristics in the area (Zhao 2004; Lei and Zhao 2005; Sun 2012; Zhang et al. 2013, 2014; Pan et al. 2014). The previous research has shown that the Songliao basin was probably formed as a result of rifting during the Mesozoic. The eastern margin of the Songliao basin, where Cenozoic volcanism is active, has a relatively thin crust, with a upwelling channel of material from the mantle. The lithospheric mantle possibly underwent destruction and transformation, and lithospheric delamination may have occurred and greatly affected the Songliao basin (Song et al. 2010; Yu et al. 2012). Other studies have used the Bouguer gravity anomaly (Wei et al. 2014), magnetic (Shu et al. 2003), geothermal (Shi 2004), seismic and geological profiles (Wan 2012) to study the tectonic evolution of the Songliao basin. The dynamic studies paid more attention to the deep mantle structure beneath the basin; while tectonic evolution studies focused on shallow structure change. However the relation between shallow and deep structures in Songliao basin still remains poorly understood. In this study, we investigated lateral and vertical variations of the mantle using P wave tomographic data and other geophysical results to determine the relation between the shallow and deep structures beneath the Songliao basin.

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2 Seismic data and method

The recent release of broadband waveform data of permanent regional seismic networks in Northeast China from the China Earthquake Administration (CEA) (Zheng et al. 2009), from the NECESSA Array, and from our temporary networks provided a rare opportunity to investigate the crustal structure of this area. There were a total of 137 CEA broadband stations, 129 NECESSA Array stations, and 116 temporary stations in the study area (115°E–135°E and 38°N–52°N) (Fig. 1). We collected waveform data from 606 earthquakes of magnitude $M_S \geq 5.0$ occurred between May 2009 and August 2011 recorded at an epicentral distance of 30°–90° (Fig. 2).

The criteria used to select teleseismic events were as follows: (1) events should have an epicentral distance of 30°–90° and try to avoid effects of mantle and complex structure of the core-mantle boundary on seismic wave travel time; (2) events should have magnitude greater than M_S 5.0 to ensure that the seismic waves arrived at stations with a high signal-to-noise ratio; (3) there should be more

than 10 records for each event. After selection, we performed the following pretreatments on the data: RMEAN, RTREND, and band-pass filter with frequencies range from 0.02~0.1 Hz. We also used the wave cross-correlation method (VanDecar and Crosson 1990; Rawlinson and Kennett 2004) to pick up the residuals. Finally, we visually checked all the seismograms and selected a total of 90,724 usable relative travel-time residuals.

This study uses seismic ray travel-time tomography to study the velocity structure of Northeast China. This method involves the following steps: firstly subdivide the research region and mesh the grid; secondly pick up ray travel time in seismic data, seismic ray tracking; thirdly build the inversion equation and solve the matrix equation; and finally evaluate the results of resolution and reliability. The results provide some reliable velocity anomaly characteristics and provide good constraints for the solution of these velocity anomalies to elucidate basin formation and the geodynamic process. In this article, our main focus is P wave velocity abnormal structures.

Fig. 1 Tectonic setting and station distribution in the studied area

Fig. 2 Distribution of teleseismic events in the study

3 Reliability analyses of inversion results

3.1 Multi-channel cross-correlation, damping coefficient, and residual analyses

To validate the multi-channel cross-correlation results, we obtained the travel-time residuals from the original data. The stack results obtained using multi-channel cross-correlation is shown in Fig. 3. It shows that the cross-correlation results are reliable. We adopted the LSQR method (Paige 1982) with damping inversion. The damping coefficient in the algorithm controls the convergence speed and constrains the smoothness of the model. From the trade-off curve (Fig. 4) of model variance and travel-time residual variance for different values of damping coefficient, it can be found apparently when the damping coefficient is 20, the model is relatively smooth and the mean square is relatively small. Thus, in the inversion, we adopted a damping coefficient of 20.

Figure 5 shows the distributions of the relative travel-time residuals before and after inversion. The relative travel-time residuals before the inversion are most focused on the time period -1.0 s to 1.0 s. After inversion, the residual distribution has a smaller range, with most values lying between -0.4 s and 0.4 s, and has the characteristics of a normal distribution.

3.2 Resolution tests

Several inversion results could be obtained for multiplicity. Thus, we performed a checkerboard test to verify inversion

Fig. 3 Stack results obtained using multi-channel cross-correlation

Fig. 4 Tradeoff curves of model variance and travel-time residual variance for different values of damping coefficient (values shown in circles)

results to show the reasonable P wave structure beneath the studied area. The checkerboard test process is as follows: we firstly built an initial model I and created a disturbance model II in which positive and negative velocity anomalies are increased or reduced respectively on the basis of the initial velocity model I. Secondly using the relative residual mentioned above as the observation, we take the model II as the initial model for imaging inversion, and take the inversion result as the model III. Finally, we compared abnormal scale between models II and III, and the minimum abnormal body should be the resolution. In this study, we firstly created checkerboard anomalies alternating between 3 % faster and slower velocity anomalies. The studied area was separated into several blocks and the size of each block is approximately $50 \text{ km} \times 60 \text{ km}$. We then

Fig. 5 Distributions of the relative travel-time residuals before (*left*) and after (*right*) inversion

generated a synthetic travel-time dataset using earthquakes and stations identical to that of the observed differential travel-time data. Random noise ranging from -0.15 s to 0.15 s was added to the synthetic data. Figure 6 shows the results of the recovered checkerboards at eight different depths. The checkerboard model fit well in the depth less than 800 km. The largest and the smallest blocks are $16.0^\circ \times 20.0^\circ$ and $0.500^\circ \times 0.625^\circ$ laterally and 800 km and 50 km vertically. The study region was parameterized with the smallest blocks. The test indicates that the P wave travel-time data have good resolution at length scales of approximately 200 km in the study region. Note that the amplitudes of the velocity anomalies in the recovered model decay steadily with depth. For structures below 400 km depth, significant smearing occurs at the edge of the study area, and the recovered velocity perturbations are less than half of the input values.

4 Results and discussion

There have been many studies on seismic structure of the Songliao basin. Liu and Niu (2011) found that the crustal thickness varies from 27.9 km beneath the eastern flank of the Songliao basin to 40.7 km beneath the Da Hinggan Ling region and suggested there would be a mantle upwelling using tele-seismic receiver function method. Zhang et al. (2013, 2014) found there is a high-velocity zone beneath the Songliao basin with some high- and low-velocity anomalies using tele-seismic tomographic data. The low-velocity anomaly was found at the depth of 400 km beneath the southern part of the Songliao basin. Tele-seismic receiver function and seismic images studies by Tang et al. (2014) also verified this characteristics of high- and low-velocities anomalies distributed jointly in

the depths of 100 km and 260 km and low velocities zone at the depth of 420 km beneath the Songliao basin.

We selected the one-dimensional Earth velocity model IASP91 (Kennett and Engdahl 1991) as the initial test model, and adopted travel-time tomographic inversion of P wave to image the velocity structure. The imaging results for each depth are shown in Fig. 7. The Tanlu faults and the gravitational gradient zone are roughly the east and west boundaries of the Songliao basin, which is basically consistent with the main boundaries of the velocity anomalies. The region of Northeast China can be divided into three parts: east, middle, and west zones by velocity anomaly. The east and west zones are low-velocity anomalies: Changbaishan and A'ershan, respectively. The middle zone is the Songliao basin; in which there is some high- and low-velocities anomalies in the background of high-velocity zone. The high-velocity zone mainly distributes from depth of 50 km to 600 km, while the low-velocity anomalies zones mainly concentrate from depth of 50 km to 400 km. We also determined one low-velocity anomaly zone at the center of the Songliao basin in depth of 50–100 km and some low-velocity anomalies zones in the north and south of the Songliao basin with depths range from 150 km to 400 km. We deduced that the low-velocity anomalies extend down to the upper mantle, which may be the result of mantle material upwelling. Our results are similar to, but not completely consistent with, the other studied results (Li et al. 2006; Li and van der Hilst 2010; Wei et al. 2012; Zhang et al. 2013, 2014). The mixture of high and low-velocity anomalies suggests that the lithospheric mantle may have been destroyed and transferred, and hence the formation of the Songliao basin may have been greatly affected by lithospheric delamination. The low-velocity anomaly beneath the southern part of the Songliao basin area is connected to the those beneath the Changbaishan and A'ershan volcanic areas. This result

Fig. 6 Results of the checkboard resolution test of depth of 50 km (a), 100 km (b), 150 km (c), 200 km (d), 300 km (e), 400 km (f), 500 km (g) and 600 km (h). The blue and red stand for high- and low-velocities, respectively. The purple lines are gravitational gradient zone. The black lines represent the Tanlu faults; The gray lines represent the tectonic dividing line; The blue lines represent the isobath curves of the subducting Pacific plate, the red dots stand for the volcano and the black triangles denote stations

Fig. 7 Velocity structure of depth of 50 km (a), 100 km (b), 150 km (c), 200 km (d), 300 km (e), 400 km (f), 500 km (g) and 600 km (h) inverted using P wave travel-time tomography. The blue and red stand for high- and low-velocities, respectively. The purple lines are gravitational gradient zone. The black lines represent the Tanlu faults; The gray lines represent the tectonic dividing line; The blue lines represent the isobath curves of the subducting Pacific plate, the red dots stand for the volcano and the black triangles denote stations

Fig. 8 Vertical section across the Songliao basin from south to north (line *a* in Fig. 1) (42°N, 120°E) to (51°N, 129°E). The *upper* figure shows the topographical relief in this vertical section; the *lower* is the velocity anomaly imaging inverted by tomography. *Dashed lines* are the 410 km and 660 km discontinuities, the *arrow* in the figure give the boundary of the basin

Fig. 9 Vertical section across the Songliao basin from west to east (line *b* in Fig. 1) (45°N, 119°E) to (45°N, 130°E). The *upper* figure shows the topographical relief in this vertical section; the *lower* figure is the velocity anomaly imaging inverted by tomography. *Dashed lines* are 410 and 660 km discontinuities, the *arrow* in the figure give the boundary of the basin

reveals that there is an upwelling material channel from the mantle beneath the Songliao basin and its surrounding area.

As mentioned above, although many studies have been performed in the Songliao basin using various geological and geophysical methods (Shu et al. 2003; Zhao 2004; Lei and Zhao 2005; Sun 2012; Wan 2012; Zhang et al. 2013, 2014; Pan et al. 2014; Wei et al. 2014), the relation between shallow and deep structures in the Songliao basin still remains poorly understood. Figures 8 and 9 show the topographical relief and imaging inverted by tomography of two vertical sections across Songliao basin from (42°N, 120°E) to (51°N, 129°E) and (45°N, 119°E) to (45°N, 130°E), respectively. The figures suggest the Changbaishan maybe a result of mantle material upwelling originated from depth near 700 km. The receiver function results shows obvious lateral variation in the upper mantle transition zone, which maybe result from mantle material upwelling (Liu and Niu 2011; Tang et al. 2014). The geothermal gradient of the Songliao basin which has a high heat value, is slightly higher than that of other basins elsewhere in the world (Nie 2004). The strain fields of Northeast and North China show NW-SE extension is weaken from east to west. The maximum strain occurs in the middle of the Tanlu fault zone, which is the boundary of the Songliao basin (Li 2013). The subducting Pacific slab and the mantle upwelling may have a remote effect.

The suggestion of mantle material upwelling is consistent with fact that in the eastern margin of Songliao basin, Cenozoic volcanism is active and crust is thin. Despite the relatively high altitude in the region, the Songliao basin has a relatively thin crust, which is probably related to Mesozoic rifting (Liu and Niu. 2011). The previous studies (Liu and Niu 2011; Gao and Li 2014; Pan et al. 2014; Wei et al.

2014) suggested that variations in crustal thickness apparently play an important role in controlling tectonic activity in the study region. Studies of the regional variations in crustal attenuation in Northeast China and the adjacent regions shows that the highest attenuation (low Q_0 values) is observed beneath the Songliao plain, which has thick sedimentary deposits and strong tectonic activity (Sun 2012). The structure of the crust in the North Songliao basin, inferred from the Bouguer gravity anomaly, is divided into three layers: upper, middle, and lower crusts (Wei et al. 2014). The seismic profiles through the two uplifts of the Songliao basin show that the crustal structure has strong vertical and lateral heterogeneities; obvious differences can be observed between the upper and lower crustal reflections (Yang et al. 2003). This result reveals that the Songliao basin experienced multistage tectonic activities, while the distribution of basalt magma in the basin possibly confirms the existence of an upwelling material channel from the mantle that affected both the crust and the tectonic activity.

Our results indicate that the formation and evolution of the Songliao basin were related to the subduction of the Pacific plate under the Eurasian plate as well as asthenosphere upwelling, both of which produced jointly crustal extension. The subduction induced one-way circulation of the asthenosphere and diapirism of the mantle magma, leading to stretching and thinning of the lower crust under the shearing action and brittle stretching of the upper crust to form a rift basin. As the subduction of the west Pacific plate steepened, the subduction zone retreated eastward and the melted mantle material extended continuously eastward. As the mantle cooled, the Songliao basin subsided and developed into a depression basin.

5 Conclusions

We selected relative travel-time residuals from teleseismic waveform data using the waveform correction method and obtained 90,724 usable relative travel-time residuals. The teleseismic waveform data were recorded by a total of 382 stations in one permanent and two temporary networks in Northeast China. We used the data to image the P wave velocity structure beneath Northeast China.

The results show that mostly a high-velocity zone exists with many high and low velocity anomalies areas beneath the Songliao basin. The low-velocity anomalies may extend down to the mantle and are possibly induced by material upwelling. The distribution of high and low velocity anomalies suggests that the lithospheric mantle possibly experienced destruction and transformation, and the formation of Songliao basin was possibly greatly affected by lithospheric delamination. The low-velocity anomaly beneath the southern part of the Songliao basin is connected to the low-velocity anomalies beneath the Changbaishan and A'ershan volcanic areas.

Formation and evolution of the Songliao basin were caused by subduction of the Pacific plate under the Eurasian plate, which induced asthenospheric upwelling and hence crustal extension. This induced one-way circulation of the asthenosphere, and the diapirism of the mantle magma led to stretching and thinning of the lower crust as a result of shearing. Brittle stretching of the upper crust formed a rift basin. When the subduction of the west Pacific plate became steeper, the subduction zone retreated to the east, and the melted material in the mantle extended continuously eastward. As the mantle cooled, the Songliao basin underwent subsidence and developed as a depression basin.

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