

Coseismic reverse- and oblique-slip surface faulting generated by the 2008 Mw 7.9 Wenchuan earthquake, China

Xiwei Xu¹, Xueze Wen², Guihua Yu¹, Guihua Chen¹, Yann Klinger³, Judith Hubbard⁴, and John Shaw⁴

¹Institute of Geology, China Earthquake Administration, Beijing 100029, China

²Earthquake Administration of Sichuan Province, Chengdu 610041, China

³Institut de Physique du Globe de Paris, CNRS-INSU, Paris, France

⁴Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

ABSTRACT

The Mw 7.9 Wenchuan, China, earthquake ruptured two large thrust faults along the Longmenshan thrust belt at the eastern margin of the Tibetan Plateau. This earthquake generated a 240-km-long surface rupture zone along the Beichuan fault and an additional 72-km-long surface rupture zone along the Pengguan fault. Maximum vertical and horizontal offsets of 6.5 m and 4.9 m, respectively, were measured along the Beichuan fault. A maximum vertical offset of 3.5 m was measured along the Pengguan fault. Coseismic surface ruptures, integrated with aftershocks and industry seismic profiles, show that two imbricate structures have ruptured simultaneously, resulting in the largest continental thrust event ever documented. Large oblique thrusting observed during this earthquake indicates that crustal shortening is an important process responsible for the high topography in the region, as everywhere along the edge of Tibetan Plateau.

INTRODUCTION

On 12 May 2008, the Mw 7.9 Wenchuan earthquake struck Wenchuan, Beichuan, and Qingchuan Counties, China, along the middle segment of the Longmenshan thrust belt, at the eastern margin of the Tibetan Plateau. Seismological data indicate that the rupture initiated in the southern Longmenshan (Fig. 1) and propagated unilaterally toward the northeast on a $\sim 33^\circ$ dipping fault for ~ 300 km. Seismic source inversion shows that the rupture could be divided into two subevents. One subevent near Yingxiu Town underwent oblique right-lateral thrusting slip, while the northeast subevent near Beichuan Town exhibited primarily right-lateral slip (e.g., Chen et al., 2008). Although seismological inversions provide constraints on the distribution of slip at depth, they are subject to several simplifying assumptions, including modeling earthquake as single planar rupture (Chen et al., 2008; Parsons et al., 2008). For this event, complex slip distribution, including a large change in slip vector direction (Nishimura and Yagi, 2008), suggests that several faults participated in the rupture. We conducted a survey of the surface ruptures within days following the event. Our results provide the first evidence that multiple faults were involved in the rupture and that the slip distribution changed throughout the rupture process.

SURFACE RUPTURE

Field investigations and detailed mapping from postearthquake satellite images (GSA Data Repository Fig. DR1¹) show that the Wenchuan earthquake ruptured both the Beichuan and Pengguan faults along the middle segment of the Longmenshan thrust belt (Fig. 1). The coseismic surface rupture zone on the Beichuan fault is called the Beichuan rupture zone, while that on the Pengguan fault is called the Hanwang rupture zone. A short northwest-striking rupture zone, here called the Xiaoyudong rupture zone, links two major rupture zones at the southern end of the Pengguan fault through a lateral ramp (Figs. 1 and 2).

¹GSA Data Repository item 2009121, Figures DR1–DR3 and Tables DR1–DR3, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

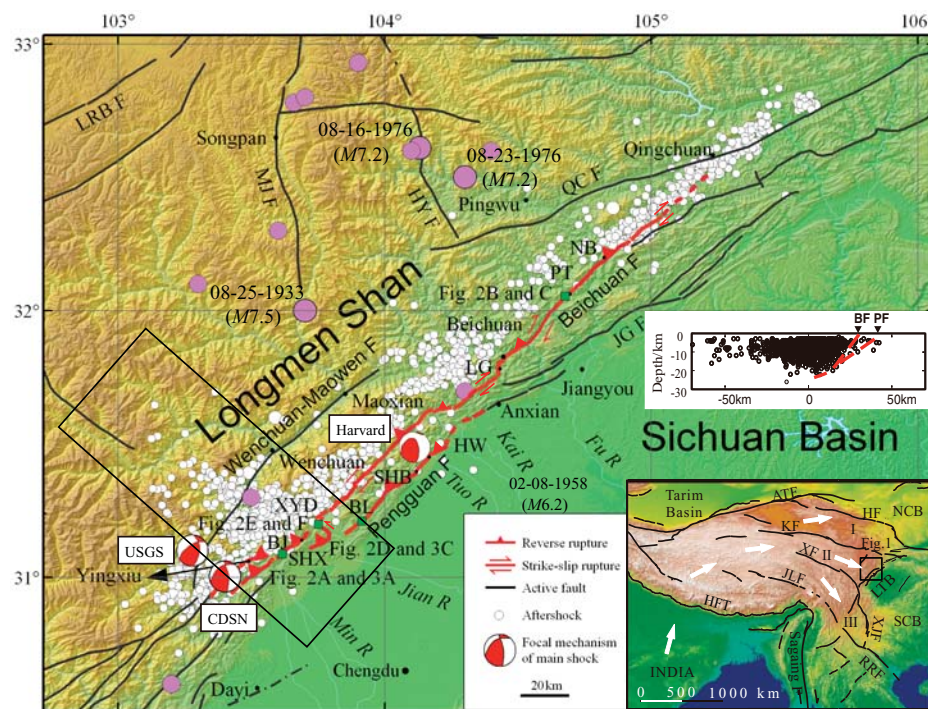


Figure 1. Surface ruptures associated with 2008 Wenchuan earthquake along Beichuan and Pengguan faults. Pink circles—historic destructive earthquakes with dates and magnitudes. White circles—aftershocks of the 2008 earthquake. Aftershock cross section is indicated by black box centered at 31.25°N , 103.5°E . BF—Beichuan fault; BL—Bailu Town; BJ—Bajiao Temple; HYF—Huya fault; HW—Hanwang Town; JGF—Jiangyou-Guanxian fault; KF—Kunlun fault; LG—Leigu Town; LRB—Longriba fault; PF—Pengguan fault; PT—Pingtong Town; QCF—Qingchuan fault; NB—Nanba Town; SHB—Shaba Village; SHX—Shenxi Village; XYD—Xiaoyudong Town. Inset map shows major tectonic features in Longmenshan vicinity: ATF—Altyn Tagh fault, HF—Haiyuan fault, JLF—Jiali fault, LTB—Longmenshan thrust belt, NCB—North China block, RRF—Red River fault, SCB—South China block, XF—Xianshuihe fault, XJF—Xiaojiang fault, I—Qaidam-Qilian block, II—Bayan Har block, III—Sichuan-Yunnan block. White arrow indicates block motion direction.

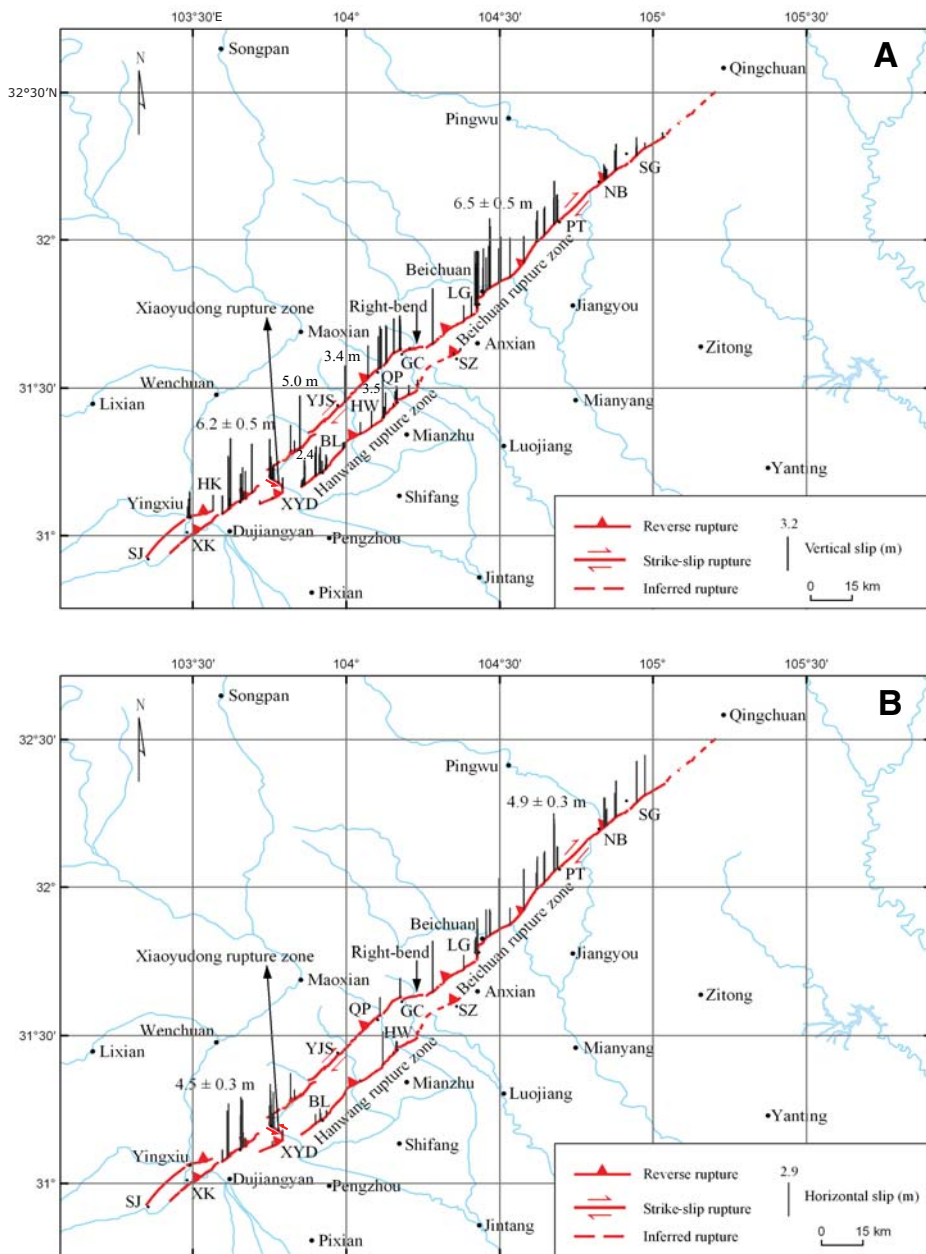


Figure 2. A: Along-strike distribution of measured coseismic vertical offsets along the Beichuan, Pengguan and Xiaoyudong rupture zones. B: Horizontal offsets. GC—Gaochuan Town; QP—Qingping Town; HK—Hongkou Town; SG—Shuiguan Town; SJ—Sanjiang Town; SZ—Sangzao Town; XK—Xuankou Town; YJS—Yuejiashan; others as in Figure 1.

Beichuan Rupture Zone

The Beichuan rupture zone, ~240 km long on the Beichuan fault, is the main rupture associated with the Wenchuan earthquake. Surface rupture starts at (31.061°N, 103.333°E) in the west, exhibiting two separate branches around Yingxiu Town, close to the Wenchuan earthquake epicenter (Figs. 1 and 2). These two branches become a single strand a few kilometers to the east of Yingxiu Town, and this single strand trends $N42^\circ \pm 5^\circ E$ along the Beichuan fault to 32.347°N, 105.034°E. The Beichuan rupture zone could be divided into two sections

of roughly similar length (Fig. 2), linked at lat 31.65°N by a 5-km-wide right bend identified by Tapponnier and Molnar (1977). This segmentation is consistent with two subevents interpreted from seismic data (Chen et al., 2008). A significant change of morphology, and lower elevation of the range north of the bend, suggest that this jog may correspond to a major fault segment boundary along the Longmenshan thrust belt.

The coseismic ruptures on the Beichuan fault show both uplift due to thrusting and horizontal offset on en echelon sections. Vertical offsets of landforms and human-made features attest to a

reverse-faulting component along this rupture zone. Lateral offsets of linear markers such as roadways and rows of crops indicate significant right-lateral motion (Figs. 3 and DR2). We observed exposed fault planes at the Bajiao (31.14522°N, 103.69189°E) and Beichuan (31.83269°N, 104.46103°E) sites. The rupture at Bajiao strikes $N32^\circ E$ and dips $N76^\circ W$. Nearly vertical slickenside striations with rakes of $77^\circ \pm 3^\circ W$ (Fig. DR2C) show reverse motion. At Beichuan, however, nearly horizontal slickensides with rakes from $25^\circ W$ to $40^\circ W$ (Fig. DR2D), show surface ruptures dominated by right-lateral faulting.

We measured numerous coseismic offsets in the field (Figs. 2 and 3; Table DR1) using total stations, ground-based Lidar (light detection and ranging), or tape measure. Maximum and minimum offset measurements at each site are used to assign uncertainties. The average vertical offset along the Beichuan rupture zone is 3–4 m, with a maximum of 6.5 ± 0.5 m measured at North Beichuan Town (31.838500°N, 104.467667°E) on the northern section and of 6.2 ± 0.5 m at Shenxi Village (Figs. 3C and 3D) on the southern section. The maximum right-lateral offset is 4.9 ± 0.3 m at Pingtong Town (31.089944°N, 103.615806°E). The westernmost end of the rupture is characterized by thrust faulting only, in the range of 1–2 m, while the northern section, northeast of Beichuan Town (104.46103°E), is dominated by right-lateral slip. Such variations in style of deformation along the rupture are consistent with the two subevent seismological solutions (Chen et al., 2008). Comparison of the 2008 coseismic rupture with offset features measured before the earthquake, possibly related to the penultimate event (Densmore et al., 2007), shows that geomorphic offsets are comparable in size. This observation suggests that the 2008 earthquake is typical of earthquakes on the Beichuan fault.

Hanwang and Xiaoyudong Rupture Zones

The Hanwang rupture zone is the second major rupture associated with the Wenchuan earthquake (Fig. 1). This rupture is located ~12 km east of the Beichuan rupture zone, along a shallow thrust fault, behind the frontal fold delimited by the Pengguan fault (Figs. 1 and 2). The Hanwang rupture zone branches out eastward from the Beichuan rupture zone to form a complex rupture ~6 km long. Part of this complex rupture zone is the Xiaoyudong tear fault, oriented $N35^\circ \pm 5^\circ W$. Along this fault, vertical offset is as large as 3.4 m (31.19670°N, 103.75194°E). This fault is almost perpendicular to the thrust belt, causing a left-lateral component of horizontal slip, reaching a maximum of 3.5 m at its northeastern end (31.19670°N, 103.75194°E; Figs. DR3A and DR3B). Northeast of the Xiaoyudong tear fault, the Hanwang rupture zone parallels the

Beichuan rupture zone, extending ~72 km north-eastward. Along this section, reverse slip dominates with only minor right-lateral slip (<1 m). The maximum vertical offset across the south-east-facing scarp is 3.5 ± 0.2 m at the Shaba site (31.3999167°N , 104.11828°E). There a, $\text{N}45^\circ\text{E}$ -striking rupture trace bends to the west to cross a riverbed, forming a new 2.4-m-high waterfall at 31.2129167°N , 103.914222°E (Figs. DR3C and DR3D). Surface ruptures cross the Bailu school to form a $\text{N}30^\circ\text{E}$ striking, 1.8-m-high fold scarp at 31.21175°N , 103.91325°E (Fig. DR2B). Northeastward, the vertical offset decreases gradually (Fig. 2; Tables DR2 and DR3).

We were unable to document any definitive coseismic surface rupture along the Wenchuan-Maowen fault associated with the Wenchuan earthquake, and we conclude that it did not rupture during this event.

THREE-DIMENSIONAL MODEL FOR RUPTURE GEOMETRY

Seismic reflection data and well logs provide chronostratigraphic control on the subsurface geology (Song, 1994; Luo, 1998; Jia et al., 2003). We integrated structure derived from seismic lines, geologic maps, and topography with aftershock geometries and mapped surface rupture pattern (Fig. 1) to propose a three-dimensional model for the Wenchuan earthquake rupture geometry (Fig. 4). The structure of the Longmenshan foothills in the epicentral zone consists of an imbricate stack of thrust faults. To the south, three major reverse faults, the Wenchuan-Maowen, Beichuan, and Pengguan faults, and a blind thrust under the Sichuan basin accommodate most of the crustal shortening. The Beichuan fault dips steeply, $>45^\circ$, at the surface, and appears to root into a basal detachment in the mid-crust (Burchfiel et al., 1995, 2008; Xu et al., 2008). The Wenchuan earthquake, with a focal depth of ~14 km to 19 km, initiated close to the base of the Beichuan fault and propagated upward. The steep, upper portion of the fault may have enabled it to accommodate large components of strike-slip motion.

In addition to slip on the Beichuan fault, part of the rupture occurred on the Pengguan fault, which merges with the Beichuan fault at depth (Hubbard et al., 2008). The Pengguan fault is one of several shallowly dipping thrust faults in the footwall of the Beichuan fault that are responsible for the topographic relief visible at the Longmenshan front. The modest westward dip of the Pengguan fault, 20° – 30° , is consistent with the observed predominantly thrust slip. To the north, the dip of the Beichuan fault in the upper crust is steepening, and proportionally less slip on geological time scales has been accommodated on faults in footwall of the Beichuan fault. Thus, the Wenchuan earthquake rupture involves slip along a variety of fault sections that

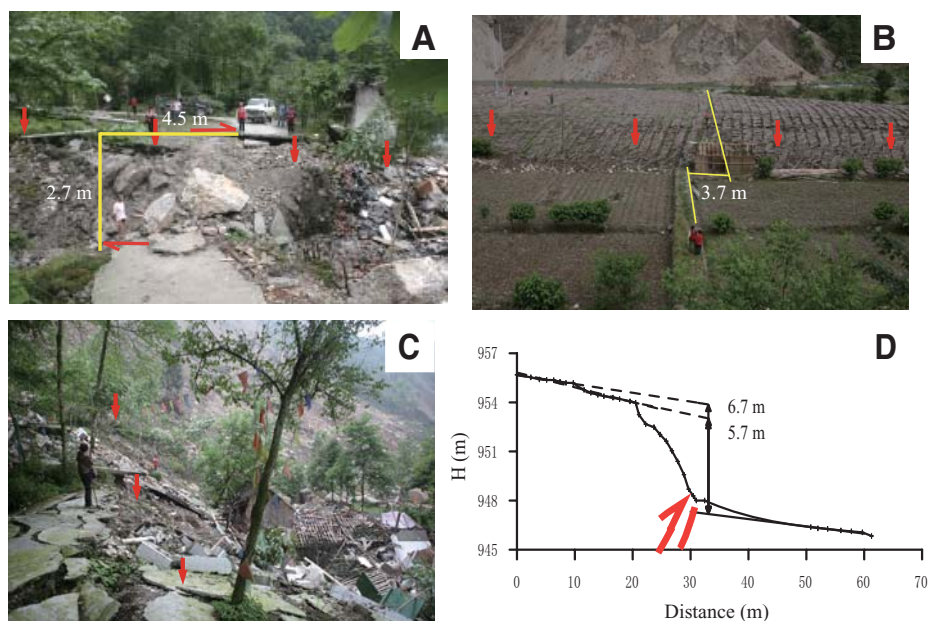


Figure 3. Photographs of typical surface ruptures of Wenchuan earthquake. Red arrows indicate coseismic scarps. **A:** $\text{N}45^\circ\text{E}$ striking scarp along Beichuan rupture zone cutting concrete road at Shenxi Village (31.089944°N , 103.615806°E), view to north. **B:** $\text{N}50^\circ\text{E}$ striking scarp along Beichuan rupture zone ~4 m high cutting road ~3.7 m in right-lateral sense at 32.05439°N , 104.67858°E on terrace near Pingtong Town; view to northwest. **C:** Vertical offset on $\text{N}50^\circ\text{E}$ striking rupture at Shenxi site (31.10472°N , 103.62225°E) along Beichuan surface rupture zone; view to northwest. **D:** Topographic profile across coseismic scarp shows vertical offset of 6.2 ± 0.5 m at Shenxi site.

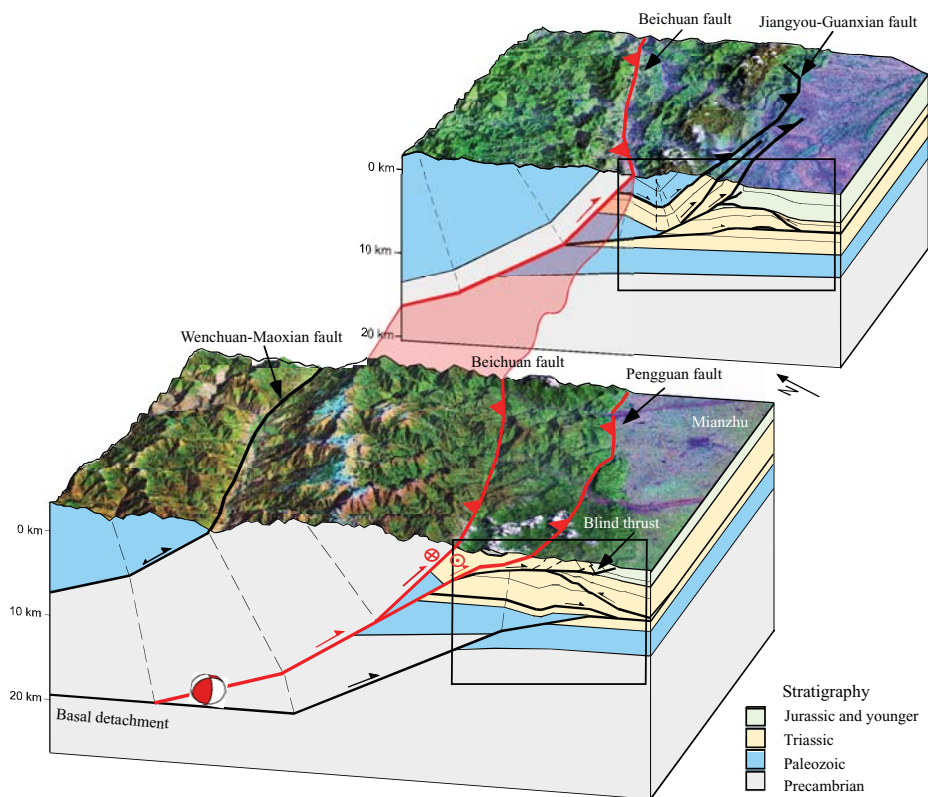


Figure 4. Three-dimensional model of Longmenshan front. Surface ruptures occurred along Beichuan and Pengguan faults, which link at depth. These faults are within imbricate thrust belt that accommodates shortening along range front and sends slip out onto detachments in the sedimentary basin. Cross sections are constructed based on geologic maps, topography, and industry seismic reflection profiles, in the areas denoted by black boxes. Surface of the model consists of multispectral satellite image registered to digital elevation model.

compose an imbricate thrust belt, and its ability to link these various fault segments enabled it to become so large.

DISCUSSION

Before the Wenchuan earthquake, the Longmenshan thrust belt had been seismically quiet for several centuries, with the exceptions of the 1933 Diexi M 7.5 and 1976 Songpan events. The 1958 M 6.2 event had been the largest ever recorded in the frontal part of the range (Chen et al., 1994; Jones et al., 1984; China Earthquake Administration, 1999). Only limited shortening (<3 mm/a) was documented across the range from geological and geodetic measurements (King et al., 1997; Zhang et al., 2004; Densmore et al., 2007). This limited seismic activity led to contradictory models for deformation of the Tibetan Plateau, including diffuse deformation (Royden et al., 1997; Burchfiel et al., 2008) and rigid block motion (Tapponnier et al., 2001). Aftershocks of the Wenchuan earthquake, relocated by the Earthquake Administration of Sichuan Province, define the eastern limit of the hanging wall of the Beichuan fault, which dips southwest at an angle of 47° in the upper crust (Fig. 1), while the Pengguan fault dips to the west at an angle of ~33° (Figs. 1 and 4). As a first approximation, the maximum crustal shortening generated by the Wenchuan earthquake can be calculated from the maximum vertical offset and fault-plane dip angle. Using these parameters, the maximum crustal shortening on the Beichuan fault may reach 5.8 m in the northwest direction, while the maximum shortening on the Pengguan fault may reach 5.4 m. Similar calculations from the coseismic offsets along the Beichuan and Pengguan faults, where they parallel each other (Fig. 2), suggest that the crustal shortening on the Beichuan fault ranges from 3.3 m to 4.7 m, and that on the Pengguan fault from 5.4 m to 3.7 m. Hence, the total crustal shortening generated by the Wenchuan earthquake on the Beichuan and Pengguan faults together is ~8.5 m. The total vertical uplift of the Longmenshan may reach 7.5 m relative to the Sichuan Basin. These values demonstrate that the Wenchuan earthquake is related to east-southeastward extrusion of the Bayan Har block (Xu et al., 2008), blocked to the southeast along the Longmenshan thrust belt (inset map in Fig. 1). Geomorphic studies provide evidence that the Longmenshan thrust belt may have been seismically locked for several thousand years (Densmore et al., 2007), accumulating elastic strain energy. The Wenchuan earthquake, when releasing such elastic energy, participates in the growth of the Longmenshan topography through crustal shortening and thence to the southeastward extension of the Tibetan Plateau (Tapponnier and Molnar, 1977; Tapponnier et al., 2001).

CONCLUSIONS

1. The Mw 7.9 Wenchuan earthquake ruptured two northwest-dipping imbricate oblique reverse faults along the Longmenshan thrust belt at the eastern margin of the Tibetan Plateau. This earthquake generated a 240-km-long surface rupture zone along the Beichuan fault characterized by right-lateral oblique faulting, and a 72-km-long surface rupture zone along the Pengguan fault characterized by dominantly dip-slip reverse faulting. Maximum vertical and horizontal offsets of 6.5 m and 4.9 m, respectively, were measured along the Beichuan fault, whereas a maximum vertical offset of 3.5 m was measured along the Pengguan fault. This coseismic surface rupture is among the most complex of recent great earthquakes and is the longest among the coseismic surface rupture zones for reverse faulting events ever reported in intra-plate settings (Yeats et al., 1997).

2. A three-dimensional model for rupture geometry shows that the Beichuan and Hanwang surface rupture zones appear to merge at depth. The total crustal shortening accommodated by the Wenchuan earthquake may reach 8.5 m and the total vertical uplift may reach 7.5 m. The oblique thrusting accomplished by the earthquake indicates that the east-southeastward extrusion of the Tibetan Plateau is transformed into crustal shortening and uplift along its eastern margin, and is responsible for the growth of high topography in the region.

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