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Structural geometry of the source region for the 2013 Mw 6.6 Lushan earthquake: Implication for earthquake hazard assessment along the Longmen Shan

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ABSTRACT

The 2013 Mw 6.6 Lushan earthquake occurred in the Longmen Shan fold-and-thrust belt, Sichuan Province, China, near the five-year anniversary of the devastating 2008 Mw 7.8 Wenchuan earthquake. To define the fault that generated the 2013 earthquake and its relationship with the Beichuan fault, which ruptured in the Wenchuan earthquake, we construct several cross sections and a 3D structural model. The sections and models reveal that the main-shock of the Lushan earthquake occurred on a portion of the Range Front blind thrust (RFBT) and that the structural geometry of this fault varies along strike. The Lushan main-shock occurred at a location along the strike of the fault where the geologic shortening and total fault slip are greatest. A lateral ramp of the RFBT appears to coincide with the northern limit of aftershocks from the Lushan earthquake, leading to a 75 km seismic gap between the Wenchuan earthquake and the 2013 earthquake sequence. Although both the Wenchuan and Lushan earthquakes occurred within the Longmen Shan fold-and-thrust belt, different faults generated the two events. Based on this structural characterization and analysis of the aftershocks of the Wenchuan and Lushan earthquakes, we suggest that the Lushan earthquake may have been triggered by the 2008 rupture but is best considered as an independent event rather than an aftershock of the Wenchuan earthquake. The RFBT that generated the Lushan earthquake is linked to a detachment that extends into the Sichuan basin along the Triassic evaporite layer. The coulomb stress change simulation suggests that other faults linked to this detachment may have been loaded by the 2008 and 2013 earthquake, posing the risk of future earthquakes along the Longmen Shan and in the densely populated Sichuan basin.

1. Introduction

The April 20, 2013 Mw 6.6 (U.S. Geological Survey, 2013) Lushan earthquake occurred in the Longmen Shan fold-and-thrust belt about 90 km to the south of the epicentral zone of the devastating 2008 Mw 7.9 Wenchuan earthquake. The Lushan event caused about 200 deaths, more than 10,000 injuries, and significant economic losses. The reports from several international agencies indicate that the hypocenter of this event is located from 12 to 18 km depth, with an average at about 16.6 km (Du et al., 2013). The focal mechanism solution suggests that the co-seismic fault trends 214°, with 39° dip and 100° rake (Du et al., 2013). According to the relocated main-shock and aftershocks provided by Fang et al. (2013), the aftershocks are concentrated in a 35 km NE trending belt at 10–25 km depth (Fig. 1(a)). There is a seismic gap extending about 75 km from the aftershock cluster of the Lushan earthquake to the main-shock of the Wenchuan event. The focal mechanism solution of the Wenchuan earthquake and the measured co-seismic slip of the surface rupture indicate that the displacement in the southern segment of the Wenchuan rupture was dominated by thrust slip (U.S. Geological Survey, 2008; Zheng, 2008; Ji, 2008) similar to the Lushan earthquake. The northern segment of the Wenchuan rupture involve significant components of right-lateral strike-slip and thrust motion (Xu et al., 2009; Lin et al., 2008, 2009; Liu-Zeng et al., 2009; Jia et al., 2010).

Field observations of the 2008 rupture suggest that two fault surfaces ruptured (Xu et al., 2009; Hubbard and Shaw, 2009; Hubbard et al., 2010). Rupture on the Yingxiu–Beichuan thrust

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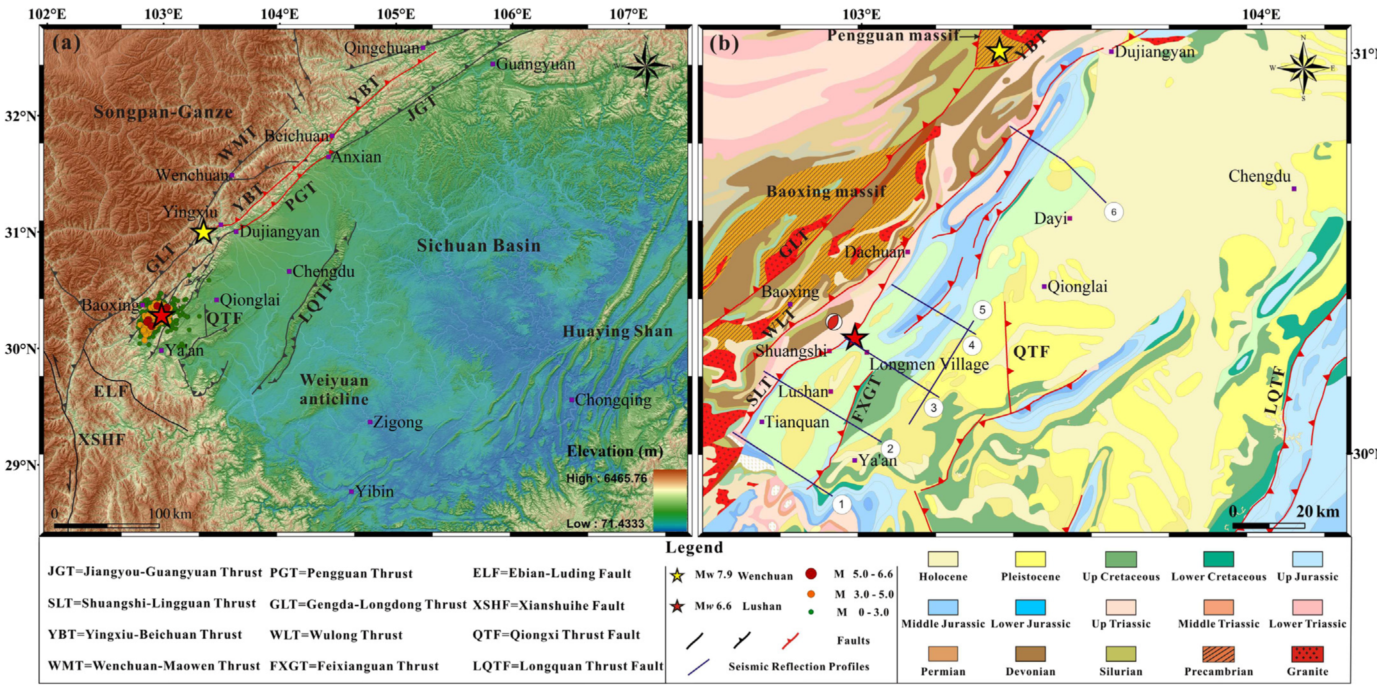

Fig. 1. (a) Topographic map (modified from Jarvis et al., 2008) of the Longmen Shan fold-and-thrust belt and Sichuan basin showing locations of the major faults. The epicenters of the main shocks for the 2008 Wenchuan and 2013 Lushan earthquakes are shown, along with the aftershocks of the Lushan event. (b) Geological map of the southernmost segment of the Longmen Shan fold-and-thrust belt, showing the locations of the six 2D seismic reflection profiles that are described in our study. The earthquake locations are provided by Fang et al. (2013).

fault (YBT) can be clearly traced more than 260 km, extending from the Yingxiu town to Qingchuan. Rupture on the Pengguan thrust fault (PGT), which is located to the southeast of the YBT, extended for 70 km from Dujiangyan to Anxian (Fig. 1(a)). In contrast, there is no surface rupture associated with the Lushan earthquake, suggesting that the source fault may be blind.

To define the fault that generated the 2013 Lushan earthquake and its relationship with the YBT and PGT, we analyzed seismic reflection profiles and well data provided by PetroChina in conjunction with the seismicity. Characterizing the subsurface structural geometry in the epicentral zone is important for understanding the regional tectonic setting of the 2013 earthquake, as well as for seismic hazard assessment. The 3D subsurface fault geometry can help to define the crustal structure of the fold-thrust belt and foreland basin (e.g., Shaw and Suppe, 1994; Shaw and Shearer, 1999; Yue et al., 2005), and the processes of mountain building (e.g. Eric et al., 2013; Cook et al., 2013). 3D fault models can also provide constrains to numerical models, such as calculations of the coulomb stress change on neighboring faults (e.g. Toda et al., 2008; Luo and Liu, 2010), and be used in numerical simulations of seismic wave propagation to forecast strong ground motions (e.g., Süss and Shaw, 2003; Komatitsch et al., 2004; Oglesby and Mai, 2012).

The structure of the Longmen Shan, like many mountain belts, is comprised of imbricated thrust faults and fault-related folds (Hubbard and Shaw, 2009; Hubbard et al., 2010; Li et al., 2010), the geometry and kinematics of which can be constrained by the fault related fold theories (e.g., Suppe, 1983; Shaw et al., 2005). Furthermore, these and other methods can help to constrain the 3D geometry of active thrust systems (Shaw and Shearer, 1999; Carena and Suppe, 2002; Carena et al., 2002; Shaw et al., 2002; Carena et al., 2004) by integrating the relocated aftershocks, seismic reflection profiles, and well data. Following this approach, we employ the methods described by Plesch et al. (2007) that were used to develop the community fault model (CFM) for Southern California. Previous studies have used these methods to describe the 2D and 3D subsurface fault geometries related to the 2008 Wenchuan earthquake (Hubbard and Shaw, 2009; Jia et al., 2010; Li et al., 2010), which involved ruptures on the YBT and PGT. The YBT dips 30–45° to the NW, rooting into a 15–17 km depth detachment in the southern segment with the boundary at Anxian. In the northern segment, the dip decreases to 20–30°, and the thrust ramp may sole to a detachment at a shallower depth of about 7–10 km (Li et al., 2010). The co-seismic fault dips ∼65° near the surface (Li et al., 2013), and ruptured to the surface almost vertically, which indicates a highly listric geometry in the upper few km of the crust (Densmore et al., 2010; Zhang, 2013). The 2008 rupture started in the south near the town of Wenchuan and propagated northward, away from the epicentral zone of the 2013 Lushan earthquake. However, the Wenchuan event may have increased the Coulomb failure stress on the adjacent faults to the south (Parsons et al., 2008; Toda et al., 2008; Luo and Liu, 2010; Wang et al., 2010; Nalbant and McCloskey, 2011). This modeled Coulomb stress change, combined with insights from 2D and 3D structural models (Hubbard and Shaw, 2009; Jia et al., 2010; Li et al., 2010) and paleoseismic trenches (M.M. Wang et al., 2013a, 2013b), suggested that the southernmost segment of the Longmen Shan was tectonically active and at high risk for future earthquakes. The 2013 Lushan earthquake confirms the activity of faults in this region, and the hazards that they pose. Therefore, understanding the geometry and activity of other faults in the Longmen Shan fold-and-thrust belt and the adjacent Sichuan basin is of great importance.

This study seeks to address several questions about the 2008 and 2013 earthquakes in the Longmen Shan. First, did the two events occur on along strike segments of the same fault system? Did the Lushan earthquake occur on a blind fault, or did it rupture the down dip portion of a fault with surface expression? What limited the extent of the 2013 Lushan rupture, and why is there a gap of almost 75 km between the main-shock of 2008 and rupture areas for the 2013 events? To address these questions, we construct six 2D sections and a 3D model of the faults in the region that are based on interpretations of 107 seismic reflection profiles,