The 20 April 2013 Lushan, Sichuan, mainshock, and its aftershock sequence: tectonic implications

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Abstract Using the double-difference relocation algorithm, we relocated the 20 April 2013 Lushan, Sichuan, earthquake (M_S 7.0), and its 4,567 aftershocks recorded during the period between 20 April and May 3, 2013. Our results showed that most aftershocks are relocated between 10 and 20 km depths, but some large aftershocks were relocated around 30 km depth and small events extended upward near the surface. Vertical cross sections illustrate a shovel-shaped fault plane with a variable dip angle from the southwest to northeast along the fault. Furthermore, the dip angle of the fault plane is smaller around the mainshock than that in the surrounding areas along the fault. These results suggest that it may be easy to generate the strong earthquake in the place having a small dip angle of the fault, which is somewhat similar to the genesis of the 2008 Wenchuan earthquake. The Lushan mainshock is underlain by the seismically anomalous layers with low- V_P , low- V_S , and high-Poisson's ratio anomalies, possibly suggesting that the fluid-filled fractured rock matrices might significantly reduce the effective normal stress on the fault plane to bring the brittle failure. The seismic gap between Lushan and Wenchuan aftershocks is suspected to be vulnerable to future seismic risks at greater depths, if any.

Keywords Lushan mainshock · Aftershock sequence · Double-difference algorithm · Shovel-shaped structure · Variable dip angle

1 Introduction

On April 20, 2013 a strong earthquake (M_S 7.0) occurred in Lushan county, Sichuan, southwestern China, which is situated in the Dachuan–Shuangshi fault (DSF), southwestern portion of the Longmenshan fault zone (Fig. 1). This earthquake resulted in 192 deaths, 23 missing home, and 11,470 injuries in and around the source zone. Till May 10, 2013, there occurred 8,552 aftershocks, among of which there are 98 (M 3.0–3.9), 22 (M 4.0–4.9), and 4 (M 5.0–5.9) earthquakes. The highest magnitude of these aftershocks is found to be 5.4 (www.cea.gov.cn).

The Lushan earthquake is the strongest earthquake in the Longmenshan fault zone, since the 2008 Wenchuan earthquake (M_S 8.0) (Fig. 1). The Longmenshan fault zone is a transition zone from Songpan–Ganzi block in the west to Sichuan basin in the east. This fault zone is composed of Wenchuan–Maowen, Yingxiu–Beichuan, Guanxian–Jiangyou faults, and a blind fault called Guangyuan–Dayi fault (Fig. 1) (Liu-Zeng et al. 2009; Ma et al. 2008; Hubbard and Shaw 2009; Li et al. 2009; Lei and Zhao 2009). It is generally suggested that the Wenchuan earthquake mainly ruptured the Yingxiu–Beichuan and Guanxian–Jiangyou faults (Fu et al. 2008; Ma et al. 2008), and that the Yingxiu–Beichuan fault has a much longer surface rupture (~ 200 – 270 km) than that (70–80 km) of the Guanxian–Jiangyou fault (Fu et al. 2008; Liu-Zeng et al. 2009; Ma et al. 2008; Xu et al. 2008; Zhang et al. 2008), while the Wenchuan–Mowen fault has no surface rupture. Ghosh and Mishra (2008) inferred that the 2008 Wenchuan earthquake was associated with the right-oblique reverse motion along the Longmenshan fault zone. The Lushan earthquake is located in the DSF, the southwestern portion of the Guanxian–Jiangyou fault. The DSF is a large thrusting fault. The geological survey showed that the fault has a

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large dip angle varying between 45° and 65° (Yang et al. 1999), while the source rupturing process investigation illustrated a dip angle of 38.5° (Wang et al. 2013). These

differences may indicate the complexity of dip angle of the fault plane related to the Lushan mainshock. In the present study, we applied the double-difference algorithm

Fig. 1 Distribution of seismic stations (*triangles*) used in the present study. *Stars* denotes the May 12, 2008 Wenchuan earthquake (M_S 8.0) and the April 20, 2013 Lushan earthquake (M_S 7.0). *White circles* denote the aftershocks (till May 3, 2013) of the Lushan mainshock. The *inset map* shows an enlarged area displaying the aftershocks and its nearby seismic stations. *Gray lines* denote major active faults (Deng et al. 2002). *SCB* Sichuan basin, *SGB* Songpan-Ganzi block, *DSF* Dachuan-Shuangshi fault

Fig. 2 **a, b** P-wave and S-wave travel-time residuals. **c, d** P-wave and S-wave observed (*black dots*) and theoretical (*red dots*) travel times. Observed travel times are extracted from the observation bulletins of China Seismic Networks Center. Theoretical travel times are calculated based on 1-D velocity models as shown in Fig. 3

(Waldhauser and Ellsworth 2000) to a large number of the Lushan aftershocks recorded at Sichuan provincial network in order to better understand the crustal dynamics of the eastern Tibetan plateau. Integrating with previous tomographic models (Lei and Zhao 2009), our results shed new insights into the mechanism of Lushan mainshock.

2 Data and method

In the present study, we collected the Lushan aftershock sequences from the China Seismic Networks Center observation bulletins between 20 April and May 3, 2013. Till 3 May, there were 7,100 aftershocks that occurred, but we can download only 5,960 aftershocks with P-wave and S-wave arrival times, among of which there are 1,107 aftershocks with magnitude greater than 2.0. We only chose the aftershocks with at least 4 seismic stations recordings. The travel time residuals of these recordings are less than 3.0 s, and epicentral distances are less than 500 km. Finally, we have chosen 5,144 earthquakes with 23,093 P-wave and 21,143 S-wave arrival times. Figure 2 illustrates travel times versus epicentral distance and travel time residuals. Most P-wave and S-wave arrivals are focused on the epicentral distance less than 200 km. From Fig. 1 we can see that seismic stations have a good azimuthal coverage around the Lushan aftershocks and there are three seismic stations very close to the aftershocks, suggesting a better control on relative high accuracy in earthquake locations, specially for focal depths (Zhang et al. 2007).

We used the double-difference algorithm (Waldhauser and Ellsworth 2000) to relocate the Lushan aftershock sequence. This technique is based on the difference of travel-time residuals and their similar ray paths from two events to the same seismic station, which suggests that it can decrease significantly the effects of velocity model uncertainties on the location. Although deep seismic soundings have been conducted around the Longmenshan fault zone (e.g., Wang et al. 2007), we still used 1-D P-wave and S-wave velocity models (Fig. 3) that are suitable to the region, because these two models were inferred from deep seismic soundings and natural earthquake data (Zhao et al. 1997). The ratio of P-wave to S-wave velocities is 1.71. Because the picking accuracy of S-wave arrival times is relatively less than that of P-wave arrival times, the weight of P-wave arrival time is set to be 1.0, while that of S-wave arrival times is set to be 0.5. The distance threshold of event pairs is 4.0 km. This technique has proven track record of applicability in different seismic zones of moderate to strong earthquakes in China and elsewhere in the world (e.g., Yang et al. 2002; Huang et al. 2008; Mishra et al. 2008; Zhang et al. 2011; Lei et al. 2012a; Mishra 2013). For details of the technique, see Waldhauser and Ellsworth (2000).

Fig. 3 Velocity models used in the present study. *Solid and dashed lines* denote P-wave (V_p) and S-wave (V_s) velocity models, respectively

3 Results

After the double-difference location, we obtained 4,567 relocated earthquakes. The average errors of root-mean squares in the east–west, north–south and depth directions are 0.17, 0.19, and 0.54 km, respectively. The relocated Lushan mainshock is confined at the longitude of 102.97°E, the latitude of 30.30°N, and focal depth of 18.3 km, and the corresponding errors are found to be 0.11, 0.12, and 0.20 km along the longitude, latitude, and depth directions, respectively. To better understand the significance of our relocation, we compared the location differences between original and relocated earthquakes (Fig. 4). Before relocation, the earthquakes are relatively scattered along the DSF in map and vertical views (Fig. 4a), while after relocation most earthquakes are more focused along the fault in map view, and some small earthquakes are located near the surface and large earthquakes occurred at deep layers as evidently shown in the vertical direction (Fig. 4b). Most aftershocks occurred to the southwest of the Lushan mainshock, suggesting that the rupture of the DSF is predominately along the southwest direction with its minor extension in the northeast direction, which is supported by the Harvard moment tensor solution

(www.globalcmt.org) and rupture process results (Wang et al. 2013; Zhang et al. 2013). The focal depth of the Lushan mainshock is improved from ~ 17.0 km in the observation bulletin (Fig. 4a) to 18.3 km after relocation (Fig. 4b), which is different from the centroid depth of 21.8 km inferred from the moment tensor solution (Zhang et al. 2013), but very close to 17.6 km of Fang et al. (2013) inferred using a similar technique as in the present study.

Use of aftershocks is regarded as one of the judicious techniques to investigate the fault geometry, we show distributions of aftershocks along eight vertical cross sections. One is along the DSF, while other seven ones are taken perpendicular to the fault (Fig. 5). It is hard to see spatial variation of aftershocks with time, suggesting that the DSF ruptured rapidly. This may be different from that of the March 10, 2011 Yingjiang earthquake (M 5.8) (Lei et al. 2012a). From vertical cross sections it can be seen that the DSF is shown as a shovel-shaped thrusting structure (Fig. 5). The dip angle of the fault gradually decreases from the northeast to the mainshock (Fig. 5b–d), and then begins to increase from the mainshock to the southwest (Fig. 5d–h). Such a variation of the fault plane may suggest a complicated tectonic environment around the Lushan mainshock. The Lushan mainshock occurred around the fault where there is a small dip angle, suggesting that the location of the small dip angle of the thrust fault could be apt to decrease the effective normal stress on inclusion of fluids into the fractured rock matrices to generate the

earthquake (Mishra and Zhao 2003; Mishra 2013). This observation is somewhat similar to that of the Wenchuan earthquake (e.g., Huang et al. 2008).

The S–P time differences from local seismic stations are usually used to judge if focal depths are reasonable after the relocation (Fukuyama et al. 2003). Around the Lushan aftershocks, there are two local seismic stations, SCBAX and SCTQU (Fig. 6), which have over ten earthquakes with epicentral distance less than 8 km. For seismic station SCBAX, the S–P time difference mainly focuses on the range of 1.5 and 2.7 s, which theoretically corresponds to focal depths of 9.5–18.0 km. These are generally consistent with those, 10–20 km, of relocated earthquakes (Fig. 6b). For seismic station SCTQU, the S–P differences are between 1.9 and 2.5 s, which theoretically correspond to focal depths of 12.4–16.3 km. These results are also in general consistent with those, 13–18 km, of relocated earthquakes (Fig. 6c). Furthermore, most relocated earthquakes fall in between two lines of epicentral distances of 0 and 8 km (Fig. 6b, c). All these results suggest that focal depths of our relocated earthquakes are generally reliable.

4 Discussion

Both Lushan and Wenchuan earthquakes occurred in the Longmenshan fault zone, so many researchers have been debating on an issue if the Lushan earthquake is an

Fig. 4 Comparison between original (a) and relocated (b) earthquakes. The star denotes the Lushan mainshock, while open circles denote its aftershocks. The size of circles denotes the magnitude of earthquake. The scale for the magnitude is shown in map view. *F* stands for earthquake frequency. DSF the Dachuan–Shuangshi fault

Fig. 5 Distributions of relocated earthquakes along eight vertical cross sections (a–h). Cross section **a** is along the DSF, while cross sections **b–h** are perpendicular to the fault. The size of circles (aftershocks) denotes the magnitude of earthquakes, and the scale for magnitude is shown in the insert map. The color filled in the circles denotes the aftershock time relative to the mainshock, and the scale for time is shown at the bottom. Topography along the vertical cross section is shown on the top. Locations of vertical cross sections are shown in the insert map. The star denotes the Lushan mainshock. The benchball illustrates the source mechanism solution of the mainshock from Harvard University. Dashed lines denote possible fault planes

aftershock of the Wenchuan earthquake (e.g., Chen et al. 2013a; Liu et al. 2013; Du et al. 2013). Here, we will not discuss this issue, but mainly focus on the dip angle of the DSF, causes of the Lushan earthquake, and the seismic gap between Lushan and Wenchuan aftershocks.

4.1 Comparison with previous results

In order to know if the aftershocks collected after 48 h since the mainshock could better reflect the geometry of the fault plane and the major active areas of seismicity, we

compare the results from two different datasets. The first dataset includes aftershocks collected after 48 h from the occurrence of the mainshock (Zhang and Lei 2013), whereas the second dataset includes aftershocks collected after 13 days, since the mainshock. Here, we only compare the relocated aftershocks within 48 h after the Lushan mainshock in these two datasets. The first difference between them is the number of aftershocks. Zhang and Lei (2013) showed only 328 relocated aftershocks (Fig. 7A), whereas the present study illustrates much more, 1032, relocated aftershocks (Fig. 7B). This may be due to many

Fig. 6 Reliability analysis for focal depths of relocated earthquakes. **a** Distribution of relocated earthquakes (circles) within an epicentral distance of 8 km off the local seismic stations (triangles SCBAX and SCTQU). The size of circles denotes the magnitude of earthquakes, while the scale for magnitude is shown at the bottom of (a). **b–c** Relationship between focal depth and S–P time difference. Two lines denote the epicentral distances of 0 and 8 km

more aftershocks that were processed within 13 days after the Lushan mainshock and that were added to the observation bulletins. The second difference is that the second dataset shows a much broad area of seismicity in map and vertical views (Fig. 7). Some small earthquakes could reach the surface, while large ones can occur at great depth of 30 km (Fig. 7f–h). However, these two datasets also show some similarities. For examples, most aftershocks occurred at depths of 15–20 km and the dip angle of the fault plane is around 45° around the mainshock and the dip angle becomes steeper to the southwest. Therefore, no substantial differences between them suggest that the aftershocks relocated using the data that are collected shortly after 48 h since the mainshock is sufficient to reflect the fault geometry and the nature of the crustal dynamics around the mainshock.

4.2 A variable dip angle

Zhang and Lei (2013) applied the same double-difference algorithm (Waldhauser and Ellsworth 2000) to relocate 328 Lushan aftershocks, and noticed a variable dip angle of the fault plane around the Lushan mainshock. However, because they relocated a limited number of aftershocks, these aftershocks only showed the dip angle of the fault plane to the southwest of the mainshock is larger than that around the mainshock (Zhang and Lei 2013). In our present

study, we relocated 4,567 earthquakes (Fig. 5), much more events than those in Zhang and Lei (2013), which conspicuously demonstrates a much detailed variation of the dip angle of the fault plane along the fault. The dip angle decreases from the northeast to the mainshock and then increases from the mainshock to the southwest (Fig. 5). This is different from those related to the Wenchuan earthquake. The dip angle of the fault plane related to the Wenchuan earthquake only increases monotonically to the northeast of the mainshock (e.g., Ghosh and Mishra 2008; Huang et al. 2008). However, the common feature between the Lushan and Wenchuan earthquakes is that both occurred in an area where the dip angle of the fault plane is relatively smaller than that in the surrounding areas. These observations suggest that strong earthquakes can occur where the dip angle of the fault is smaller.

4.3 Causes of the Lushan mainshock

Lei and Zhao (2009) used a large number of arrival times to invert for 3-D P-wave and S-wave velocity (V_P , V_S) and Poisson's ratio (σ) anomalies, and their results showed that the structure of the Longmenshan fault zone north of the Wenchuan mainshock is very different from that south of the mainshock. The northern segment exhibits more scattered heterogeneities, where most aftershocks occurred, whereas the southern segment contains a broad zone with

Fig. 7 Comparison between previous (**A**, Zhang and Lei 2013), and present (**B**) relocated earthquakes. These two datasets are all within 48 h after the Lushan mainshock, but different numbers of aftershocks are collected due to a gradual increase number of processed aftershocks with time. The 328 and 1,032 aftershocks are shown in **A** and **B**, respectively. **a, e** Map view; **b–d, f–h** vertical cross sections. The *size and color of circles* denote the magnitude and time of aftershocks relative to the mainshock. The scales for magnitude and time are shown at the *lower right corner of a and e* and the *bottom of A and B*. The fault data are from Deng et al. (2002). DSF the Dachuan–Shuangshi fault

low- V_p , low- V_s , and high- σ anomalies (Fig. 8a, d, g). A prominent low- V_p , low- V_s , and high- σ anomaly exist under the Wenchuan mainshock hypocenter (Fig. 8a, c, d, f, g, i), suggesting that in addition to compositional variations, fluids-filled fractured rock matrices may exist in the

Longmenshan fault zone, which may have influenced the generation of the large Wenchuan earthquake. The presence of fluids below the mainshock source zones using the integrated tools of geosciences (e.g., seismic tomography and magnetotelluric soundings) has also been documented

by several researchers (e.g., Zhao et al. 1996, 2002; Mishra and Zhao 2003; Lei et al. 2008; Lei 2011, 2012; Mishra et al. 2008). Such a fluid upward intrusion could be related to the lower crustal flow under the Tibetan plateau proposed by Royden et al. (1997), due to the Indo-Eurasian collision. The seismic images around the Lushan mainshock may somewhat different from those around the Wenchuan mainshock. Around the Wenchuan mainshock,

the low- V_P , low- V_S , and high- σ anomaly zone are cut by a high- V_P , high- V_S , and low- σ anomaly (Fig. 8c, f, i), whereas around the Lushan mainshock a continuous low- V_P , low- V_S , and high- σ anomaly are imaged from the crust down to upper mantle (Fig. 8b, e, h). However, there also exists a similar pattern of velocity anomalies under the Lushan and Wenchuan mainshocks. Under the Lushan mainshock exists a prominent low- V_P , low- V_S , and high- σ

Fig. 8 P-wave and S-wave tomographic (V_P , V_S) and Poisson's ratio (σ) images (Lei and Zhao 2009) around the Longmenshan fault zone. **a–c** V_P images; **d–f** V_S images; **g–i** σ images. Cross section NS (**a**, **d**, **g**) shows the images along the Longmenshan fault zone right passing through the 2013 Lushan (LS) earthquake (M_S 7.0) and the 2008 Wenchuan (WC) earthquake (M_S 8.0). Cross sections W1-E1 (**b**, **e**, **h**) and W2-E2 (**c**, **f**, **i**) show the images passing through the LS and WC earthquakes, but perpendicular to the Longmenshan fault zone. Red colors denote low- V and high- σ anomalies, whereas blue colors denote high- V and low- σ anomalies. The scale for velocity and Poisson's ratio anomalies is shown at the bottom. Stars denote the LS and WC mainshocks. Small black crosses in **a–i** and white dots in the insert map denote the Lushan (present study) and Wenchuan (Huang et al. 2008) aftershocks. Dashed lines denote the Moho discontinuity. Topography along vertical cross section is shown on the top. SCB Sichuan basin, SGB Songpan–Ganzi block

anomaly (Fig. 8a–b, d–e, d–h), suggesting that the generation of the Lushan earthquake could also be related to the fractured rock matrices filled by fluids that is helpful to decrease the effective normal stress on the fault plane of the DSF. Similar examples are the July 13, 1605 Qiongsan (M 7.5), 10 March 2011 Yingjiang (M 5.8) and 17 January 1995 Kobe (M 7.2) earthquakes (e.g., Zhao et al. 1996; Lei et al. 2009, 2012b).

4.4 A seismic gap between Lushan and Wenchuan aftershocks

Because of the deficiency of seismic tensor release and large aftershocks after the Wenchuan earthquake along the Longmenshan fault zone, Chen et al. (2008) proposed that there existed seismic risks (M_W 6.7–7.3) around the Baoxing–Xiaojin area along the southwestern portion of the Longmenshan fault zone, which has been demonstrated by the 2013 Lushan earthquake (Chen et al. 2013b). These results are strongly supported by a significant increase of Coulomb stress in the southern segment of the Longmenshan fault zone (Parsons et al. 2008) and an evident increase of apparent stress around the Baoxing region after the 2008 Wenchuan earthquake (Yi et al. 2013). Chen et al. (2013b) further inferred that there could exist a future seismic risk (M_W 6.8) in the gap between Lushan and Wenchuan aftershocks (Fig. 8). However, Zhao et al. (2013) found that the source rupture of the 2013 Lushan mainshock stopped when it extended less than 20 km along the northeast direction, which suggests that the crustal structure could change there. In order to figure out the seismic structure in the seismic gap, we show the tomographic images of V_P , V_S , and σ along vertical cross sections (Lei and Zhao 2009) (Fig. 8). It is clearly observed that there exists a seismic gap between two series of Lushan and Wenchuan aftershocks (Fig. 8a, d, g), suggesting that there could be a seismically vulnerable zone and the risk for future earthquakes in the gap (e.g., Chen et al. 2013b; Gao et al. 2013; Du et al. 2013; Xu et al. 2013). The vertical cross section NS illustrates the relationship between Lushan and Wenchuan earthquakes in tomographic images (Fig. 8a, d, g). The Wenchuan mainshock and its aftershocks occurred in more heterogeneous areas, and its aftershocks extended southwestward to only the boundary of low- V_P , low- V_S , and high- σ anomalies (Fig. 8a, d, g). In contrary to the Wenchuan earthquake, the Lushan mainshock and its aftershocks occurred in and around a low- V_P , low- V_S , and high- σ anomalous area, and its aftershocks extended northeastward only about 12 km (Zhang and Lei 2013) and met low- V_P , low- V_S , and high- σ anomalies (Fig. 8a, d, g). However, it is visible that obvious low- V_P , low- V_S , and high- σ anomalies are imaged above 20 km depth in the gap (Fig. 8a, d, g). This observation suggests that there may not be an apt environment to

accumulate the stress to generate the strong earthquake in the aftershock gap. Such seismic models may explain why Lushan aftershocks predominately extended southwestward, while Wenchuan aftershocks mainly extended northeastward. However, the presence of a high- σ feature in the gap below 20 km depth may correspond to an apt environment to accumulate the stress to generate strong earthquakes, which can lead to possible seismic risks in the future as witnessed by several past damaging intraplate earthquakes elsewhere in the world (Mishra et al. 2008). This seems indicative of possible seismic risks there, if any.

5 Conclusions

In the present study, we have relocated the Lushan mainshock and 4,567 aftershocks using the double-difference algorithm. Our results show that the dip angle of the fault plane around the Lushan mainshock is relatively smaller than that in the surrounding area along the existing fault, suggesting that it is easy to release the energy there. This observation is in unison to the Wenchuan earthquake. In addition, the Lushan mainshock hypocenter is underlain by low- V_P , low- V_S , and high- σ anomalies, suggesting that the fluid-filled fractured rock matrices could play an important role in the generation of the Lushan mainshock. The gap between the Lushan and Wenchuan aftershocks may be regarded as a seismically vulnerable zone that can cause seismic hazards due to moderate to strong earthquakes at greater depths of the crust, if any.

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