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Parameters of Coseismic Reverse- and Oblique-Slip Surface Ruptures of the 2008 Wenchuan Earthquake, Eastern Tibetan Plateau

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Abstract: On May 12th, 2008, the M_w7.9 Wenchuan earthquake ruptured the Beichuan, Pengguan and Xiaoyudong faults simultaneously along the middle segment of the Longmenshan thrust belt at the eastern margin of the Tibetan plateau. Field investigations constrain the surface rupture pattern, length and offsets related to the Wenchuan earthquake. The Beichuan fault has a NE-trending right-lateral reverse rupture with a total length of 240 km. Reassessment yields a maximum vertical offset of 6.5±0.5 m and a maximum right-lateral offset of 4.9±0.5 m for its northern segment, which are the largest offsets found; the maximum vertical offset is 6.2±0.5 m for its southern segment. The Pengguan fault has a NE-trending pure reverse rupture about 72 km long with a maximum vertical offset of about 3.5 m. The Xiaoyudong fault has a NW-striking left-lateral reverse rupture about 7 km long between the Beichuan and Pengguan faults, with a maximum vertical offset of 3.4 m and left-lateral offset of 3.5 m. This pattern of multiple co-seismic surface ruptures is among the most complicated of recent great earthquakes and presents a much larger danger than if they ruptured individually. The rupture length is the longest for reverse faulting events ever reported.

Key words: surface rupture zone, coseismic offset, Wenchuan earthquake, Longmenshan

1 Introduction

Earthquake rupture length and maximum offset are two valuable parameters in describing surface ruptures that can be linked to moment magnitude (M_w) through empirical relationships and used in seismic hazard assessment for similar segmented long active faults (Wells and Coppersmith, 1994; Yeats et al., 1997; Xu et al., 2006). At 14:27:57.097 LT on 12th May, 2008, the M_w7.9 Wenchuan earthquake occurred along the middle segment of the Longmenshan thrust belt (Fig. 1). The rupture initiated at 103.3525°E, 30.9607°N with a focal depth of 18.8 km (Chen et al., 2009). Preliminary teleseismic waveform analysis shows that the earthquake could be divided into two 6–9 m sub-events that propagated unilaterally to the northeast on a 300 km long, moderately-dipping (32–39°) fault (Chen et al., 2008; Zhang et al., 2008, 2009; Wang et al, 2008). One sub-event near Yingxiu Town underwent oblique right-lateral thrusting slip, while the northeast sub-event near Beichuan (Qushan Town) exhibited primarily right-lateral displacement (Parsons et al., 2008; Nishimura and Yagi, 2008). Although inversions of seismic data such as these provide important constraints on slip distribution and source rupture process at depth, they are subject to several simplifying assumptions, including the assumption of a single, planar fault model (Nishimura and Yagi, 2008) or simple double-listric finite-fault model (Wang et al., 2008). Therefore, many research groups did field investigations soon after the Wenchuan earthquake and a large amount of data such as coseismic offsets and surface rupture length have been collected (Dong et al., 2008; Xu et al., 2008; He et al., 2008; Chen et al., 2008; Ma et al., 2008; Li et al., 2008; Fu et al., 2008, 2009; Li Y. et al., 2008; Liu et al., 2008; Chen et al., 2009; Lin et al., 2009). These data are helpful for understanding the earthquake surface rupturing process, but some of the surface rupture parameters, especially the maximum coseismic vertical and horizontal offsets, their associated surface rupture length, and even the surface rupture pattern, are still under debate. Many researchers reported that the Wenchuan

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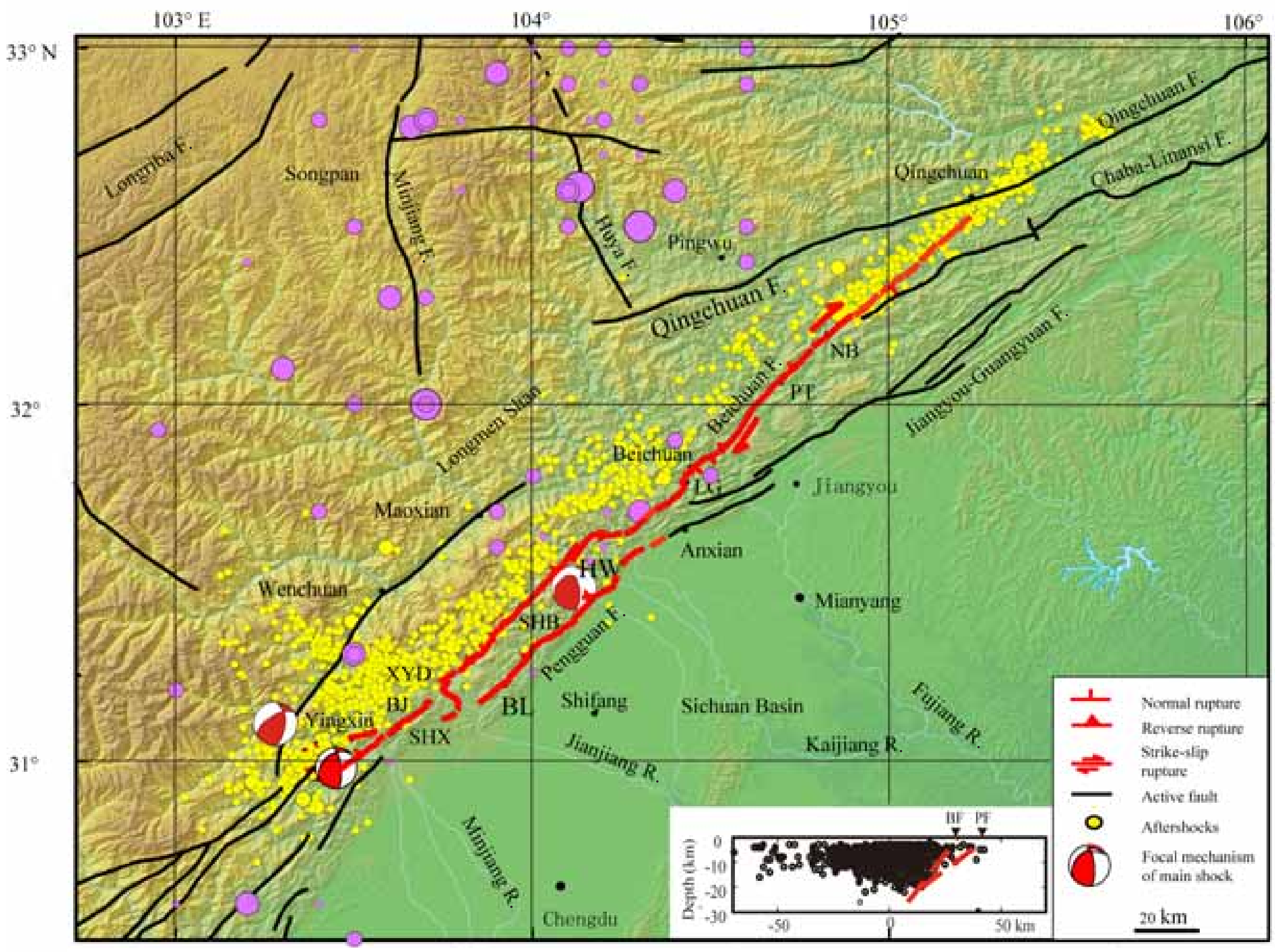

Fig. 1. Simplified map showing distribution of active faults in Longmen Shan and surface ruptures of the 2008 Wenchuan earthquake along Beichuan and Pengguan faults, Longmenshan thrust belt (after Xu et al., 2009).
Pink circles—historic destructive earthquakes with dates and magnitudes. Yellow circles—aftershocks of the 2008 earthquake and its cross section at left lower corner. BF—Beichuan fault; PF—Pengguan fault. BL—Bailu Town; BJ—Bajiao Temple; HW—Hanwang Town; LG—Leigu Town; PT—Pingtong Town; NB—Nanba Town; SHB—Shaba Village; SHX—Shenxigou Village; XYD—Xiaoyudong Town.

earthquake ruptured, in reverse- and oblique-slip sense, two NE-trending imbricate reverse faults, the Beichuan and Pengguan faults along the middle segment of the Longmenshan thrust belt, and a NW-trending short fault (Fig. 1), the Xiaoyudong fault, which links the Beichuan and Pengguan faults through a lateral ramp (Dong et al., 2008; Xu et al., 2008; Ma et al., 2008; Li et al., 2008; Fu et al., 2008, 2009; Li Y. et al., 2008; Liu et al., 2008; Chen et al., 2009), while others reported that it also ruptured the ENE-trending Qingchuan fault along the northern segment of the Longmenshan thrust belt (Lin et al., 2009). The surface rupture lengths range from 285 km to 180 km. In addition, the maximum coseismic vertical offset varies from 5.0 m to 11 m and the maximum right-lateral offset from 4.8 m to 12 m (He et al., 2008; Li et al., 2008; Fu et al., 2008, 2009; Xu et al., 2008, 2009; Liu et al., 2008; Li Y., 2008), and even a maximum coseismic left-lateral offset of about 4.2 m is reported on the southern section of the Beichuan fault (Lin et al., 2009). Better constraint on those parameters is, however, critical to estimate magnitude of future earthquakes along the eastern margin of the Tibetan Plateau.

Here we present surface rupture features from field measurements and include a reassessment of the surface rupture pattern, surface rupture length and its maximum offsets. These results have important implications for both the general nature of seismic hazard along oblique-thrust fault systems and the east-southeastward growth of the Tibet Plateau.

2 Earthquake Surface Rupture Features

The surface ruptures can be complicated, but the distinct surface rupture features, produced during the Wenchuan earthquake, differ fundamentally from those of normal fault scarps because the hangingwall block overrides the footwall. The features seen include simple thrust scarp, hanging-wall collapse scarp, simple pressure ridge, dextral pressure ridge, back-thrust pressure ridge, fault-related fold scarp, crocodile-mouth-like scarp and local normal fault scarp (Fig. 2). A simple thrust scarp occurred only at Bajiao Temple, Hongkou Village of Dujiangyan City (Fig. 2a). Generally, the over-hanging part of a newly formed thrust scarp immediately collapses onto the footwall to form a hanging-wall collapse scarp (Fig. 2b). The collapse may produce a free face and a debris slope composed of the remains of the hangingwall (Yeats et al., 1997). That is why hanging-wall collapse scarps are common and simple thrust scarps very few. In both cases tensile cracks usually form on the hangingwall (Fig. 2b). The simple and dextral pressure ridges are widely developed along the Wenchuan surface rupture zones. In these two features near-surface materials such as turf, soil and concrete pavement were entrained in the fault and override the ground surface on the hangingwall block (Fig. 2c and d). In this case the vegetation such as crops and trees on the top of the scarp lean with the flexing of the ground, and the declination become greater toward the lower part of the scarp, until they fall. This forms so called "drunkard woods" (Fig. 2c). The back thrust scarp is named for the subsidiary reverse fault scarp developed on the hanging wall of the main reverse fault scarp, and its dip is opposite to the main reverse fault (Fig. 2e). Linear warp occurs in between the main and subsidiary scarps, and secondary tension cracks sub-parallel to the scarp were developed on the warp. Fault-related fold scarp is used to describe the scarp formed by folding or kinking of near surface strata (Fig. 2f). For example, sub-horizontal yellowish brown terrace deposits on the northern bank of Jianjiang River, Qushan Town, Beichuan County, were bent, resulting in a 3.1-m-high scarp on the ground. The concrete pavement was broken during the earthquake (Fig. 2f), and the yellow-colored center line on the pavement offset 2.4 m right-laterally on both side of the fold scarp. The fold scarp is a fault propagation fold produced by blind thrust faulting (Yeats et al., 1997). The crocodile-mouth-like scarp occurred often on concrete pavement across the scarp. It resulted from thrusting and shortening below the ground (Fig. 2g). The above fault scarp features are often observed in thrust faulting events, such as the 1968 Meckering, Australia, earthquake (Gordon and Lewis, 1980); the 1978 Tabas-e-Golshan, Iran, earthquake (Berberian, 1979), and the 1988 Tennant Creek, Australia, earthquake (Crone et al., 1992). Moreover, normal fault scarps were also observed for about 7 km between Maoba Village and Dengjia Village, north of Qushan Town, Beichuan County and about 500 m between Sujiayuan Village and Kuangpingzi Village, Shikan Town, Pingwu County (Figs.1 and 2h). At both sites, the normal fault scarps had developed on hillsides whose slopes are consistent to the thrust fault dips. Their northwestern sides consist of the Cambrian sandstone and their southeastern sides the Carboniferous limestone (Fig. 3). During the Wenchuan earthquake, crustal shortening on the thrust fault beneath forced the softer Cambrian sandstone up onto the stronger Carboniferous limestone and back-tilting at the fault tip near the ground surface and then forms local normal fault scarp. This normal fault scarp has not been reported for any other earthquakes along a thrust belt. This type of the near-surface normal faulting still indicates a crustal shortening similar to their adjacent ruptured sections.

3 Pattern and Length of Surface Ruptures

3.1 Beichuan rupture zone

Beichuan rupture zone along the Beichuan fault is the main one among the three coseismic surface rupture zones produced by the Wenchuan earthquake (Dong et al., 2008; Xu et al., 2008, 2009; Li et al., 2008). The surface rupture exhibits two separate northern and southern branches at its westernmost termination (Fig. 1). The surface rupture starts at Maliu Village (N30.94472°, E103.36656°), Sanjiangkou Town, in the west, for the northern branch, close to the rupturing initiation point or epicenter of the Wenchuan earthquake (Chen et al., 2009), where N50°E-trending linear ground fissures and N70°E-trending pressure ridges about 2 m wide and 0.5 m high were found. From there the rupture zone strikes N65°±5°E and extends discontinuously northeastwards to cut Yuzixi River and the highway from Yingxiu to Gengda (N31.061416°, E103.48286°), Yingxiu Logistic Distribution Center (N31.06308°, E103.48558°), different terraces of Minjiang River and the national highway from Dujiangyan City to Wenchuan County (E103.48967°, N31.06528°) to form fault-related fold scarps (Fig. 4a) with vertical offsets of about 0.9 m, 1.5 m and 2.3 m, respectively. The southern branch was initiated at Hongmiaoshan Village (N30.97622°, E103.46125°), Xuankou Town, where a fault-related fold scarp about 15 cm high and cracks occurred on a road and its subgrade, showing its northwestern side uplifted. Those two branches become a single strand a few kilometers to the east of Yingxiu Town, and this single surface rupture zone trends N42°±5°E and passes through Bajiaomiao Town, Dujiangyan City, Longmenshan Town, Pengzhou City, Yuejiashan, Shifang City, Qingping Town, Mianzhu City, Leigu Town and Qushan Towns, Beichuan County, Pingtong and Nanba Towns, Pingwu County, and Shiba Town, Qingchuan County, along the Beichuan fault. The

Fig. 2. fault scarp features of the Wenchuan earthquake (Red arrow indicates the scarp).

a: Reverse fault scarp about 4 m high at Baojiaomiao (N31.14522°, E103.69189°) along the Beichuan rupture zone; b: Hangingwall collapse scarp 2.7 m high at Shenxigou Village (N31.08925°, E103.61492°) and tension cracks on the hangingwall along the Beichuan rupture zone; c: Simple pressure ridge ~5 m high and tilted cement road at Shenxigou Village (31.08886°N, 103.61428°E) along the Beichuan rupture zone; d: Dextral pressure ridge ~2.5 high with 1.9 m right-lateral offset and en echelon transtensional cracks on the pressure ridge that cut a pavement at Pingtong Town (32.06356°N, 104.68878°E) along the Beichuan rupture zone; e: Back-thrust scarp on the flood-plain of Pingtong River (31.08886°N, 103.61428°E), between the main and back-thrust scarps is a 31-m-wide linear warp where tension cracks were developed along the Beichuan rupture zone; f: Fault-related fold scarp about 3.1m high at Qushan Town north of the Jianjiang River (31.82894°N, 104.45689°E) along along the Beichuan rupture zone; g: Crocodile-mouth-like scarp with a 1.4-m overlap at Longquan Village (31.41289°N, 104.12797°E) along the Hanwang rupture zone; h: Local normal fault scarp ~4 m high that dips to the southeast with a dip angle of 60°–90° between Maoba and Shaba Villages (31.83478°N, 104.46433°E), northern Qushan Town, along the Beichuan rupture zone.

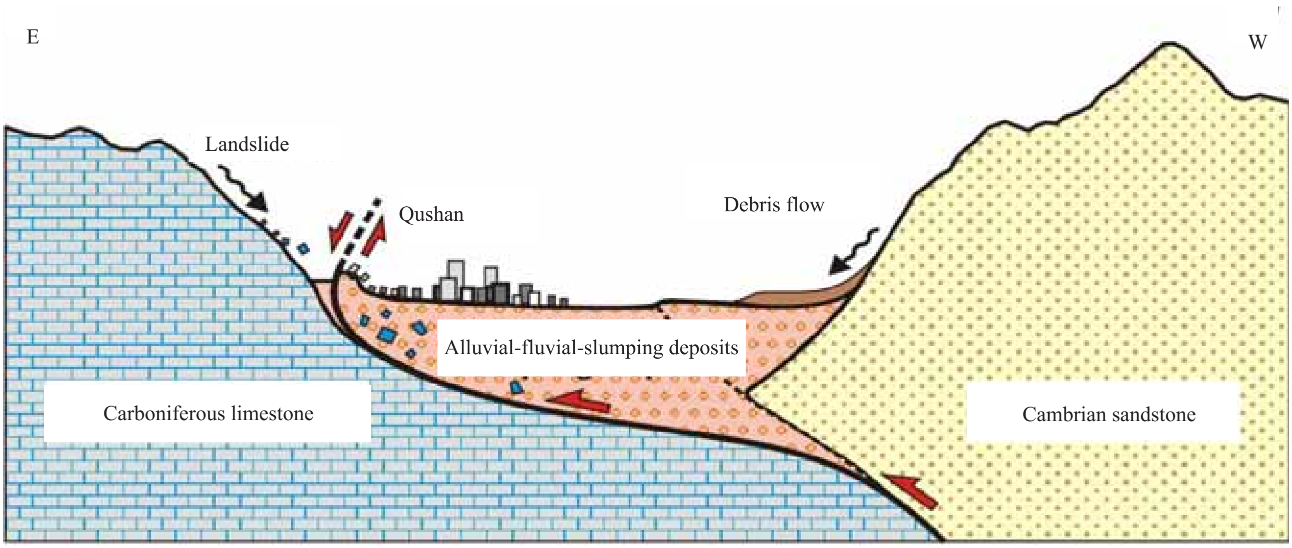

Fig. 3. Tectonic model showing normal fault scarp formed in a compressive setting between Dengjia and Maoba Villages, north of Qushan Town, along the Beichuan rupture zone.

Beichuan rupture zone terminates at Donghekou Village (N32.40572°, E105.11081°), Hongguang Town, Qingchuan County. This is the huge Hongguang landslide occurred to block rivers and form large sag ponds. At an observation site (N32.40380°, E105.10848°), nearby the main scarp of this huge landslide, a fault, which dips to the N36°W with a dip angle of ~80°, was ruptured during the quake. In addition a series of domino-like ground tension cracks which strike N40°W, dip to the southwest with a visible depth of ~3 m are present (Fig. 4b). This kind of tension cracks can also be found at Dongjia Village (N32.34719°, E105.03392°), Shiba Town, Qingchuan County, several kilometers west of the huge landslide, while the right-lateral faulting ruptures are found at Woqian Village (N32.34719°, E105.03392°), Magong Town, Qingchuan County, where the Beichuan rupture zone cut ladder ridge and tree rows with a right-lateral offset of about 3.4 m (Fig. 4c). No any surface ruptures can be found further east. The previous reported ruptures at Guangzhuang Town (Liu et al., 2008) and at Muyu Town (Li et al., 2008), are parts of landslide scarps that formed during the Wenchuan earthquake.

Thus, the Beichuan rupture zone strarts at Maliu Village (N30.94472°, E103.36656°), Sanjiangkou Town, in the west, and ends at Donghekou Village (N32.40572°, E105.11081°), Hongguang Town, Qingchuan County, in the east, with a total length of 240 ± 5 km.

3.2 Hanwang rupture zone

The Hanwang rupture zone along the Pengguan fault is the second longest surface rupture zone produced by the Wenchuan earthquake (Dong et al., 2008; Xu et al., 2008, 2009; Li et al., 2008; Liu et al., 2008 ; Li Y. et al., 2008) (Fig. 1). Its westernmost end is at the west of Jianan Village (N31.1650278°, E 103.852694°), Tongji Town, Pengzhou City, in the west, where a N40°E-trending fault-related scarp about 35 cm high with six tension cracks on its NW side exists. The scarp extends continuously eastwards and its height becomes 52 cm, where it cut and destroyed the yard of Mr. Yangan Zhu at Jianan Village (N31.166889°, E 103.855028°). The surface rupture zone strikes N45°±5°E and passes through Bailu Town, Pengzhou City, Hanwang Town and Quanxin Village, Mianzhu City, and then extends intermittently to Chuanzhu Village (31.39811° N，104.11836° E), Shangzao Town, Anxian County, in the east. At Chuanzhu Village the scarp is less than 15-cm-high and it disappears to the west of Anchang Town. Thus, the total length of the Hanwang rupture zone is 72 km (Xu et al., 2008, 1009; Li et al., 2008).

3.3 Xiaoyudong rupture zone

The Xiaoyudong rupture zone along the Xiaoyudong fault is a secondary surface rupture zone that strikes N50° ±5°W and cuts the arable lands and roads with a left-lateral, oblique offset (Fig. 5). The rupture zone is located between the western end of the Hanwang rupture zone and western rupture gap on the western section of the Beichuan rupture zone (Fig. 1). The Xiaoyudong rupture zone is discontinuous. Its trace at both the northern and southern ends deviates from NW-trending to nearly NS-trending and obliquely connect with the NE-trending Beichuan rupture zone on its northern end (Fig. 6). This NW-trending rupture zone is only 7 km long and is characterized by reverse left-lateral faulting.

The Wenchuan earthquake generated three surface

Fig. 4. Earthquake surface ruptures at both terminations for the Beichuan rupture zone.

a: Trench log showing a folded strata by several events excavated across a cumulative scarp ~8 high on the T2 terrace of Minjiang River at north Yingxiu Town (N31.06483°, E103.48972°) and red arrow indicates location of the fault-related fold scarp); b: Domino-like N40°W-trending ground tension cracks with a visible depth of ~3 m at southeast of the Hongguang huge landslide (N32.403935°, E105.108765°); c: Typical coseismic en-echelon right-lateral faulting ruptures at Woqian Village (N32.34719°, E105.03392°), Magong Town.

rupture zones along the Beichuan, Pengguan and Xiaoyudong faults, about 240 km, 72 km and 7 km long, respectively. The shortest Xiaoyudong rupture zone links the two major rupture zones at the southern end of the Pengguan fault through a lateral ramp (Xu et al., 2009). No rupture has been identified along the Wenchuan-Maowen fault associated with the Wenchuan earthquake, and we conclude that it did not rupture during this event. Here it is worth to point that some researchers reported that the Wenchuan earthquake also ruptured the ENE-trending Qingchuan fault along the northern segment of the Longmenshan thrust belt (Lin et al., 2009). We checked all sites where they gave data on locations and ruptures along the Qingchuan fault and found that all the ruptures are only NE-trending parts of the main scarps of the landslides at the road bends (Fig. 7), and no surface ruptures along the Qingchuan fault.

The coseismic surface rupture pattern generated by the Wenchuan earthquake is the most complicated among the historical coseismic surface rupture zones and its surface rupture about 240 km long along the Beichuan fault is the longest for reverse faulting events ever reported in an intra-plate setting (Yeats et al., 1997).

4 Coseismic Offsets and Distribution

Field investigations and seismic source inversions indicate that the Wenchuan earthquake is an oblique-slip faulting event. Its surface ruptures are demonstrated by a mix of the fault rupture features. In most cases those rupture features represent crustal shortening during the quake (Xu et al., 2008, 2009; Hubbard and Shaw, 2009; Lin et al., 2009). In order to quantify coseismic offsets, including vertical and horizontal ones, along the surface rupture zones, we utilized displaced liner-, surface- and artificial-markers such as roads, stream channels, gullies, terraces, terrace risers, and arable lands, which are generally perpendicular to the surface rupture zones. Owing to the right-lateral slip component, at many sites, the Beichuan rupture zone obliquely cut the hillsides to form brow-ridge-like scarps. If only their heights are measured, this will overestimate their vertical offsets. Near Shaba Village (N 31.325°, E 104.46877°) northeast of Qushan Town, the brow-ridge-like scarp is about 3.6 m high (Fig. 9a in Fu et al., 2009), but this value does not represent the vertical offset at this site owing to a right-lateral offset about 3 m. Furthermore, if the linear markers are notr perpendicular to the scarp, the crustal shortening across the scarp will cause an apparent lateral offset and not a true one (Angelier et al., 2003; Chen et al., 2009). For this reason, we just measure those displaced markers perpendicular or sub-perpendicular to the surface rupture

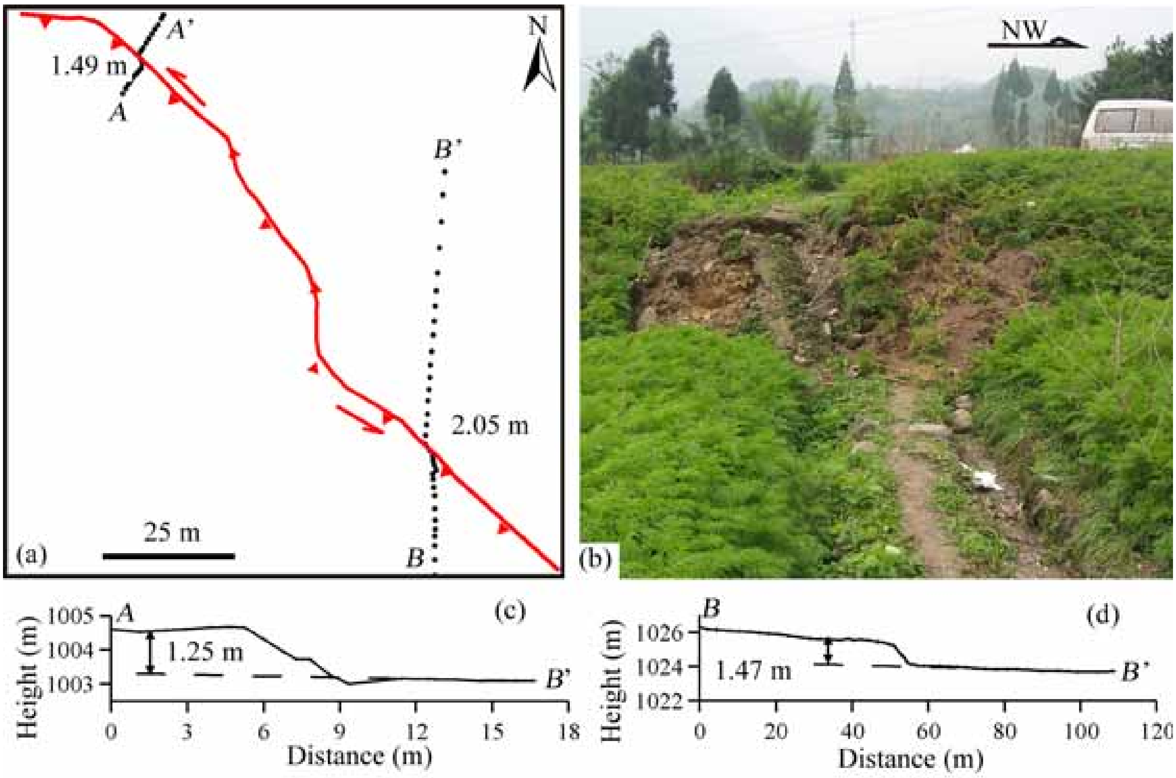

Fig. 5. Oblique slip ruptures showing folded scarp and left-lateral offset of the road and arable lands at the site (31.19497° N, 104.75389°E) west of Xiaoyudong Town.

a: Measured surface rupture traces and profile locations shown by dotted lines A-A´ and B-B´, and numbers are left-lateral offsets; b: Photo showing the scarp and road offset in left-lateral sense; c: Topographic profile A-A´ showing coseismic vertical offset of 1.25 m; d: Topographic profile B-B´ showing coseismic vertical offset of 1.47 m.

zones. Both the vertical and horizontal offsets were surveyed here by total station, 3D laser scan or tape measure and this provides a basis for analyzing the maximum offset and along-strike distribution of the offsets for the Wenchuan earthquake.

4.1 Maximum vertical and horizontal offsets

Field measurements reveal that the maximum co-seismic vertical offset for the Wenchuan earthquake is 6.5±0.5 m (Fig. 8), measured at Shaba Village (N 31.83739°, E 104.46806°), north of Qushan Town, Beichuan County, along the Beichuan rupture zone. There the surface rupture zone consists of en echelon normal faulting bedrock scarps and those scarps strike N50°E and dips towards SE with a dip angle of about 70°±10°. According to the topographic maps at scale of 1:50,000 and that at scale of 1:1,000 that was made in 2001 for land planning use, it is known that there exists a pre-existed bedrock scarp with a maximum height of ~7 m before the quake. The measured total height of the bedrock scarp at a site nearby a three-floor building of Jizhong Zhou ranges from 12.6 m to 13.3 m. Since the profile P1 crosses the dominant position of the present scarp of about 13.3±0.3 m high, the balance about 6.3±0.3 m between the present scarp and the pre-existed 7-m-high scarp might represent the possible maximum coseismic vertical offset along this profile (Fig. 8a, b, d). Fortunately, the upper part of the bedrock scarp is covered by a soil layer, on which Bamboo and palm trees have been growing (Fig. 8a), and that indicates the upper part already existed and only the lower part was newly formed during the Wenchuan earthquake. This is also shown by the soft grey fault gouge, which only occurs on the lower part of the scarp. From the topographic profile P15 across the soil-covered scarp, we obtained another measurement of the possible maximum vertical offset of 6.7±0.4 m (Fig. 8a, b, c). Thus the measurements at this site yields an average vertical offset of 6.5±0.5 m. This is the maximum vertical offset measured along the Wenchuan earthquake surface ruptures. This maximum vertical offset is consistent with that published by Xu et al. (2009), but quite different from those reported by others, who had proposed the maximum vertical offsets between 9 m to 11m at the same site (Li et al., 2008; Liu et al., 2008). We argue that their reported maximum vertical offsets include pre-quake scarp and thence are cumulative offsets for at least two events.

In addition, the maximum right-lateral offset was measured on the youngest terrace of Pingtong River at a

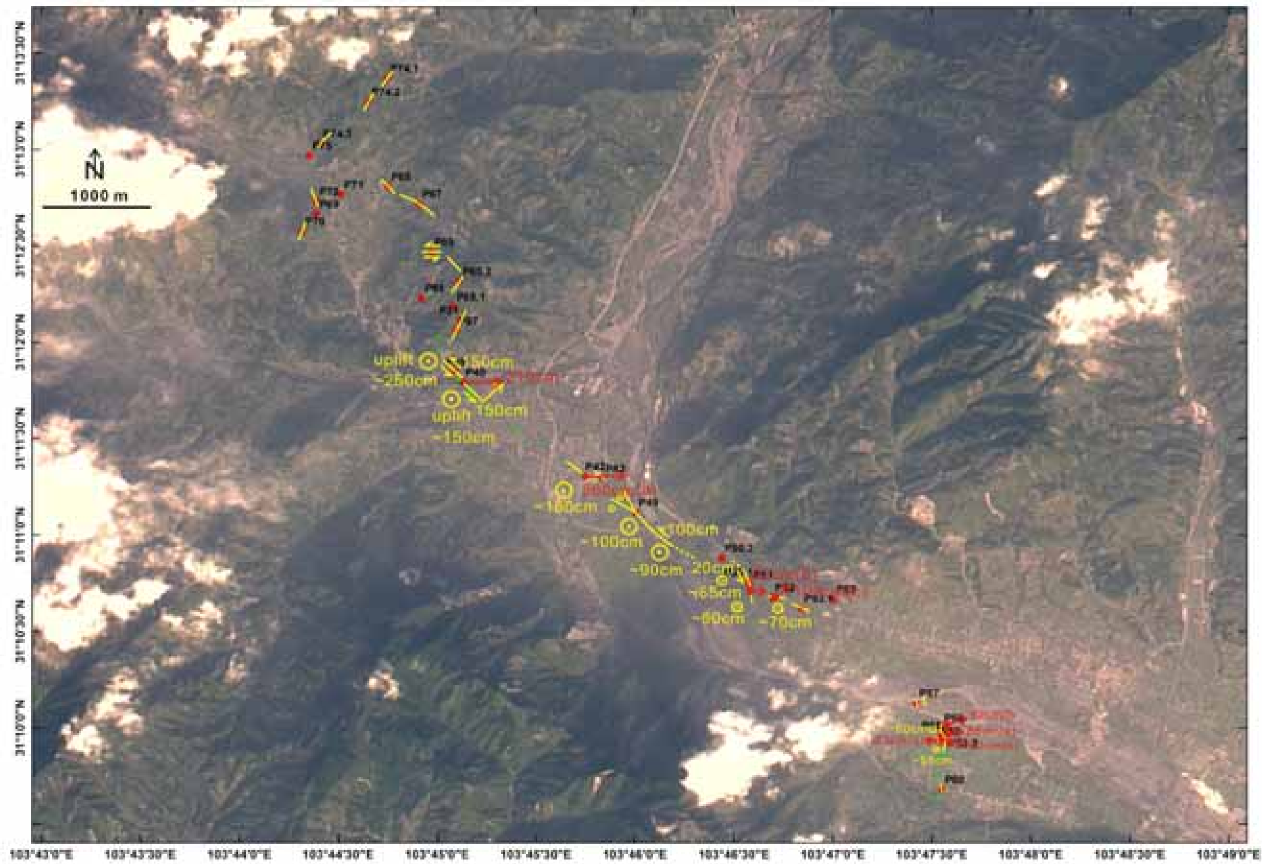

Fig. 6. Distribution of the surface ruptures (yellow lines) along the Xiaoyudong fault. Yellow circle with dot inside is location where coseismic uplift is measured; Red dot and its arrow represent horizontal slip vector in cm.

Fig. 7. Main scarps of the landslide occurred during the Wenchuan earthquake at a site (32.65250° N, 105.41833°E) east of Muyu Town along the Qingchuan fault.

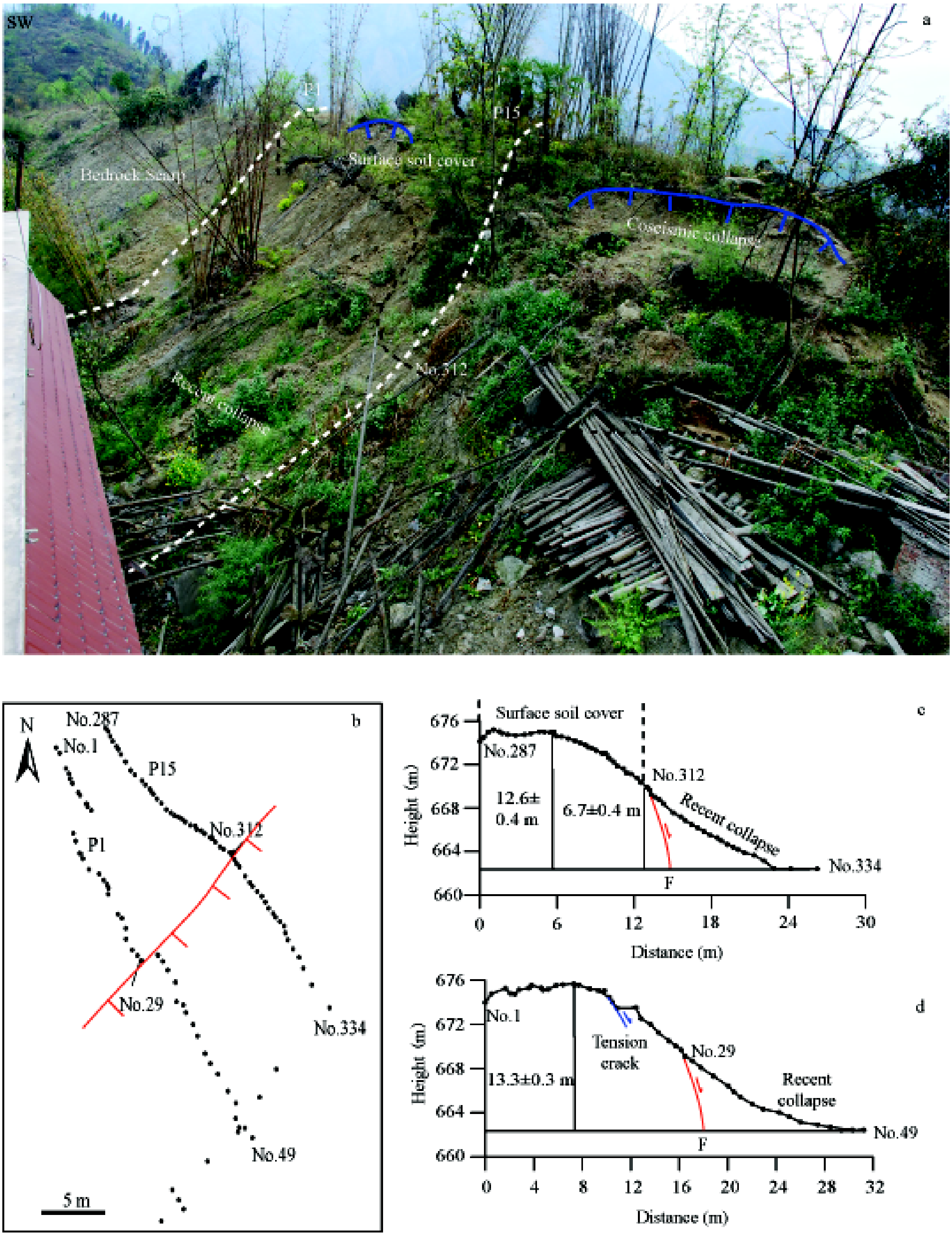

Fig. 8. Map showing relationship between the maximum vertical offset and cumulative height of the bedrock scarp at Shaba Village (N 31.83739°, E 104.46806°), north of Qushan Town.

a: Photo of the bedrock scarp that is covered by a surface soil layer and this shows a pre-existed scarp, blue line with bars: tension cracks associated with coseismic collapses, Dashed lines P1 and P15: measured profile locations, Black dashed line: lower margin of the surface soil cover; b: Distribution of the P1 and P15 profiles and the dots are measured points by Differential GPS; c: P15 topographic profile showing the possible maximum coseismic vertical offset of ~6.7 m derived from young scarp at the lower part and cumulative height of the bedrock scarp; d: P1 topographic profile showing the cumulative bedrock scarp height of 13.3±0.3 m.

site (N 32.05403°, E 104.67725°), South Pingtong Town, along the northern segment of the Beichuan rupture zone, where a rut was displaced about 4.9 m in a right-lateral sense, with ~1.5 m vertical offset (Xu et al., 2008, 2009). This value is much less than those published by others, who gave a value as large as 8–10 m or even larger than 12 m at a site (N 31.83208°, E 104.46006°) near Maoba element school (Figure 8A in Li et al., 2008). We checked this site and argued that this site is not suitable for measuring the horizontal offset, owing to collapse of the ridges between cornfields to lead to error measurement. We never obtained such a large horizontal offset nearby this site along the rupture zone. For example, the right-lateral offset is only 2.4 m with a vertical offset about 3.1 m, measured from a displaced cement road at a site (N 31.82894°, E 104.45689°), Qushan Town, less than 300 m south of Maoba element school, and about 3.7 m measured from a displaced trod at another site (N 31.83328°, E 104.46250°) about 150 m to the north. It can clearly be seen that the horizontal offset of 8–10 m may be completely wrong.

Moreover, some researchers gave the maximum horizontal and vertical offsets measured at Zhaojiagou Village (N 31.80536°, E 104.42964°), Leigu Town, Beichuan County, but we think this scarp is the main scarp of a landslide, since the scarp becomes tension cracks and disappears when it crosses both hillsides to the north and to the south. Thus, the maximum vertical and horizontal offsets produced by the Wenchuan earthquake is ~6.5 m and ~4.9 m, respectively, measured from Shanba Village, north of Qushan Town, and south of Pingtong Town, respectively, along the northern segment of the Beichuan rupture zone.

3.2 Along-strike variation of offsets

The measurements along the Beichuan, Pengguan and Xiaoyudong rupture zones show a large variation of both vertical and horizontal offsets associated with the Wenchuan earthquake. Although the offset is larger in the middle along each rupture zone, the offset curve is characterized by multiple peaks separated by low offsets (Fig. 9).

In summary, there are two maximum vertical offsets along the Beichuan rupture zone. One is located on the southern segment of the Beichuan rupture zone and is as large as 6.2±0.5 m with an average vertical offset of 2.5–3 m, while the measured maximum right-lateral offset reaches 4.5±0.3 m with an average horizontal offset of less than 2 m (Xu et al., 2009). This maximum vertical offset is obtained from a N45°E-trending fold scarp at Shenxi Village, Hongkou Town (Xu et al., 2009). The maximum right-lateral slip of 4.5±0.3 m is measured at the site (31.089944°N, 103.615806°E), where a cement-covered road was cut by the surface rupture zone, with a vertical slip of 2.8 m (Xu et al., 2008). In any case we did not discover left-lateral offset along this segment, as described by Lin et al. (2009). The other maximum vertical offset is located on the northern segment and is as large as 6.5±0.5 m, while the maximum right-lateral offset reaches 4.9±0.5 m, with an average vertical and horizontal offsets of 3–4 m (Xu et al., 2009).

It is noteworthy that no right-lateral displacements were discovered on the westernmost end of the Beichuan rupture zone at Yingxiu Town, near the epicenter. This may indicate that the main shock of the Wenchuan earthquake initiated as a pure reverse faulting event on an ENE-trending fault in the west. Right-lateral offsets are observed along the main section between Hongkou Town (103.67078°E) to Pingtong Town (104.79853°E), and along this section the co-seismic vertical offsets appear equal to or even larger than the horizontal one (Fig. 9). We infer that the main section of the Beichuan rupture zone is dominated by reverse faulting with a subsidiary strike-slip component during the quake. In contrast, east of Pingtong Town (104.79853°E) the right-lateral and vertical offsets are comparable. This offset segmentation along the Beichuan rupture zone agrees quite well with the focal mechanism changes from reverse faulting in the west to strike-slip faulting in the east, and is consistent with two sub-event seismological solutions (Chen et al., 2008).

In contrast, our measurements indicate that the Hanwang rupture zone is quite different from the Beichuan rupture zone and is dominated by reverse faulting with a minor right-lateral component (Fig. 9). The maximum vertical offset of 3.5±0.2 m is measured across a southeast-facing scarp at the Shaba site (31.3999167°N, 104.11828°E) and its average vertical offset ranges from 1 m to 2 m along the Hanwang rupture zone (Xu et al., 2009). Finally, the maximum left-lateral offset along the NW-trending Xiaoyudong rupture zone occurred at a site (31.19669°N, 103.86667°E) where the left-lateral offset reaches 3.5 m and vertical offset about 1.9m (Xu et al., 2008). At its northern and southern ends where the strike of the Xiaoyudong rupture zone changes to N15°E, the maximum vertical offset increases to 3.4 m with a right-lateral offset of 1.6m at its northern end (31.19933°N, 103.75000°E), while the left-lateral offset is only 0.38m and vertical offset 0.3 m (Fig. 6) at its southern end (31.164111°N, 103.792167°E).

5 Conclusions

The Wenchuan earthquake generated the most complicated and longest intra-plate reverse fault-type

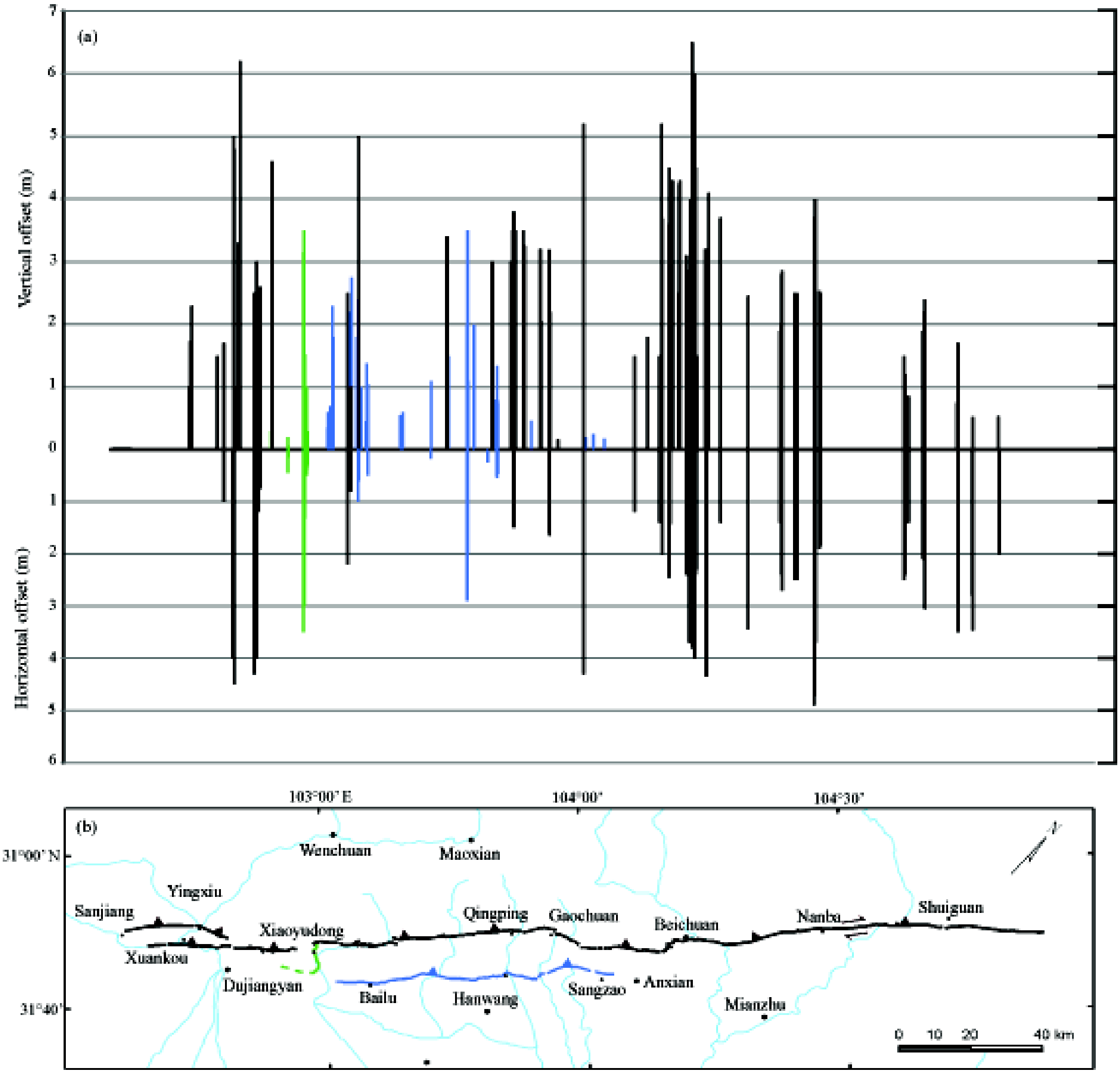

Fig. 9. Distribution of the co-seismic offsets measured along the Beichuan, Pengguan and Xiaoyudong rupture zones.
a: Each offset amount was measured at an individual surface rupture. b: Co-seismic ruptures along the Beichuan Rupture zone (black), Pengguan rupture zone (blue) and Xiaoyudong rupture zone (yellow green). Colors in (a) correspond to those in (b).

surface rupture zone that has ever been reported. The earthquake generated two imbricate NE-trending surface rupture zones, Beichuan and Pengguan rupture zones, and a secondary NW-trending rupture zone, the Xiaoyudong rupture zone. They basically consist of simple thrust, hanging-wall collapse, fault-related fold, crocodile-mouth-like and local normal fault scarps, and simple pressure, dextral pressure and back-thrust pressure ridges. The Beichuan surface rupture zone is 240 km long with the maximum vertical and horizontal offsets of 6.5 m and 4.9 m, the about 72 km long Pengguan rupture zone has a maximum vertical offset of 3.5 m, and the 7 km long Xiaoyudong rupture zone has a maximum vertical offset of 3.4 m and left-lateral offset of 3.5 m, respectively.

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