Article Chinese Science Bulletin

SPECIAL TOPIC
Coseismic Deformation and Rupture Processes of the 2013 Lushan Earthquake

October 2013 Vol.58 No.28-29: 3437–3443
doi: 10.1007/s11434-013-5999-4

Lushan M_S7.0 earthquake: A blind reserve-fault event

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Received May 22, 2013; accepted June 24, 2013; published online July 23, 2013

In the epicenter of the Lushan M_S7.0 earthquake there are several imbricate active reverse faults lying from northwest to southeast, namely the Gengda-Longdong, Yanjing-Wulong, Shuangshi-Dachuan and Dayi faults. Emergency field investigations have indicated that no apparent earthquake surface rupture zones were located along these active faults or their adjacent areas. Only brittle compressive ruptures in the cement-covered pavements can be seen in Shuangshi, Taiping, Longxing and Longmen Townships, and these ruptures show that a local crustal shortening occurred in the region during the earthquake. Combining spatial distribution of the relocated aftershocks and focal mechanism solutions, it is inferred that the Lushan earthquake is classified as a typical blind reverse-fault earthquake, and it is advised that the relevant departments should pay great attention to other historically un-ruptured segments along the Longmenshan thrust belt and throughout its adjacent areas.

Lushan earthquake, earthquake surface rupture zone, blind reverse-fault earthquake, Longmenshan thrust belt, Qinghai-Tibetan Plateau

Citation: Xu X W, Wen X Z, Han Z J, et al. Lushan M_S7.0 earthquake: A blind reserve-fault event. Chin Sci Bull, 2013, 58: 3437–3443, doi: 10.1007/s11434-013-5999-4

The Lushan M_S7.0 earthquake on 20 April, 2013, is another destructive earthquake which struck Sichuan Province almost exactly five years after the 2008 Wenchuan earthquake. Its epicenter was located at 30.314°N, 102.934°E, in Lushan County, along the southern segment of the Longmenshan thrust belt, a crustal shortening boundary which was caused by the southeastward moving of the Bayan Har Block and colliding with the South China Block, and located about 85 km away from the initial nucleation point or epicenter of the Wenchuan earthquake [1–4] (Figure 1). As the Lushan earthquake occurred at the site where the Coulomb stress positively increased due to occurrence of the Wenchuan earthquake [5,6], a controversy as to whether or not the Lushan earthquake was a strong aftershock of the Wenchuan earthquake has since arisen in the seismological community [7]. Meanwhile, there are several surface-visible NE-trending and NW-dipping active reverse faults running from northwest to southeast in the region, namely the Gengda-Longdong, Yanjing-Wulong, Shuangshi-Dachuan and Dayi faults, and the instrumental epicenter of the Lushan earthquake was located on the footwall of the Shuangshi-Dachuan fault. If this is the case, then which one of these surface-visible faults is the seismogenic fault of the Lushan earthquake? Is there any relationship between its seismogenic fault and the Shuangshi-Dachuan fault, or between the Lushan earthquake and Wenchuan earthquake? An in-depth study of these issues will provide a deeper understanding of the earthquake rupturing segmentation of the Longmenshan thrust belt, and provide a case study for determining where a future earthquake might occur along other active faults in and around the Qinghai-Tibetan Plateau, and how large it would be.

Our research group reached the epicenter only one day

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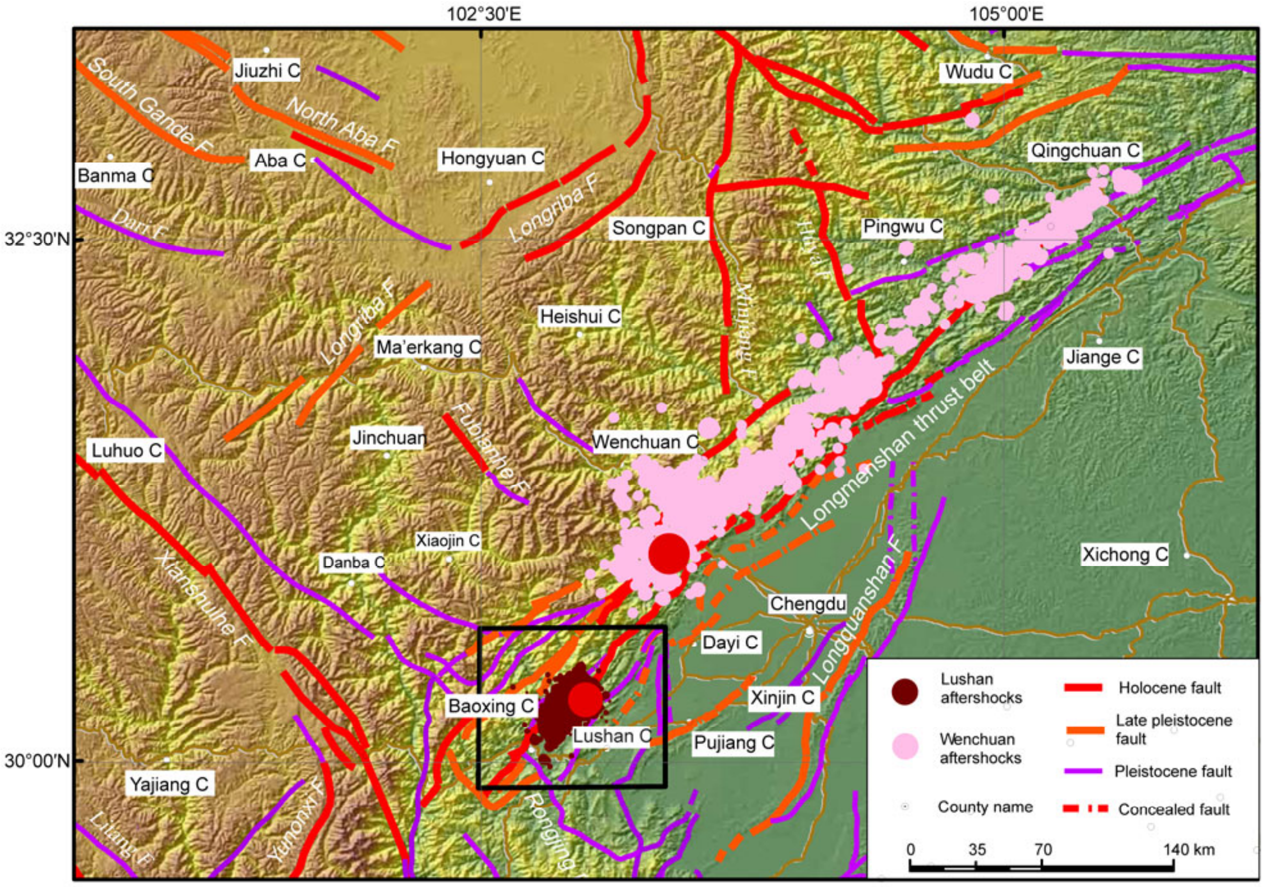

Figure 1 Tectonic map showing the spatial distribution of the Lushan and Wenchuan earthquakes, and their aftershocks along the Longmenshan thrust belt.

after the occurrence of the Lushan earthquake for emergency field observations, and obtained first-hand data on secondary surface ruptures. Here we first present the characteristics of the secondary surface ruptures of the Lushan earthquake, then discuss the Lushan seismogenic structure model based on focal mechanism solutions and relocated mainshock and aftershocks, as well as their spatial distribution, and finally conclude that the Lushan earthquake is a typical blind reverse-fault earthquake. This study provides a new type of seismogenic structure in the compressive tectonic environment for mainland China, and is very useful for determining whether or not the Lushan earthquake was a strong aftershock of the Wenchuan earthquake. More importantly, this seismogenic structure model will help us to understand mechanic conditions for earthquake nucleation and rupturing initiation, and to test prediction of future earthquakes along the Longmenshan thrust belt and in its surrounding areas.

1 Tectonic setting in brief

The Longmenshan thrust belt, located at the eastern margin of the Qinghai-Tibetan Plateau, along which the Lushan and Wenchuan earthquakes occurred, is composed of three surface-visible sub-parallel imbricate reverse faults, namely the mountain-back, mountain-central and mountain-frontal faults, as well as a frontal blind thrust fault [8–12] (Figure 1). Among these, the long-term vertical slip rate of the Beichuan-Yingxiu fault, the middle segment of the mountain-central fault, is 1–2 mm/a, and the inferred vertical slip rate of the Longmenshan thrust belt as a whole is as high as 4–6 mm/a [11–13]. The NW-trending crustal shortening rate across the Longmenshan thrust belt is inferred by geological study to be 10 mm/a [14], and the balance geological cross-section shows that its total crustal shortening amount is as high as 40%–60% [15]. GPS study demonstrates that the crustal shortening across the Longmenshan thrust belt is not significant, and its present rate is less than 3 mm/a [16–21], or about 7 mm/a in a 700-km wide range across the thrust belt [22]. Two end-member models for the Qinghai-Tibetan Plateau have also been proposed to explain the crustal and upper mantle deformation from a geo-scientific perspective, including a distributed continuous deformation and its revised channel flow model [17,18,23], and a block-like motion model along the localized mega-strike-slip faults [3,24,25]. The Lushan earthquake occurred along the southern segment of the Longmenshan thrust belt, where there are NEstriking and NW-dipping imbricate reverse faults, namely, from northwest to southeast, the Gengda-Longdong, Yanjing-Wulong, Shuangshi-Dachuan and Dayi faults (Figure 2). Similar to the tectonic origin of the Wenchuan earthquake [3,26], the Lushan earthquake is considered to be originated from an abrupt slip on a low angle reverse fault of the southern segment of the Longmenshan thrust belt between the Bayan Har Block and South China Block, where local crustal shortening has been dominated as a result of the Bayan Har Block moving southeastward and colliding with the South China Block [3,10–16]. Due to the fact that the epicenter of the Lushan earthquake was located at the site where the Coulomb stress increment was calculated by occurrence of the Wenchuan earthquake [5,6], we thus consider that this Coulomb stress increment may have potentially hastened the occurrence of the Lushan earthquake on a critically stressed reverse fault. The Lushan earthquake occurred under the compressive tectonic settings described above.

2 Secondary surface ruptures and focal parameters

According to statistics regarding surface-rupturing earthquakes it is known that an $M_W \geqslant 6.5$ earthquake can generate a surface rupture zone several km to several hundred km in length along its seismogenic active fault [27], but there is generally an exception for a reserve faulting earthquake with a similar magnitude on a hidden fault which does not rupture the Earth's surface. This type of earthquake is known as a blind thrust earthquake or fold earthquake [28,29]. The 1994 Northridge, 1987 Whittier Narrows, 1983 Coalinga, 1980 EL Asnam, and 1906 Manas earthquakes are well known blind thrust events [29–33]. A common feature of these events is that they do not generate a surface rupture zone along a surface-visible active fault, but instead a broad arch, known as an anticline, is formed above the blind reverse fault by fault-upward-propagation, reflecting a crustal shortening, and their aftershocks are widely distributed on

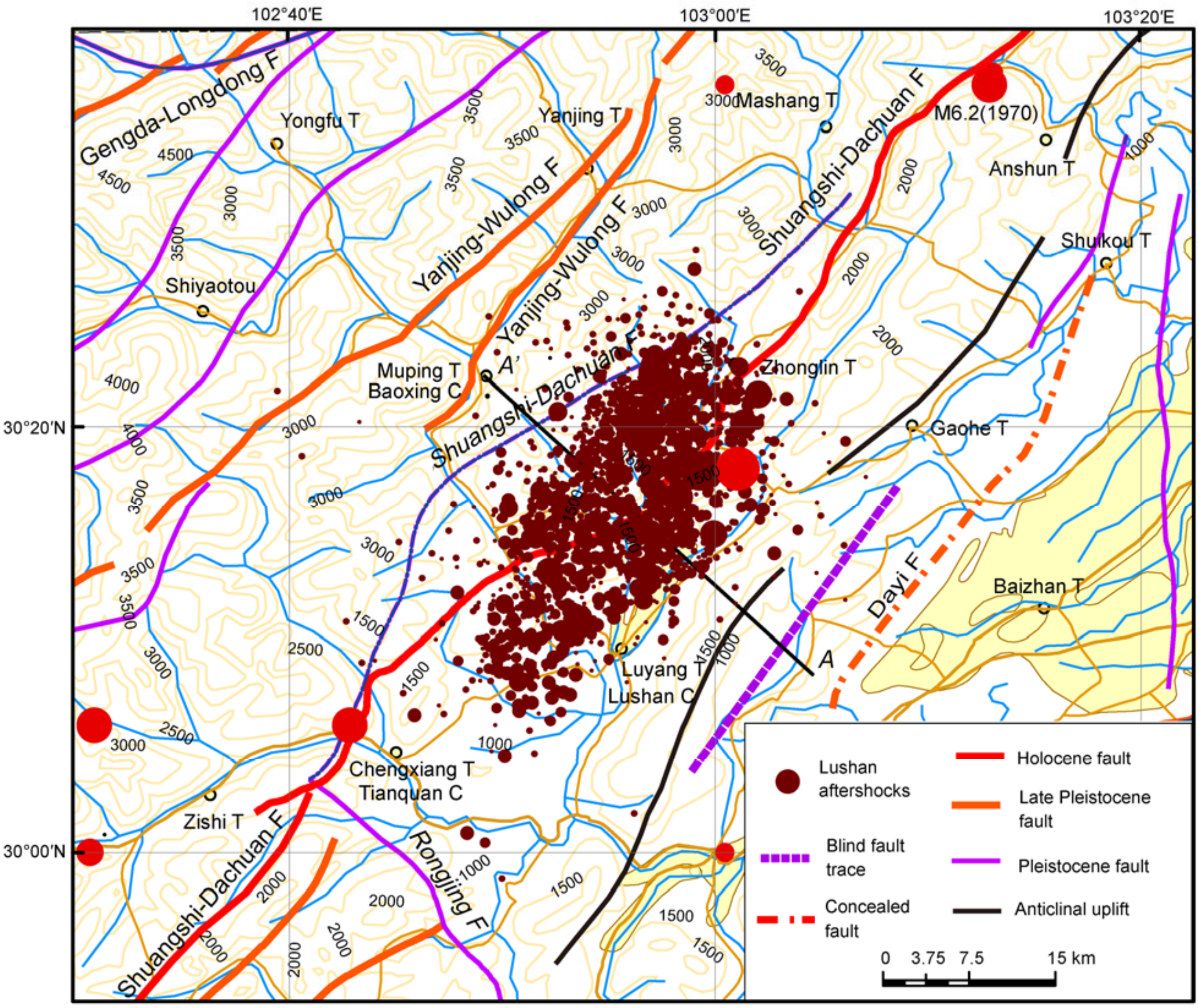

Figure 2 Spatial distributions of the Shuangshi-Dachuan fault and aftershocks in the epicenter of the Lushan earthquake. Aftershocks occurred during the periods of 20 April 2013 and 26 April 2013; *A*-*A*′: aftershocks' profile.

the vertical cross-section perpendicular to the strike of the blind reverse fault [29–33]. Such a widely distributed pattern contrasts strongly with that of a surface-visible fault earthquake, in which most of the aftershocks are aligned with the fault [29]. This is why we often observe an anticlinal uplift hill in the epicenter of the blind reverse-fault earthquake.

During the period of 21 April to 1 May, 2013, our emergency field observations performed in the epicenter, where the earthquake intensity reached levels VIII and IX, indicated that no earthquake surface rupture zone was found along the Dayi, Shuangshi-Dachuan, Yanjing-Wulong or Gengda-Longdong faults of the southern segment of the Longmenshan thrust belt. There were NE- and NW-striking tensional ground fissures, landslides, bedrock collapses and liquefactions found on the terraces or floodplains and steep piedmont zones in Taiping, Baosheng, Longmen, Shuangshi, Daxi, Lingguan, Shangli, Zhongli and Xiali Townships, Lushan and Baoxing Counties, and Yucheng District of Ya'an City. For example, there was a N75°E-striking tensional ground fissure zone about 1 km in length, along which water and sand sprayed out to form sand cones in en echelon along the ground fissures at the Yankan group, Shuanghe Village, Shuangshi Township (Figures 3(a)–(b)). Trench excavation across the ground fissure and sand cones further shows that the water and sand spray occurred along the SE-dipping tensional ground fissures (Figure 3(b)–(c)). To the northeast across one tributary of the Qingyi River to its eastern floodplain terraces, there were also many water-and-sand spraying sites, most of which occurred along the NW-striking tensional ground fissures. From these phenomena it is inferred that almost all of these ground fissures are the secondary surface breaks triggered by slope instability and vibration during the Lushan earthquake.

It is worth noting that the cement-covered pavement of the N60°W-trending highway from Shuangshi to Luyang was broken to form a compressive surface rupture near the Shuangshi-Dachuan fault. Measurements of the overlap amount of the broken cement-covered pavement and bend amount of cement-retaining embankment of the roadside gutter show that there is a 6 cm local crustal shortening at this observation site (Figure 3(d)–(e)). This type of local crustal shortening phenomenon can also be seen at other sites, such as on the highway to the Cizhupo group, Shuanghe Village, northeast of Shuangshi Township, as well as at Qinglong Village, Longmen Township, and Longxing Village to the north of Luyang Township, reflecting a NW-SE trending local crustal shortening in the order of 6–8 cm in the epicenter (Figure 3(f)–(g)).

In addition, a large number of tensional ground fissures were found in the bedrocks and Quaternary sediments along the Shuangshi-Dachuan and Dayi faults. The ground fissures run parallel to the strikes of the surface-visible faults, and especially those along one of the branches of the Dayi fault are concentrated on the steep hillsides, about 1500 m a.s.l., to the west of Shangli, Zhongli and Xiali Townships. We may regard these as the secondary surface breaks triggered by the coseismic ground uplifting during the Lunshan earthquake.

Therefore it can be seen that although many secondary surface breaks, landslides and bedrock collapses exist on the steep hillsides, as well as pre-existing faults or fault scarps in the epicenter, no any apparent earthquake surface rupture zone was generated by the Lushan earthquake. In other words, the seismogenic fault of the Lushan earthquake did not cut the Earth's surface, and this earthquake is thus classified as a blind reverse-fault event. Seismic waveform inversions indicate that the moment magnitude (M_W) of the Lushan earthquake is 6.7. Its focal depth ranges from 10 to 15 km in the upper crust and its focal fault, a typical blind reverse fault, strikes N40°E and dips towards NW with a dip angle of about 35°. The maximum coseismic net slip on the blind fault is estimated to reach 1.6 m below the Earth's surface [34]. This blind reverse-fault model is partially supported by the distributed pattern of the aftershocks which followed the Lushan earthquake.

3 Aftershock distribution and seismogenic model

By using seismic phase data of the Lushan earthquake and its aftershocks during the period of 20 April to 26 April 2013, downloaded from China Earthquake Network Center and based on the double-difference location algorithm [35], 2291 aftershocks were relocated. The relocated aftershocks did not occur along the Shuangshi-Dachuan fault, and were densely distributed in a N32°E-trending concentrated zone. This aftershock concentrated zone, about 45 km in length to the NE and 27 km in width to the NW, however, clearly beveled the Shuangshi-Dachuan fault (Figure 2), indicating that the Lushan earthquake appears to not be associated with the Shuangshi-Dachuan fault. From the temporal and spatial distribution of the main shock and its aftershocks it can be inferred that the Lushan earthquake rupture propagated from the NE (epicenter) to SW, while the Wenchuan earthquake rupture propagated from the SW (epicenter) to NE, i.e. the ruptures of the Lushan and Wenchuan earthquakes propagated in opposite directions (Figure 1). In addition, there is a 35-km-long aftershock gap between the aftershock concentrated zones of the Lunshan and Wenchuan earthquakes (Figure 1), where an M6.2 earthquake occurred on 24 February, 1970 (Figure 2). The future destructive earthquake risk of this aftershock gap requires further monitoring and re-assessment.

Here it must be noted that the relocated aftershocks which followed the main shock are widely distributed in the NW-trending cross-section. This distributed pattern is similar to that of the Coalinga earthquake [29]. Besides, the focal depths of the aftershocks range mainly from 9 to 19 km, and

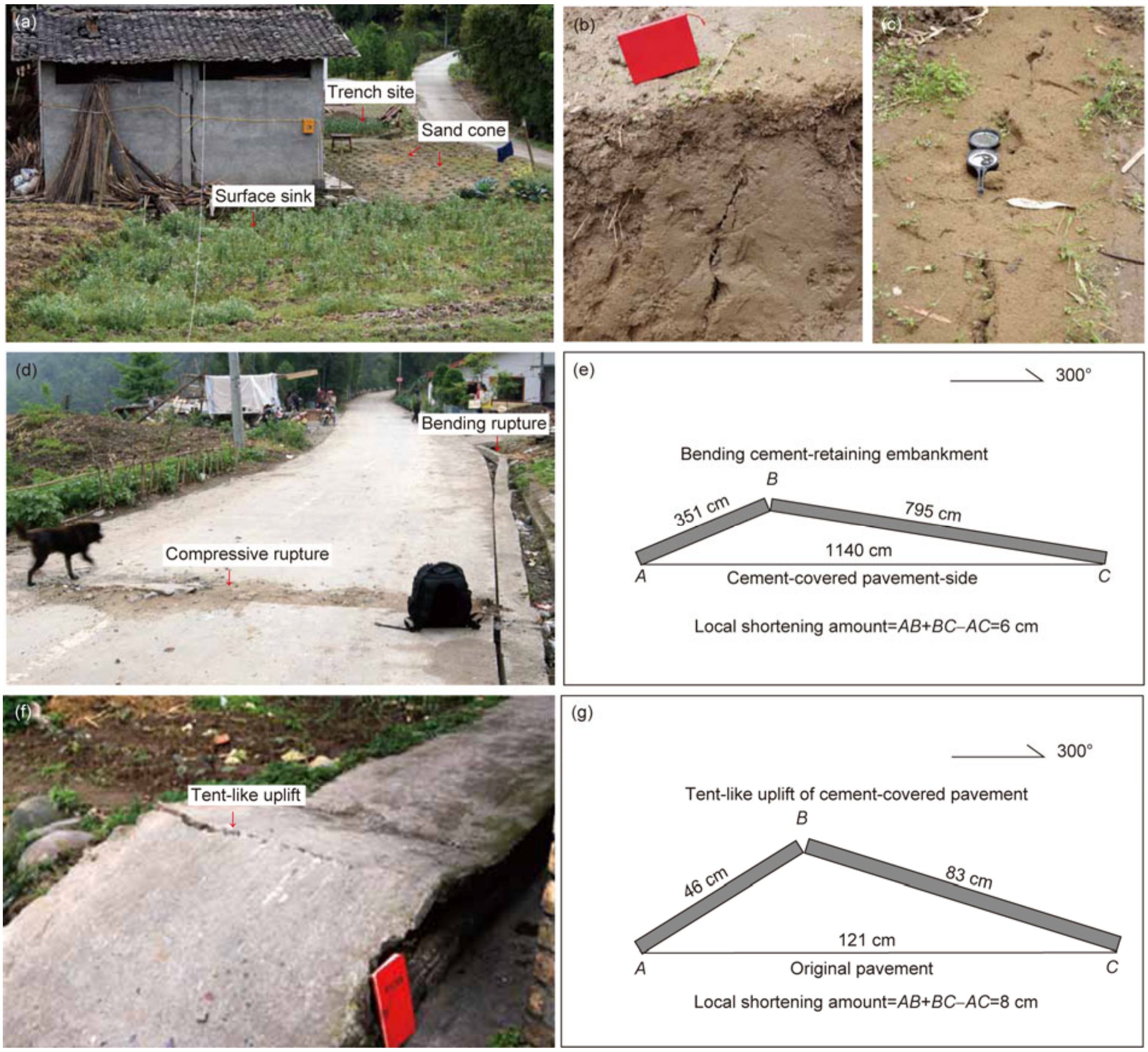

Figure 3 Secondary surface breaks in the epicenter of the Lushan earthquake. (a) Liquefaction phenomena and ground sink at Yankan group, Shuanghe Village, Shuangshi Township; (b) N75°E-striking and SE-dipping tensional fissure associated with water and sand spraying on the trench wall; (c) N75°E-striking tensional ground fissures in en echelon and associated sand-spraying cones; (d) compressive surface rupture of cement-covered pavement and bend of cement-retaining embankment of the roadside gutter on the highway at Yankan Group; (e) bend of cement-retaining embankment of the roadside gutter and local crustal shortening amount on the highway at Yankan group; (f) tent-like uplifting phenomenon at Wanghuo group, Qinglong Village, Longmen Township; (g) Local crustal shortening amount of the tent-like uplift at Wanghuo group.

few occurred at depths of less than 9 km in the crust (Figure 4). This signifies that the seismogenic fault of the Lushan earthquake is likely to be a blind reverse fault about 9 km deep in the crust. Another vivid feature of the relocated aftershocks illustrates a NW-dipping concentrated zone, which coincides with the focal fault inferred by the focal mechanism solutions [34]. Supposing that these aftershocks in the NW-dipping concentrated zone are directly associated with the seismogenic fault at the focal depth, then from the least square fitting to this NW-dipping concentrated zone it is known that the deep blind reverse fault strikes 212° and dips to the NW with a dip angle of 35±4° for the lower section (F1) around the main shock hypocenter (Figure 4). The number of aftershocks decreases rapidly upwards, but a NW-dipping steep linear zone exists at the depths of 12 to 7 km (Figure 4). We infer that this linear zone may be a newly-born upper section (F2) of the blind reverse fault, with an average dip angle of about 54±4°. As the dip angle of the upper section (F2) is too steep to slip on this fault plane, this may be the partial reason for which the focal fault did not propagate upward to cut the Earth's surface, and no any surface rupture zone exists. The uppermost part of the crust, i.e. above 7 km, where there are few aftershocks, may be a fault-propagation-anticline, which corresponds to the anticlinal hills observed in the field between Lushan County and Yucheng District of Ya'an City (Figure 2). Therefore, the steep linear zone (F2) at the depths of 7–12 km may also be an axial surface (trace) of a kink band at a

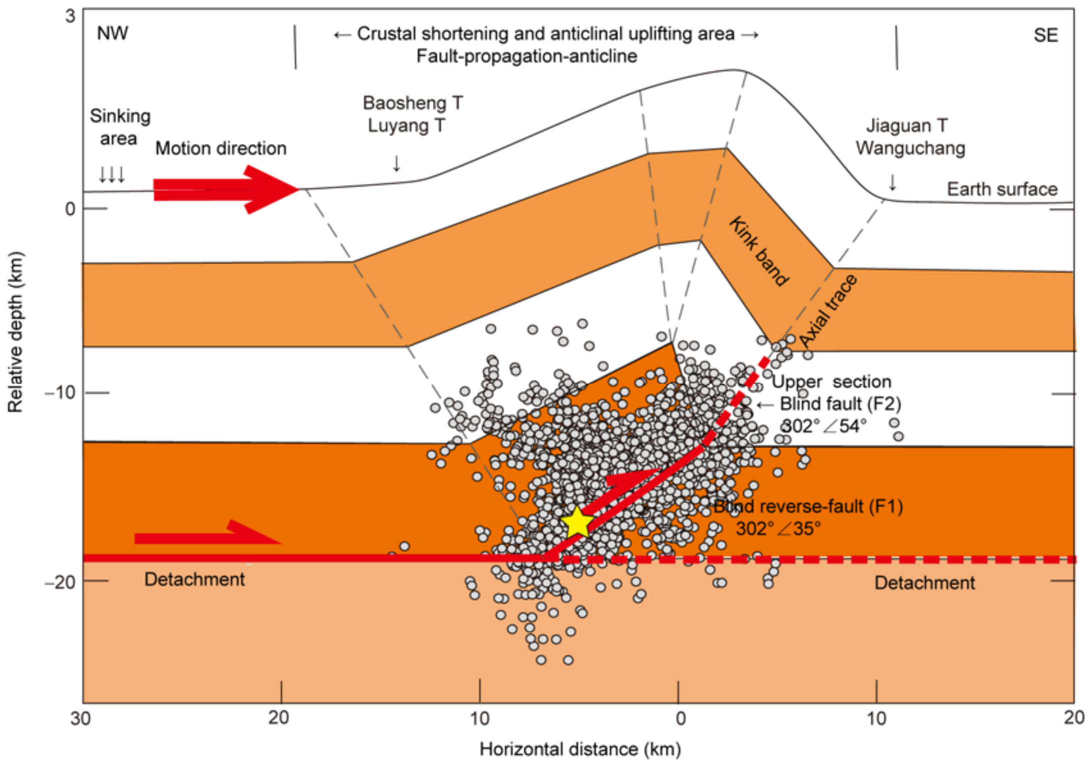

Figure 4 Balanced fault-propagation anticline showing the seismogenic fault model of the Lushan earthquake. White circles represent relocated aftershocks; yellow star represents the Lushan earthquake hypocenter; profile location is marked by *A-A′* in Figure 2.

steep limb side (Figure 4).

4 Conclusion and discussion

The Lushan earthquake occurred near the Shuangshi-Dachuan fault of the southern segment of the Longmenshan thrust belt, and its relocated aftershock concentrated zone clearly beveled the Shuangshi-Dachuan fault. Owing to no earthquake surface rupture zone along the surface-visible active fault, such as the Dayi, Shuangshi-Dachuan, Yanjing-Wulong or Gengda-Longdong faults, the Lushan earthquake appears to not be associated with the Shuangshi-Dachuan fault, or any other active fault visible in the epicenter. The spatial distribution of the relocated aftershocks and the focal mechanism solutions indicate that the Lushan earthquake is classified as a blind reverse-fault event. This blind reverse fault, located under the anticlinal hills between Lushan County and Yucheng District, strikes at 212° and dips to the NW, with a dip angle of 35±4°. The steep linear zone, with a dip angle of 54±4°, located above the blind reverse fault, may be either a newly-born section of the blind reverse fault or merely an axial surface of the kink band at the steep limb of the fault-propagation-anticline. Both of these two possibilities may explain why the focal blind fault did not propagate upward to cut the Earth's surface and why no surface rupture zone exists in the epicenter in terms of Structural Geology.

In addition, if we assume that the spatial distribution of the aftershocks represents the rupturing length limits, then it may be seen that there is no any overlap between the two focal ruptures of the Wenchuan and Lushan earthquakes, and if this is the case then the two earthquakes can be considered as independent rupturing events. If the Lushan earthquake is an independent event, however, is it the foreshock of an upcoming larger earthquake, or only the main shock? This is a scientific problem which must be taken seriously, as this problem will have a direct impact on further seismic monitoring and earthquake risk assessment for other un-ruptured parts of the southern segment of the Longmen thrust belt and Xianshuihe-Anninghe-Xiaojiang fault zone.

The authors thank two anonymous reviewers and Dr. Zhang Peizhen, an invited editor of this special issue, for their helpful comments and suggestions to improve the manuscript. This work was supported by the National Natural Science Foundation of China (91214201 and 40821160550) and the Special Fund for Scientific Investigation of the Lushan Earthquake.

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