High-resolution seismic tomography of the upper crust in the source region of the April 20, 2013 Lushan earthquake and its seismotectonic implications

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Received: 5 June 2013 / Accepted: 23 July 2013 / Published online: 30 October 2013

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Abstract Both P- and S-wave arrivals were collected for imaging upper crustal structures in the source region of the April 20, 2013 Lushan earthquake. High-resolution, three-dimensional P and S velocity models were constructed by travel-time tomography. Moreover, more than 3700 aftershocks of the Lushan earthquake were relocated via a grid search method. The P- and S-wave velocity images of the upper crust show largely similar characters, with high and low velocity anomalies, which mark the presence of significant lateral and vertical heterogeneity at the source region of the Lushan earthquake. The characteristics of the velocity anomalies also reflect the associated surface geological tectonics in this region. The distributions of high velocity anomalies of both P- and S-waves to 18 km depth are consistent with the distributions of relocated aftershocks, suggesting that most of the ruptures were localized inside the high velocity region. In contrast, low P and S velocities were found in the surrounding regions without aftershocks, especially in the region to the northeast of the Lushan earthquake. For the relocated aftershocks of the Lushan earthquake from this study, we found that most

aftershocks were concentrated in a zone of about 40 km long and 20 km wide, and were located in the hanging wall of Dayi–Mingshan fault. The focal depths of aftershocks increase from the southeast to the northwest region in the direction perpendicular to the fault strike, suggesting that the fault ruptured at an approximate dip angle of 45°. The main depths of the aftershocks in the northwest of the main shock are significantly shallower than expected, revealing the different seismogenic conditions in the source region.

Keywords Lushan earthquake · Tomography · Velocity structure · Upper crust

1 Introduction

The M_s 7.0 Lushan earthquake on April 20, 2013 (hereafter referred as the Lushan earthquake) was another occurrence of a strong earthquake in this region that resulted in many casualties and injuries, and has been compared with the 2008 Wenchuan M_s 8.0 earthquake along the Longmenshan fault zone (LMSFZ) at the eastern margin of the Tibetan plateau (Fig. 1). The epicenter of the Lushan earthquake was also located at the LMSFZ at its southwestern segment. However, the ruptured fault that caused the Lushan earthquake is neither the extension of the central, nor is it part of the series of front-range faults of LMSFZ. The potential relationship between the Lushan and the Wenchuan earthquake could be analyzed through the 3-D crustal velocity model, the aftershock distributions and rupture process of the two earthquake shown in a few studies (Xu et al. 2010; Zhang et al. 2013; Zheng et al. 2009, 2013). Both earthquakes occurred in the collision boundary between the Tibetan plateau and the rigid Sichuan Basin. The India plate has been moving northward and subducting beneath central Asia, which has thickened

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Fig. 1 Distribution of aftershocks of the Lushan earthquake and the seismic stations. *Black circles* indicate the aftershocks collected in this study. The *triangles* and *squares* indicate the permanent and temporary seismic stations around the source region, respectively. *F1* Dayi–Mingshan Fault, *F2* Dachuan–Shuangshi Fault

the Tibetan plateau crust, tectonically forcing it eastward. Moreover, along the LMSFZ, the continental collision has formed the steepest topography gradient in the world (Li et al. 2011, 2012), which rises steeply westward from ~ 500 m in the Sichuan basin to $>4,000$ m elevation in the eastern Tibet plateau over a horizontal distance of ~ 50 km. The continental collision between India and Eurasian plates is believed to be the cause of both the Lushan and Wenchuan earthquakes (Zhang et al. 2010; Zheng et al. 2009).

Many studies have been conducted in the recent months as a result of the Lushan earthquake. The focal mechanisms, source rupture processes, stress changes, among other topics, are of great interest to geophysicists studying this region (Liu et al. 2013a, b; Zeng et al. 2013; Xie et al. 2013; Wang et al. 2013; Zhang et al. 2013; Shan et al. 2013). Many tomographic results from different methods and datasets near the LMSFT also provide helpful velocity models to study the background of the Lushan earthquake (Guo et al. 2009; Liu et al. 2009; Wu et al. 2009; Lei and Zhao 2009; Xu et al. 2010; Li et al. 2011, 2012; Zheng et al. 2013). However, the tomographic resolution of most previous results is usually around several tens of kilometers or larger, which is not enough to analyze the velocity variation at the source region and determine seismotectonic implications of the Lushan earthquake. In order to better analyze the seismotectonic characteristics of the Lushan earthquake, a detailed velocity model with better resolution (e.g., several kilometers) of the source region of the Lushan earthquake is essentially needed.

High-resolution crustal velocity models, especially P- and S-wave velocities at the source region are important for

determining the seismogenic environment of the earthquake. After the Lushan earthquake, the China Earthquake Administration placed 15 temporary seismic stations around the source region and recorded thousands of aftershocks. These data offer an opportunity to investigate the high-resolution velocity structure of the epicenter region. The main purpose of this study is to give a detailed velocity model of the source region. Based on the P- and S-wave arrivals collected from April 22, 2013 to May 1, 2013, the high-resolution three-dimensional P and S velocity models were constructed by travel-time tomography. Moreover, more than 3700 aftershocks of the Lushan earthquake were simultaneously relocated.

2 Method

In this study, we conduct a joint inversion of P- and S-wave velocity and source parameters using the P and S arrival times, simultaneously (Li et al. 2009a, b). The residuals of P arrivals can be represented as:

$$\delta t_{ij}^p = t_{ij}^{\text{obs},p} - t_{ij}^{\text{cal},p} = \sum \frac{\partial t}{\partial s_k^p} \Delta s_k^p + \sum_{l=1}^4 \frac{\partial t}{\partial q_l^i} \Delta q_l^i, \quad (1)$$

where $t_{ij}^{\text{obs},p}$ and $t_{ij}^{\text{cal},p}$ are the observed and synthetic P-wave travel times from the i th earthquake to the j th station, respectively; s_k^p is the P-wave slowness at the k th grid, q_l^i ($l = 1, 2, 3, 4$) is the source parameter for the i th earthquake (e.g., focal depth, latitude, longitude, and origin time). Similarly, the residuals of S arrivals δt_{ij}^s can be represented as:

$$\delta t_{ij}^s = t_{ij}^{\text{obs},s} - t_{ij}^{\text{cal},s} = \sum \frac{\partial t}{\partial s_k^s} \Delta s_k^s + \sum_{l=1}^4 \frac{\partial t}{\partial q_l^i} \Delta q_l^i, \quad (2)$$

where $t_{ij}^{\text{obs},s}$ and $t_{ij}^{\text{cal},s}$ are the observed and synthetic S-wave travel times from the i th earthquake to the j th station, respectively; s_k^s is the S-wave slowness at the k th grid. With Eqs. (1) and (2), the P- and S-wave velocity structures, together with the source parameters, can be jointly inverted with the P and S arrival times.

The travel time calculations and ray tracing in the complex three-dimensional model are conducted using finite difference techniques in the Cartesian coordinate system with an Earth flattening transform (Vidale 1988; Roecker et al. 2006; Li et al. 2009a, b). Compared with other ray tracing techniques, such as shooting or bending methods, the finite difference technique can improve the accuracy of the travel-time calculations and ray tracing in strongly heterogeneous media, which reduces the ambiguity in determining the global travel-time minima. Since the number of seismic stations is far less than the number of earthquakes, we take the stations as the sources to calculate travel times to all grids in three-

dimensional model to save time in the calculations. After obtaining travel-times from the stations to all grids, hypocenters can be determined conveniently via a grid search approach, which can always find the true minimum in data variance. Before each inversion for velocity and source parameters, the hypocenters of all earthquakes are relocated via the grid search approach. The linear equations for tomographic inversion are solved using the damped least-square QR dissolution (LSQR) algorithm (Paige and Saunders 1982). The source parameters remain in the equations and are solved simultaneously to reduce the bias to the velocity structures. However, the source parameters used in the next iteration are adopted from the grid search approach rather than by solving linear equations.

A fine grid spacing of 0.5 km is adopted for travel time computation with a finite difference technique, and a nominal coarser grid of 2 km is chosen in the horizontal and vertical (depth) directions for wave-speed inversion. In order to mitigate the introduction of artifacts only appearing at 1–2 grids, a moving average window smoothing with $3 \times 3 \times 3$ grids ($\sim 6 \times 6 \times 6 \text{ km}^3$) is applied twice in the 3-D space for the raw perturbations from inversion in all directions before updating the model.

3 Data and initial model

After the occurrence of the Lushan earthquake, the China Earthquake Administration placed 15 temporary seismic stations around the source region and recorded thousands of aftershocks. In this study, 12 temporary seismic stations together with 4 permanent seismic stations near the source region were used in the tomographic inversion. Over 4,000 earthquake catalogs with phase data were collected until the end of May 1 (Fig. 1). The P and S arrival times during this period from the temporary seismic stations and nearby permanent stations were collected from the database of the China Earthquake Networks Centre that were submitted by Earthquake Administration of Sichuan Province. The selection of arrival times is based on the following criteria: each earthquake had to be recorded by at least four stations with both P and S arrivals; travel time residuals had to be within $\pm 1.5 \text{ s}$ after earthquake relocation in the one-dimensional initial model. After data quality control, the entire dataset consists of 3,757 earthquakes with 23861 P arrivals and 24096 S arrivals. The P and S arrivals generally have good ray path coverage in and around the source region of the Lushan earthquake.

We prefer a one-dimensional model as the starting initial model. In western Sichuan and eastern Tibet, many previous studies have provided reliable starting models in the recent years, which have afforded background models for this study (Lei and Zhao 2009; Guo et al 2009; Liu et al.

Fig. 2 1-D P- and S-wave initial model. *Dotted line* indicates the S-wave velocity and *solid line* indicates the P-wave velocity

2008, 2009; Xu et al. 2010; Li et al. 2011, 2012; Wu et al. 2009; Zheng et al. 2013). However, the large scale regional model in the western Sichuan and eastern Tibet may not be very proper for the relative smaller area of the Lushan earthquake. In order to obtain a better one-dimensional model, we adjust the initial model according to the travel time residuals of the current dataset via several trial tomographic inversions. Finally, the one-dimensional initial model used in this study has proven to be much better in obtaining a reasonable tomographic result (Fig. 2).

4 Results and discussions

After four iterations, the P and S velocity model can fit the observed arrival times very well, and the root-mean-square (RMS) of both P and S arrival time residuals do not decrease significantly (Fig. 3). For all P and S arrivals, the RMS reduced from 0.39 to 0.24 s after the inversion. For P arrivals only, the RMS was reduced from 0.30 to 0.16 s after the inversion. For S arrivals only, the RMS reduced from 0.40 to 0.30 s after the inversion.

Checkerboard tests were conducted to evaluate the resolution. An anomaly size of $6 \times 6 \text{ km}^2$ (or 3×3 grid spacing) in the horizontal and depth directions were used in the checkerboard model. The recovered model indicates up to 18 km depth, the resolution is generally good at areas with good ray path coverage (Fig. 4). However, at greater than 20 km depth, the resolution becomes low due to the absence of ray path coverage. In this study, we only show the velocity images in the depth range of 0–18 km with relatively good resolution (ray path hit counts greater than

Fig. 3 Distributions of **a** P and **b** S travel-time residuals before and after the inversion

Fig. 4 Checkerboard resolution tests for **a** P and **b** S wave velocity results. The checkerboard size is $3 \times 3 \times 3$ grids in longitude, latitude and depth direction (i.e., $6 \times 6 \times 6 \text{ km}^3$)

Fig. 5 P wave velocity images from 0 to 18 km depth. *Red star* indicates the epicenter of the Lunshan earthquake. *Black circles* indicate the relocated aftershocks within ± 2 km depth of each image

Fig. 6 S-wave velocity images from 0 to 18 km depth. Red star indicates the epicenter of the Lunshan earthquake. Black circles indicate the relocated aftershocks within ± 2 km depth of each image

5 or more). The resolutions of our tomographic images shown in this paper could reach 6 km or better in most areas with good ray coverage. Our results provide acceptable velocity images to discuss the relationship between velocity anomalies and aftershock distributions, and the subsequent seismotectonic implications.

The three-dimensional P- and S-wave velocity structures of the source region of the Lushan earthquake were obtained by travel-time tomography. The horizontal slices of the P- and S-wave velocities for different depths are shown in Figs. 5 and 6, respectively. The P- and S-wave velocity images of the upper crust show similar characters of high and low velocity anomalies, which all indicate significant lateral and vertical heterogeneous at the source region of the Lushan earthquake. The pattern of velocity anomalies also reflects the associated surface tectonics in this region. The high velocity zone with most of the aftershocks are bounded by the Dayi–Mingshan Fault to the southeast and Dachuan–Shuangshi Fault to the northwest. The two faults also approximately form the boundaries between the high and low velocity zones at shallow depth. The distribution of high velocity anomalies of both P- and S-waves from surface to a depth of 16 km is all consistent with the distribution of relocated aftershocks, suggesting that most of the ruptures are localized inside the high velocity region. In contrast, low P and S velocities were found in the surrounding regions without aftershocks, especially in the region to the northeast area of the Lushan earthquake.

In this study, we provide three vertical profiles with one perpendicular to and two parallel to the strike of the rupture fault. The locations of these profiles are shown in Fig. 7, while the P and S velocity profiles are shown in Fig. 8. On these profiles, the high P and S velocity anomalies inside the source region, the Lushan earthquake are very clear. The low velocity anomalies to the northeast of the source region are also significant, with depths greater than 16 km. The low velocity anomalies to the northeast of the source region without aftershocks are very important, which will be helpful to understand why the aftershocks (rupture zone) are not extended northeastward to this area. The low velocity anomalies are located in the gap between the rupture zones of the Wenchuan earthquake on 2008 and the Lushan earthquake on 2013, which shows an aseismic zone. As relative weak upper crustal materials in the low velocity zone, it may be easier to accumulate enough stress to reach the criteria of rupture in the high velocity zone rather than low velocity zone.

Moreover, the aftershocks of the Lushan earthquake were simultaneously relocated while conducting the tomographic study. 3,757 earthquakes recorded by at least four stations with both P and S arrivals were relocated via a grid search approach using the three-dimensional velocity model that we determined. The distributions of the main

Fig. 7 Relocated aftershock distribution. The dashed lines show the position of three vertical profiles in Fig. 8. Red star indicates the epicenter of the Lushan earthquake. Black squares show the locations of seismic station used in this study

shock and aftershocks of the Lushan earthquake are showed in Fig. 7. For the relocated aftershocks, we found that most aftershocks were concentrated in a zone of about 40 km long and 20 km wide along the hanging wall of the Dayi–Mingshan fault, while only a few aftershocks were located in the footwall.

From the vertical profiles (Fig. 8), the focal depths of aftershocks gradually become deeper from the southeast to the northwest region in the direction perpendicular to the fault strike. The dip angle of these aftershocks was $\sim 45^\circ$, indicating the dip angle of the ruptured fault of the Lushan earthquake. The fault dip angle inferred from the distribution of the aftershocks at the profile AA' (Fig. 8a, b), and is consistent with the results of focal mechanism studies (Liu et al. 2013a, b; Xie et al. 2013; Zeng et al. 2013).

Abnormal focal depth distributions were found to the north of the source region and to the northwest of the main shock. The dominant depths of the aftershocks along profile CC' (Fig. 8e, f) at the northeast segment are different from that at the southwest segment, while the dominant focal depth along profile BB' (Fig. 8c, d) is almost the same at the different segment. In the north of the source region, the focal depths of the aftershocks are obviously shallower than that to the south, may suggest the different seismogenic conditions in this region. Another significant characteristic is that the focal depths of aftershocks were

Fig. 8 The velocity images of three vertical profiles (AA', BB' and CC') shown in Fig. 7. Black circles indicate the aftershocks within ± 2 km from the vertical profile. The distance is the length of the profile and X/Y is the projection of the profile in EW or NS direction shown in Fig. 7

less than 20 km in depth, while most of these aftershocks occurred inside the depth ranges of 8–18 km. The distribution of the aftershock focal depths from this study is also consistent with that determined by the “cut and paste” (CAP) technique (Xie et al. 2013; Zeng et al. 2013).

5 Conclusions

High-resolution P- and S-wave velocity images of the upper crust were obtained by three-dimensional travel-time tomography. The finite difference technique used in this

study can satisfy the accuracy requirement of the travel-time calculation and ray tracing in strongly heterogeneous media, which could improve the reliability of the high-resolution tomographic results. Earthquake relocation via a grid search approach with closely spaced, temporary seismic stations also provides reliable locations and focal depths of the Lushan earthquake aftershocks. The high-resolution P and S velocity structures, together with the relocated aftershocks, could provide helpful results to analyze the seismogenic model of the Lushan earthquake.

Similar characteristics of high and low velocity anomalies are found in the P- and S-wave velocity images of the

upper crust at the source region of the Lushan earthquake, which indicates significant lateral and vertical heterogeneous variations. The pattern of velocity anomalies also reflects the associated surface geological tectonics in this region. The distribution of high velocity anomalies of both P- and S-waves to 18 km depth is consistent with the distribution of relocated aftershocks, suggesting most of the ruptures are localized inside the high velocity region. In contrast, low P- and S-wave velocities are found in the surrounding regions without aftershocks, especially to the northeast region of the Lushan earthquake. For the relocated aftershocks from this study, we found that most aftershocks are concentrated in a zone of about 40 km long and 20 km wide in the hanging wall of Dayi–Mingshan fault, and few aftershocks are located in the footwall of the fault. The focal depths of aftershocks increases from the southeast to the northwest region in the direction perpendicular to the fault strike, which indicates that the ruptured fault had a dip angle of $\sim 45^\circ$. The mean focal depth of the aftershocks in the northwest of the main shock is significantly shallower than expected, revealing the different seismogenic conditions in this region.

Acknowledgments The seismic phase data were provided by China Earthquake Networks Centre. The authors are grateful for the people contributed to these datasets. We benefited from discussions with Prof. Zhonghuai Xu, Prof. Sidao Ni, and Prof. Lianfeng Zhao. This work was supported by Research Project in Earthquake Science (No. 201308018, No. 201108002), National Natural Science Foundation of China (No. 40904012), and National Basic Research Program of China (No. 2013CB733203, No. 2013CB733204).

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