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Complex surface rupturing and related formation mechanisms in the Xiaoyudong area for the 2008 Mw 7.9 Wenchuan Earthquake, China

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ABSTRACT

The large oblique reverse slip shock of the 2008 Mw = 7.9 Wenchuan earthquake, China, produced one of the longest and most complicated surface ruptures ever known. The complexity is particularly evident in the Xiaoyudong area, where three special phenomena occurred: the 7 km long Xiaoyudong rupture perpendicular to the Beichuan-Yingxiu fault; the occurrence of two parallel faults rupturing simultaneously, and apparent discontinuity of the Beichuan-Yingxiu rupture. This paper systematically documents these co-seismic rupture phenomena for the Xiaoyudong area. The discussion and results are based on field investigations and analyses of faulting mechanisms and prevalent stress conditions. The results show that the Beichuan-Yingxiu fault formed a 3.5 km wide restraining stepover at the Xiaoyudong area. The Xiaoyudong fault is not a tear fault suggested by previous researches, but a frontal reverse fault induced by the oblique compression at this stepover; it well accommodates the 'deformation gap' of the Beichuan-Yingxiu fault in the Xiaoyudong area. Further, stress along the Peng-Guan fault plane doubles due to a change in dip angle of the Beichuan-Yingxiu fault across the Xiaoyudong restraining stepover. This resulted in two faults rupturing the ground's surface simultaneously, to the north of the Xiaoyudong area. These results are helpful in deepening our understanding of the dynamic processes that produced surface ruptures during the Wenchuan earthquake. Furthermore, the results suggest more attention be focused on the influence of dextral slip component, the change of the control fault's attitude, and property differences in rocks on either side of faults when discussing the formation mechanism of surface ruptures.

1. Introduction

On 12 May 2008, the Mw = 7.9 Wenchuan earthquake struck the Longmenshan area, Sichuan Province, China. The earthquake occurred along a mid-segment of the Longmenshan thrust belt in the eastern margins of the Tibetan Plateau (Fig. 1). Shortly after the earthquake, many research groups performed field surveys, and ascertained a great deal of valuable data and materials (e.g., Dong et al., 2008; He et al., 2008; Liu et al., 2008; Xu et al., 2008, 2009a, 2009b; Chen et al., 2009; Lin et al., 2009; Shen et al., 2009; and Yu et al., 2010). Seismological data indicate that co-seismic surface rupture zones along the Beichuan-Yingxiu and Peng-Guan faults propagated unilaterally toward the northeast (Wang et al., 2008).

The Wenchuan earthquake provides a rare opportunity to study the rupture geometry, dynamics, and crustal loading processes of a great intraplate thrust earthquake. The earthquake produced three obvious ruptures (Fig. 1): the Beichuan-Yingxiu rupture (240 km in length) on the NW-dipping Beichuan-Yingxiu fault; the Peng-Guan rupture (70 km in length) on the more shallowly NW-dipping Peng-Guan fault (Hubbard and Shaw, 2009; Hubbard et al., 2010; Jia et al., 2010); and the NW trending Xiaoyudong rupture, which links the above two major ruptures. The rupture zone encompassing these three ruptures is recognized as one of the most complicated co-seismic rupture zones ever known (Xu et al., 2009a; Liu-Zeng et al., 2009).

This paper focuses mainly on the Xiaoyudong area (Fig. 1), where three special phenomena occurred: the 7 km long Xiaoyudong rupture, which is perpendicular to the Beichuan-Yingxiu

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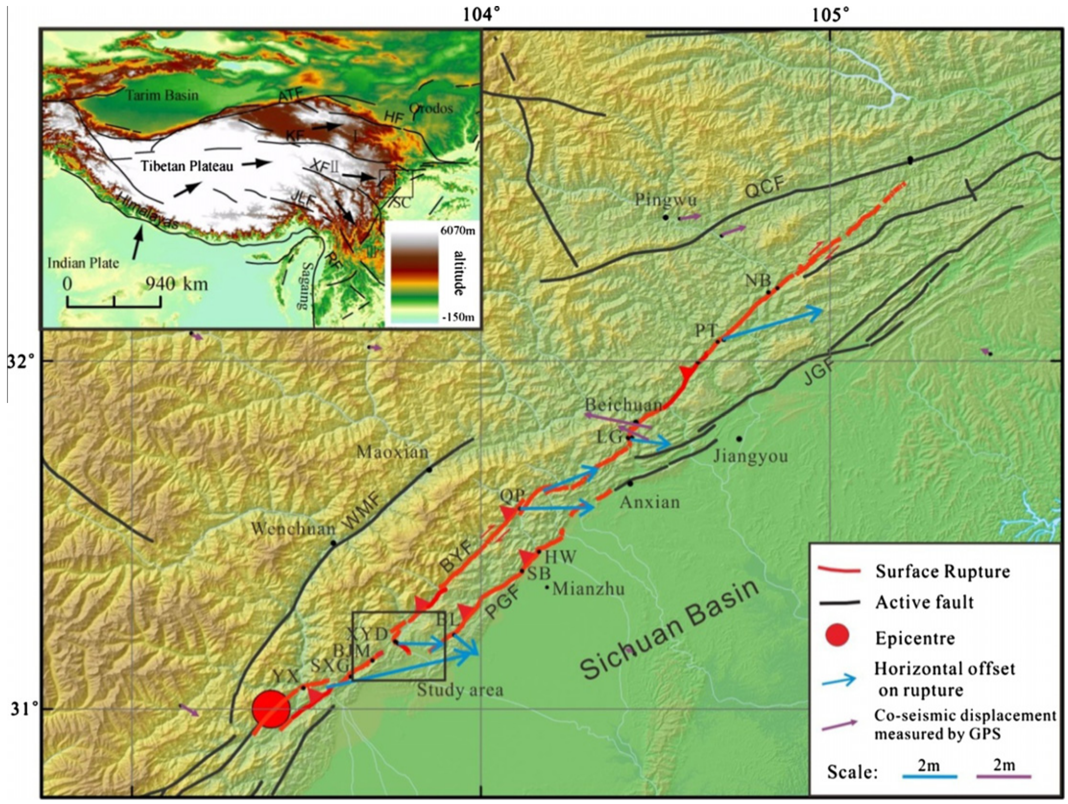

Fig. 1. Surface ruptures and co-seismic displacement induced by the Wenchuan earthquake. Inset figure shows the location of Longmenshan (dark rectangle) and the main fault system around it. The dark arrows indicate the movement of micro blocks due to the collision of Indian and Eurasian plates. The ruptures are revised from Xu et al. (2008, 2009a). The horizontal slip data of the ruptures is referenced from Chen et al. (2008, 2009). The GPS data of co-seismic displacement are provided by the research group of Crustal Movement Observation Network of China (2008). Abbreviations: BL–Bailu; QP–Qinping; LG–Leigu; YX-Yingxiu; HW–Hanwang; XYD–Xiaoyudong; BJM–Bajiaomiao; SXG–Shenxigou; SB–Shaba; PT–Pintong; NB-Nanba; JGF–Jiangyou-Guanxian Fault; QCF–Qinchuan Fault; PGF-Peng-Guan Fault; WMF–Wenchuan-Maoxian Fault; BYF–Beichuan-Yingxiu Fault; ATF–Altyn Tagh Fault; HF–Haiyuan Fault; KF–Kunlun Fault; JLF–Jiali Fault; XF–Xianshuihe Fault; RF–Red river Fault.

fault; the simultaneous rupturing of the two parallel faults; and the discontinuous nature of the Beichuan-Yingxiu rupture – something that has often been ignored by other researchers. These interesting rupture phenomena have been the subject of several in-depth discussions (Liu-Zeng et al., 2009; Li et al., 2009; Chen et al., 2009; Deng et al., 2011); however, no generally accepted conclusion on the mechanisms describing these phenomena has been reached. In this study, we systematically document co-seismic ruptures in the Xiaoyudong area for the Wenchuan earthquake. The study is based on assiduous, repetitious field investigations, including the determination of the distribution of surface ruptures and related parameters as well as co-seismic slip vectors. The results are then discussed in terms of the formation mechanism of the Xiaoyudong rupture and the co-seismic slip partitioning on the two parallel faults. The results of this study should provide us with greater insight into the formation mechanism and dynamics of ruptures induced by a great intraplate thrust earthquake.

2. Tectonic setting

The Longmenshan Range, where the Wenchuan earthquake occurred, is experiencing uplift as a result of the collision between the India and Eurasian plates. It is adjacent to the Sichuan Basin and defines the sharp and steep middle part of the eastern margin of the Tibetan Plateau (Fig. 1; Tapponnier et al., 1982, 2001; Burchfiel et al., 1995; Chen and Wilson, 1996; Kirby et al., 2002). Active convergence with dextral deformation occurs at this margin along three NE-trending major faults (Fig. 1). From northwest to southeast, the faults are called the Wenchuan-Maoxian fault, Beichuan-Yingxiu fault, and Jiangyou-Guanxian fault, respectively (Tang and Han, 1993; Burchfiel et al., 1995, 2008) (Fig. 1). Over a distance of several tens of kilometers, these major faults result in a difference in elevation of up to 4000 m between the Tibetan plateau and Chengdu plain, a part of the Sichuan Basin. According to geodetic measurements, no significant shortening has been observed across the Longmenshan Range on a time scale of 10 years (King et al., 1997; Chen et al., 2000).

The Wenchuan–Maoxian fault, which trends 025–045° and dips to the northwest, has had a dextral-slip rate of 0.8–1.4 mm/yr since the Pleistocene and an uplift rate of its hanging wall of 0.5 mm/yr during the Holocene (Tang and Han, 1993; Ma et al., 2005). The Beichuan-Yingxiu fault, also called the central fault, trends 035–045° and dips to the northwest. The 2008 Mw 7.9 Wenchuan earthquake occurred along this fault. The hanging wall of Beichuan-Yingxiu fault uplift in rate of 0.6–1 mm/yr and it has had a dextral-slip rate of 1 mm/yr since the Pleistocene (Deng et al., 1994; Ma et al., 2005; Li et al., 2006; Densmore et al., 2007). The Jiangyou–Guanxian fault trends 035–045° and dips 50–70° to the northwest; it marks the eastern edge of the Tibetan Plateau, where the steep front of the Longmenshan Range meets the Sichuan Basin. Its vertical slip rate has been approximately 0.2 mm/yr since the middle Pleistocene (Ma et al., 2005). The segment of the Jiangyou–Guanxian fault located in the Xiaoyudong area is often referred to as the Peng-Guan fault.

Although several earthquakes of $M \geqslant 7$ have occurred in the surrounding areas, historical seismicity within the Longmenshan thrust system is characterized by moderate earthquakes, including five $M = 6$–7 earthquakes since the 14th century. According to China's historical seismicity catalogs, no earthquakes larger than

$M = 7$ were recorded in the Longmenshan thrust system over the last millennium (Tang and Han, 1993; Division of Earthquake Monitoring and Prediction, China Seismologic Bureau, 1995, 1999).

3. Ruptures in the Xiaoyudong area

Investigations have shown that the ruptures produced by the Wenchuan earthquake are very complex (Xu et al., 2009a; Liu-Zeng et al., 2009), especially in the Xiaoyudong area. Fig. 2a and b and Table 1 show the distribution localities and parameters of ruptures based on our field investigations. Our distribution localities in the western portion of the Xiaoyudong rupture (Fig. 2a) are somewhat different from those of other researchers (Li et al., 2009; Liu-Zeng et al., 2009, 2010).

3.1. Beichuan-Yingxiu rupture

The principal rupture of the Wenchuan earthquake was the Beichuan-Yingxiu rupture with length of about 240 km, along the Beichuan-Yingxiu fault. This rupture displays as oblique slip, with

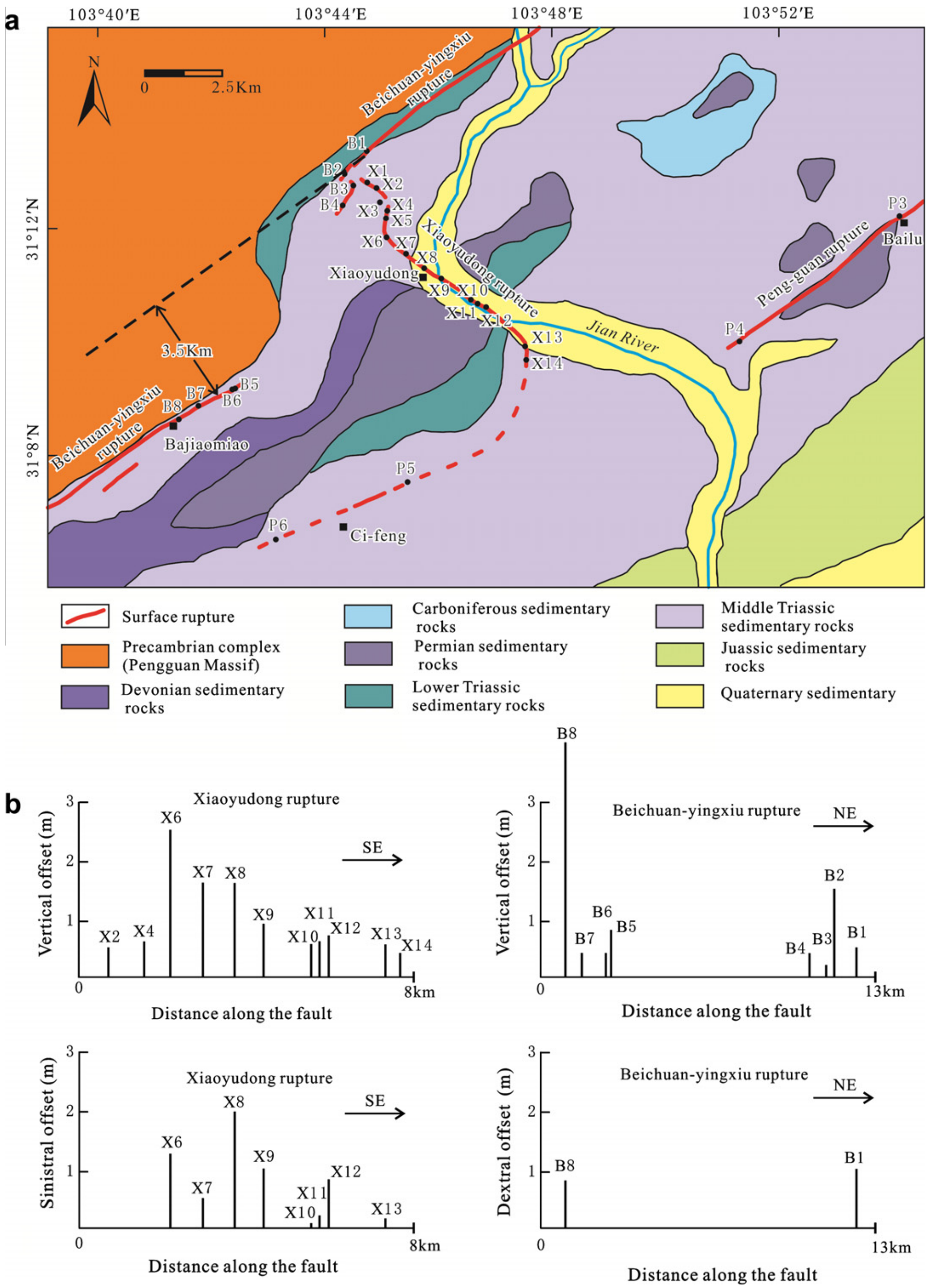

Fig. 2. (a) Distribution of the surface ruptures and geological map and (b) vertical and sinistral offset of the Xiaoyudong rupture and the Beichuan-Yingxiu rupture in the Xiaoyudong area.

Table 1
Investigation points of the ruptures in the Xiaoyudong area.

No.	Latitude	Longitude	Strike	Uplift (cm)	Lateral offset* (cm)	Offset features	
Beichuan-Yingxiu rupture							
B1	N31.22283	E103.74575	35°	~50	R ~100	Courtyard	
B2	N31.21617	E103.73920	10°	150	0	Plantation	Fig. 4a
B3	N31.2128	E103.74187	315	20		Terrace	
B4	N31.20690	E103.73862	20°	40	0	Road, beton pillars	Fig. 4b
B5	N31.15297	E103.70683	50°	80	0	Small road	Fig. 3a
B6	N31.15278	E103.70628	50°	40	0	Land	Fig. 3b
B7	N31.14789	E103.69638	45°	40		Courtyard	
B8	N31.14527	E103.69210	45°	400	R 80	Terrace, gully	
Xiaoyudong rupture							
X1	N31.21347	E103.74585	315°			Land	
X2	N31.21200	E103.74847	310°	50	0	Courtyard	Fig. 5e
X3	N31.20780	E103.74947	80°			Land	Fig. 6b
X4	N31.20528	E103.75187	20°	60		Small road	Fig. 5d
X5	N31.20308	E103.75135	30°				
X6	N31.19745	E103.75148	315°	250	L 125	Terrace	Fig. 5a
X7	N31.19248	E103.75726	310°	160	L 50	Road	Fig. 5b
X8	N31.18840	E103.76247	310°	160	L 193	Ridge of field	Fig. 5c
X9	N31.18532	E103.76672	310°	90	L 100	Ridge of field	
X10	N31.17903	E103.77633	353°	55	L 8	Ridge of field	
X11	N31.17795	E103.77818	320°	60	L 20	Ridge of field	
X12	N31.17702	E103.78065	275°	70	L 81	Ridge of field	
X13	N31.16537	E103.79282	350°	55	L 15	Ridge of field	Fig. 6c
X14	N31.16132	E103.79247	350°	40	0	Ridge of field	
Peng-Guan rupture							
P1	N31.21102	E103.91298	45°	180	0	Schoolyard	
P2	N31.20687	E103.90992	50°	150	0	Terrace	
P3	N31.20377	E103.90215	60°	150	0	Plantation	
P4	N31.16690	E103.85508	45°	50	0	Road, Courtyard	
P5	N31.12543	E103.75768					Fig. 7
P6	31.10854	103.71907					

* R: Right lateral offset and L: left lateral offset.

larger amounts of vertical slip in the southern segment and with larger amounts of dextral slip in the northern segment (Yu et al., 2010; Xu et al., 2010). The rupture is clearly evident in some parts of the trace; however, in the Xiaoyudong area, its distributions remains quite ambiguous (Li et al., 2009; Lin et al., 2009; Xu et al., 2009b; Liu-Zeng et al., 2010). It is known from field investigations, that the Beichuan-Yingxiu rupture is discontinuous in this area (Fig. 2). In order to facilitate our discussion of the Beichuan-Yingxiu rupture, we divide the rupture into two parts; i.e., those parts north and south of Xiaoyudong township.

In the southern part, field investigations have been previously performed as far as Bajiaomiao village, where the rupture is still clearly evident with fresh scarps of about 4 m in height (Point B8 in the Fig. 2a). Rupturing to the north of this scarp is ambiguous and for the most part shown as a dashed line in other studies (e.g. Lin et al., 2009; Li et al., 2008, 2009). According to our field work, the rupture continues for about 2 km north of the Bajiaomiao village and then quickly dies out (Fig. 3). Interestingly, a new rupture about 500 m in length can be observed before the rupture disappears completely (Fig. 3a and b; Points B5 and B6 in Fig. 2). This means our surface rupture map for this part is somewhat different to that of previous researches (Xu et al., 2009b; Liu-Zeng et al., 2010); for example, Xu et al. (2009b) thought there may be some rupturing in a valley north of the village (shown in Fig. 3c as the purple line), and Liu-Zeng et al. (2010) thought that the rupture in the Bajiaomiao village stopped at about the B7 position.

We investigated the exact location of the boundary between the Peng-Guan massif and the Paleozoic–Mesozoic sedimentary rock mass to the north of the Bajiaomiao village (Fig. 3c). The newly found rupture developed in the Mesozoic sedimentary rock mass to the northeast of the Bajiaomiao village, while the conjectured ruptures in this area are located in the Peng-Guan massif (Figs. 2a and 3c). This evidence suggests the conjectured ruptures do not actually exit, meaning there should be no rupturing to the west of and parallel to the newly observed rupture (points B5 and B6), as all of the ruptures along the south segment of the Beichuan-Yingxiu fault present to the east of the Peng-Guan massif.

Similar to the southern part of the rupture, vertical slip in the northern part changed southwardly from 1.5 m at point B2 (Fig. 2a) to about 40 cm at B4 (Fig. 2a), then the rupture once again disappeared rapidly. Rupturing at B2 and B4 is shown in Fig. 4a and Fig. 4b, respectively. The rupture at B2 shows an old scarp, which is similar in height to the fresh scarp. At B4, there are several marks (Fig 4b–e) on the wall, road and beton pillars, which reflect the coseismic slip of the fault. Since all the marks show 'sinistral slip', Liu-Zeng et al. (2010) and Li et al. (2009) thought the rupturing was part of the Xiaoyudong rupture; however, as all the marks are not perpendicular to the ruptures (Fig. 4d), the apparent 'sinistral slip' may have been caused by thrust, something that was described in detail by He et al. (2011).

To better understand the nature of displacement at B4, we conducted detailed measurements at the site and found the horizontal slip vector to be 74.5 cm in a 113° direction, by the same method with He et al. (2011). This result shows that the rupture was almost a pure thrust rupture with only a 3° directional difference. We need to be cautious, however, about the data because the marks we chose had only small intersectional angles of 20° and slight amounts of slip, both of which could lead to significant error in measurement of the horizontal slip vector. All the same, we cautiously conclude that the evident 'sinistral slip' is only apparent in nature, and the true cause of displacement is thrust. In addition, our field work shows the rupture at B4 extends more than 1 km in the 020° direction (Fig. 4c) and, therefore, this rupture is not likely to be part of the Xiaoyudong rupture, but rather part of the Beichuan-Yingxiu fault.

In the areas absent of the Beichuan-Yingxiu rupture, several channels developed parallel to the fault. No more rupture points

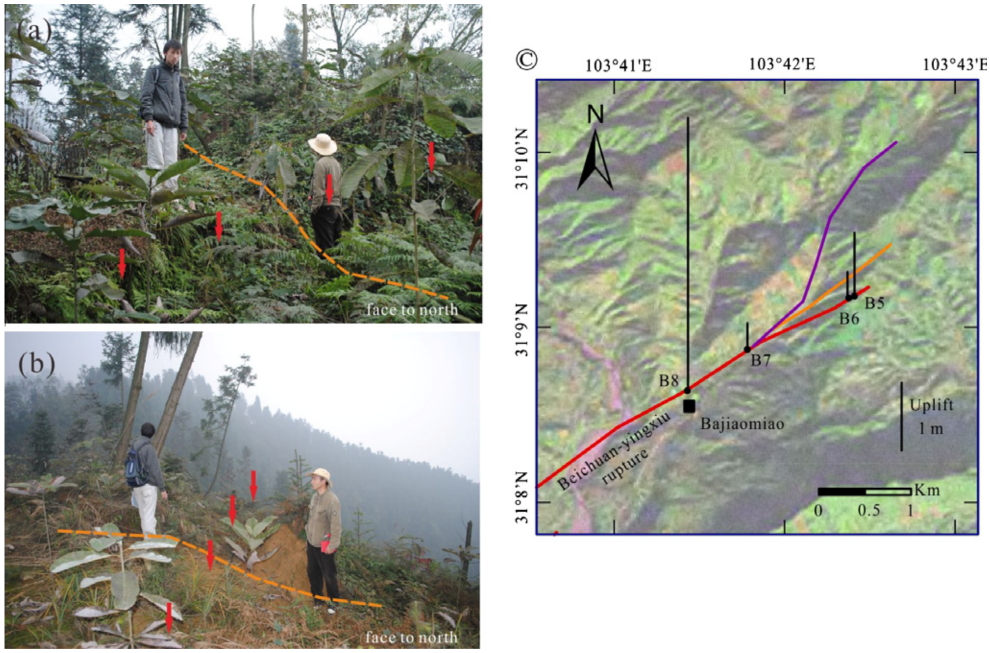

Fig. 3. (a) Rupture photos at point B5; (b) Rupture photos at point B6; and (c) the map of the Beichuan-Yingxiu rupture shown as the red line in the Bajiaomiao area. The yellow line is the boundary between the Peng-Guan massif and sedimentary rocks, and the purple line is the conjectured rupture in reference. The yellow dashed lines represent the topography lines of fault scarps.

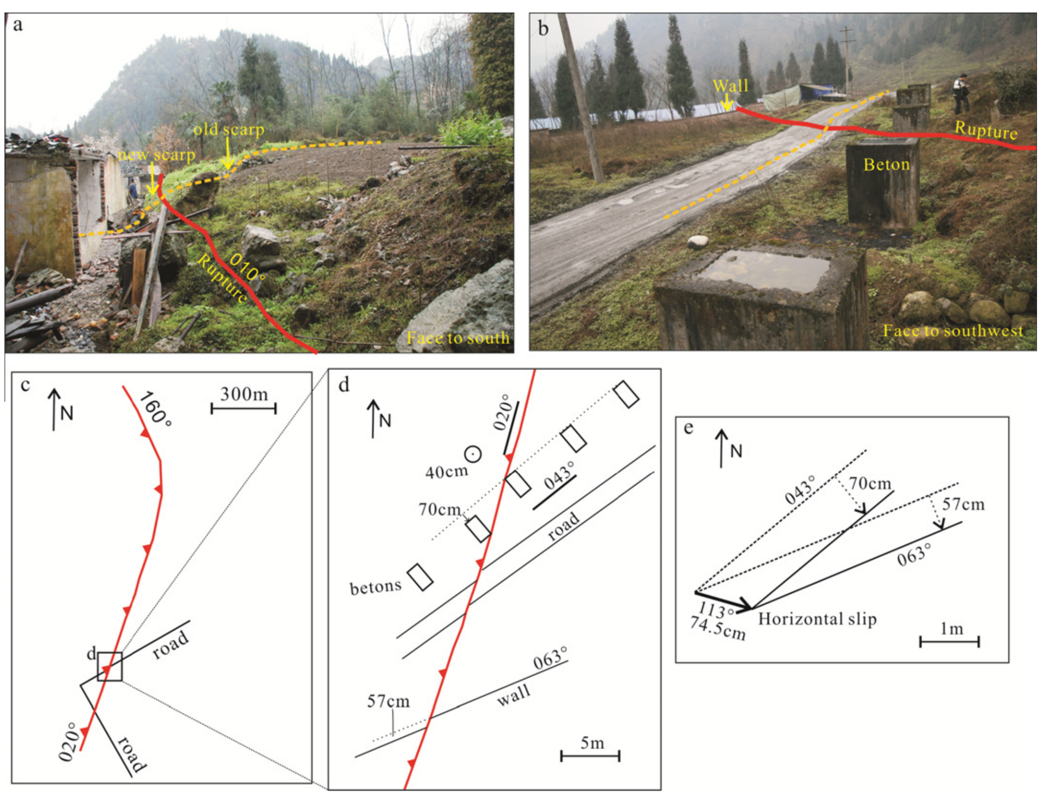

Fig. 4. (a) Rupture photo at point B2; (b) Rupture photo at point B4; (c) and (d) are the sketch maps of the rupture near B4 in a different scale; and (e) the horizontal slip of the rupture at B4. The yellow dashed lines represent the topography lines of fault scarps.

were observed in these areas, and the damage caused by the earthquake was not as heavy as in the rupture areas.

According to our field investigations, the Beichuan-Yingxiu fault is cut off near the earth's surface in the Xiaoyudong area (Fig. 2). In addition, the north part of the Beichuan-Yingxiu fault is not in a line with the south part, but step northwest with a distance of 3.5 km (Fig. 2), which may play an important role in the complicated rupture phenomena occurred in the Xiaoyudong area.

3.2. Xiaoyudong rupture

Throughout the Xiaoyudong region, the NW-trending Xiaoyudong fault rupture is obvious in most segments, evidenced by about 1–2 m high scarps (Fig. 5a and b). The surface rupture offset the river channel, terraces, roads, and buildings, forming a continuous fault scrap (Fig. 5c). However, at its northwest and southeast extremes, different researchers have come to varying conclusions about the rupture's distribution (e.g. Lin et al., 2009; Chen et al., 2009; Liu-Zeng et al., 2010). Some researchers consider the Xiaoyudong fault rupture distribution to follow a simple NW trace in most segments with the southern segment being connected to the Peng-Guan fault (e.g. Liu et al., 2008; Liu-Zeng et al., 2009). Others conjecture that the Xiaoyudong fault extends southeastwardly and then breaks the Peng-Guan fault (e.g. Li et al., 2008, 2009).

To get a clearer understanding of what occurred at the ends of the Xiaoyudong fault rupture, we investigated the points reported by these researchers. We also found additional rupture points (X1–X5, Fig. 2), especially in the northwest segment of the Xiaoyudong rupture (Fig. 5d and e). In the northwest segment, the strike of the Xiaoyudong rupture changed from 310° to 025° then back again to 310°. The fault ruptured a small road and some cemented ground (Fig. 5d and e). In addition, in Fig. 6a, the rupture is not continuous at the point b (between points X2 and X4, Fig 2). It is replaced by en echelon rupture, which shows the southern block moving at a directional angle of 080° (Fig. 6b).

At the southeastern end of the Xiaoyudong rupture (Fig. 6), its strike is virtually north–south. In this segment, there is also a change in strike direction from 310° to 350° (Fig. 6a). Where the rupture bends, some back thrust is observed (the inlet in Fig. 6a), suggesting that the dip angle of the fault is gentler at depth (Fig. 11 in Liu-Zeng et al., 2010). The rupture here is composed of several forked ruptures, and vertical slip is about 50 cm (Fig. 6c). The southeasterly end of the Xiaoyudong rupture is a pure thrust rupture with about 40–60 cm of vertical displacement before it quickly disappears.

From the new points we obtained that were well marked, we were able to calculate the co-seismic slip vectors of some of the sites (Fig. 6) using the same method shown in Fig. 4e. The horizontal slip vectors showed that the hanging wall of the Xiaoyudong fault moved in a direction of about 057–091° (blue arrows of Fig. 6a). Based on the data in Table 2, we used *tan* θ *= uplift/shortening* to calculate the dip angle, θ, of the Xiaoyudong fault, and the results were ~35–48°. These results are similar to those revealed by trench excavation in Ran et al. (2010). Their trench was located on the roadside of a village called Luoyuan (N31°11′38.9″; E103°45′16.5″) in the Xiaoyudong area (Fig. 6), and their results gave a dip angle of the Xiaoyudong fault at ~40°. Chen et al. (2009) also achieved a similar result by analyzing co-seismic slip vector data; they suggested the dip angle of the Xiaoyudong fault to be ~35°.

Rupture distribution and co-seismic slip vectors of the Xiaoyudong fault (Fig. 6 and Table 2) indicate that the strike angle of the

Fig. 5. (a) Rupture photo at point X6; (b) Rupture photo at point X7; (c) photo of the middle segment of Xiaoyudong rupture which has clear and continuous scarp; (d) Rupture photos at point X4; and (e) Rupture photos at point X2. The yellow dashed lines represent the topography lines of fault scarps.

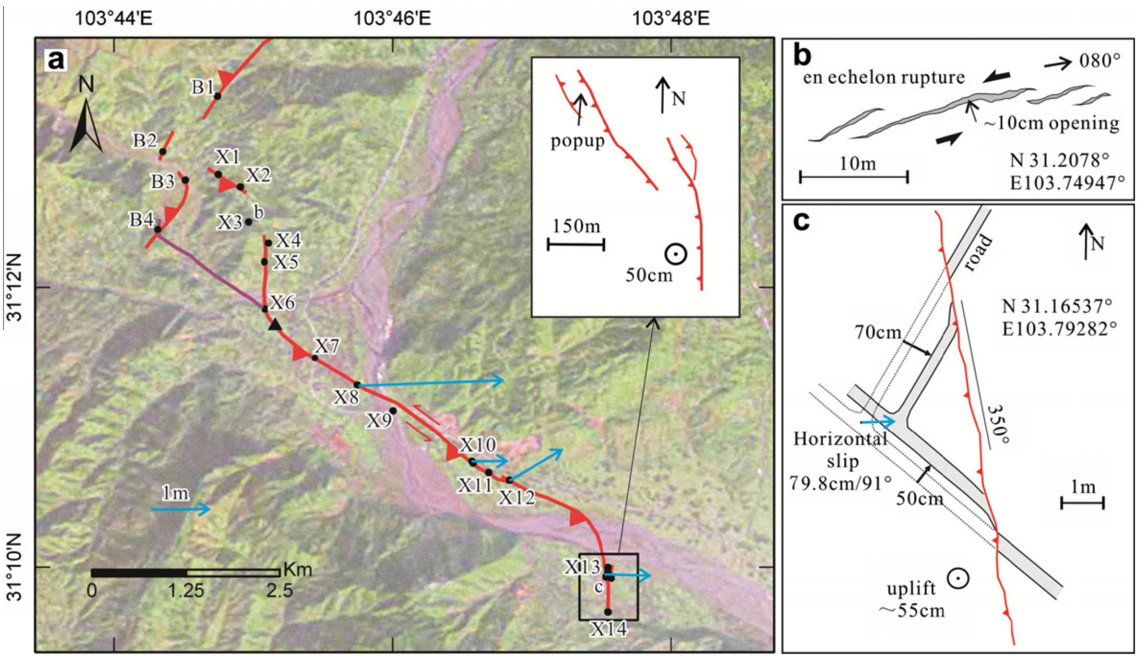

Fig. 6. Distribution of the Xiaoyudong fault rupture: (a) Locations of the investigation points (listed in the Table 2) and the co-seismic horizontal slip vectors (blue arrows); the purple line is the rupture at the northwest extreme of the Xiaoyudong fault suggested by Li et al. (2009) and Liu-Zeng et al. (2010). The black triangle is the location of the trench by Ran et al. (2010). (b) Sketch map of point X3; and (c) Sketch map and measured data of point X13 in detail.

Table 2
Co-seismic slip vectors and their components of the Xiaoyudong fault rupture.

Points	Slip vector direction (°)	Horizontal component of the slip vector (m)	Uplift (m)	Shortening (m)	Sinistral strike slip (m)	Dip angle of the fault (°)
X8	88	2.6	1.6	1.74	1.93	43
X10	90	0.62	0.55	0.62	0.08	42
X12	57	1.03	0.7	0.63	0.81	48
X13	91	0.79	0.55	0.79	0.15	35

rupture changes a lot, and the dip angle of the Xiaoyudong fault is relative small. It also indicates that the general direction of horizontal slip for the hanging wall is almost eastward, which is similar to the slip direction of the hanging wall of the Beichuan-Yingxiu fault (Fig. 1 and He et al., 2011). In addition, some segments of the rupture feature mainly thrust movement while others feature both thrust and sinistral slip movement; this is evidenced by the large change in strike direction of the Xiaoyudong rupture.

3.3. Peng-Guan rupture

The northeast-trending Peng-Guan rupture starts from Xiaoyudong area and ends northeast of Hanwang township (Fig. 1). Previous researchers reported scarps in the southern end of the Peng-Guan rupture. For example, Xu et al. (2008) observed scarps of about 20 cm high at Ci-feng township (P5 and P6, Fig. 2). Liu-Zeng et al. (2009) reported a 1.65 m-high scarp extending for about 100 m between P5 and P6 (solid red line Fig. 2). From our reinvestigation, we think some scarps may have been caused by landslides because these phenomena were often located on the forward side of steep slopes with small fissures at their rears and had very irregular distributions over only a limited area (Fig. 7).

Our field investigation tells us that the Peng-Guan rupture near the Ci-feng township is not obvious nor is it continuous. Given all these data and according Wang et al. (2008)'s inversion results, it seems very plausible that the Peng-Guan fault in this region also ruptured during the Wenchuan earthquake, though much of the rupturing is not evident at the ground's surface. The only evidence of rupturing is the co-seismic landslides along the fault trace. In other words, the Peng-Guan rupture is unclear south of the Xiaoyudong area, while it is clearly evident north of the Xiaoyudong area (Fig. 2).

4. Discussion

4.1. Formation mechanism of the Xiaoyudong fault rupture

The formation mechanism of the Xiaoyudong fault rupture has been described variously by different researchers. Li et al. (2009) treated the Xiaoyudong fault as a tear fault because they thought that the Xiaoyudong fault rupture displayed mainly sinistral slip movement based on their investigation and measured data. Chen et al. (2009), however, thought that the Xiaoyudong fault was the result of oblique slip because the dip angle is very low at ~30°, but they provide no more explanation for oblique extrusion occurring in this area.

In addition to previous field material, we conducted further field investigations and measurements in this area. Our evidence reveals some additional features for the Xiaoyudong fault. We find a large change in strike along the Xiaoyudong fault as well as a low dip angle of ~35–48°. Additionally, there are larger amounts of thrust than sinistral slip in most part, especially in the southeast and northwest extremes (Fig. 2b). The fault rupture does not break the Peng-Guan fault, but it changes its strike to be nearly NS nearby the Peng-Guan fault. This evidence indicates that the Xiaoyu-

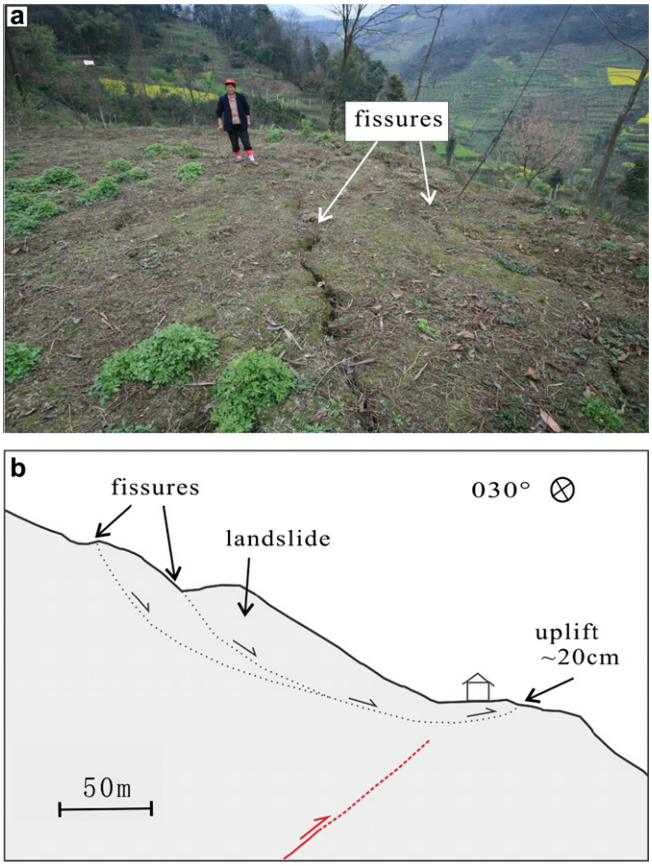

Fig. 7. Photo (a) and sketch map (b) of the fissures induced by sliding in the south segment of Peng-Guan fault. (The photo was taken at point P5 shown in Fig. 2).

dong fault is not a steep and pure sinistral slip fault, but rather a shallow thrust fault with sinistral slip component in most part.

In general, a tear fault is a fault occurring in rocks above a low angle thrust fault. It is often a steep to vertical fault, which some consider to be a type of strike-slip fault (Escalona and Mann, 2006). Based on the rupture features associated with the Xiaoyudong fault, it appears to have few of the features of a tear fault, and thus we think it unreasonable to consider this fault a tear fault in explaining the complex rupture phenomena of the Xiaoyudong area.

The causative fault of the Wenchuan Earthquake was the Beichuan-Yingxiu fault. This fault does not pass through the Xiaoyudong area (at shallow depths); furthermore, its northern part has migrated north-westward and forms a 3.5 km wide restraining stepover at the Xiaoyudong area (Fig. 2a). Although the southern segment of the Beichuan-Yingxiu fault displays larger thrust movement than the northern segment, dextral slip motion still should not be neglected because it is substantial with its largest value being 4 m (Yu et al., 2010). Generally, a pressure ridge and a frontal reverse fault present in the restraining stepover when strike slip faulting occurs: for example, during the 1999 Duzce earthquake, a dextral shock occurred on North Anatolia fault in Turkey, a pressure ridge and a frontal reverse fault were formed in the Kaynasli dextral restraining stepover (Fig. 8a; Duman et al., 2005). Compared to the ruptures of the Kaynasli restraining stepover, the ruptures in the Xiaoyudong area are of a similar distribution style (Fig. 8), and even have similar inner sinistral branches at similar locations (Figs. 6 and 8), which make us believe that the main cause of the Xiaoyudong rupture is the 3.5 km wide restraining stepover, named the Xiaoyudong stepover.

However, there are some differences between the Kaynaslistepover and the Xiaoyudong stepover (Fig. 8, Table 3). In the stepover formed by pure strike slip faulting, like the Kaynasli case, the pressure ridge often forms in the stepover, and the frontal reverse fault is usually a pure thrust fault. However, in the Xiaoyudong area, a great part of the pressure ridge formed outside the stepover, secund to the footwall, and the Xiaoyudong rupture featured both thrust and sinistral slip movement in most segments (Fig. 2 and 8).

It is well known that the Beichuan-Yingxiu fault displays large amounts of thrust and dextral slip (Xu et al., 2009b; Yu et al., 2010). These thrust and dextral slip could have resulted in the pressure ridge and frontal reverse fault, i.e., Xiaoyudong fault with thrust and strike slip features (Fig. 9a). In addition, in the Xiaoyudong area the Peng-Guan Massif is the main component of the hanging wall of the Beichuan-Yingxiu fault, while the footwall is composed of the Paleozoic–Mesozoic sedimentary rock (Fig. 2a). Compared to the Peng-Guan Massif, the Paleozoic–Mesozoic sedimentary rock is so soft that the pop-up deformation occurred mainly in the footwall area (Figs. 8 and 9).

Due to the almost eastward slip vector of the hanging wall of the Beichuan-Yingxiu rupture, we schematically contrast vertical offset with latitude, which is parallel to the horizontal movement, and show that the 'deformation gap' between B4 and B5 is totally accommodated by the Xiaoyudong rupture (Fig. 9a and c).

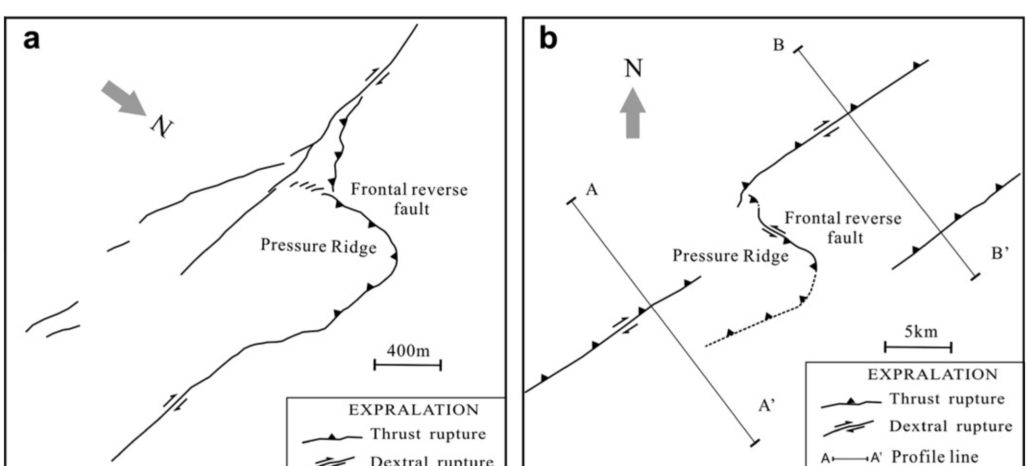

Fig. 8. Distribution of rupture types in the restraining step-over area: (a) The Kaynasli restraining stepover (Revised from Duman et al., 2005) and (b) The Xiaoyudong restraining stepover.

Table 3
Comparison of the Kaynsli stepover and the Xiaoyudong stepover.

	Kaynasli step over	Xiaoyudong step over
Activity type of the main fault	Pure dextral	Thrust with dextral amount
Width of the step over	About 500 m	3.5 km
Frontal reverse fault	Thrust and mainly in the step over with a little outside	Thrust with sinistral amount, and half of it is outside of the step over
Inner sinistral branches	Almost in the same position	

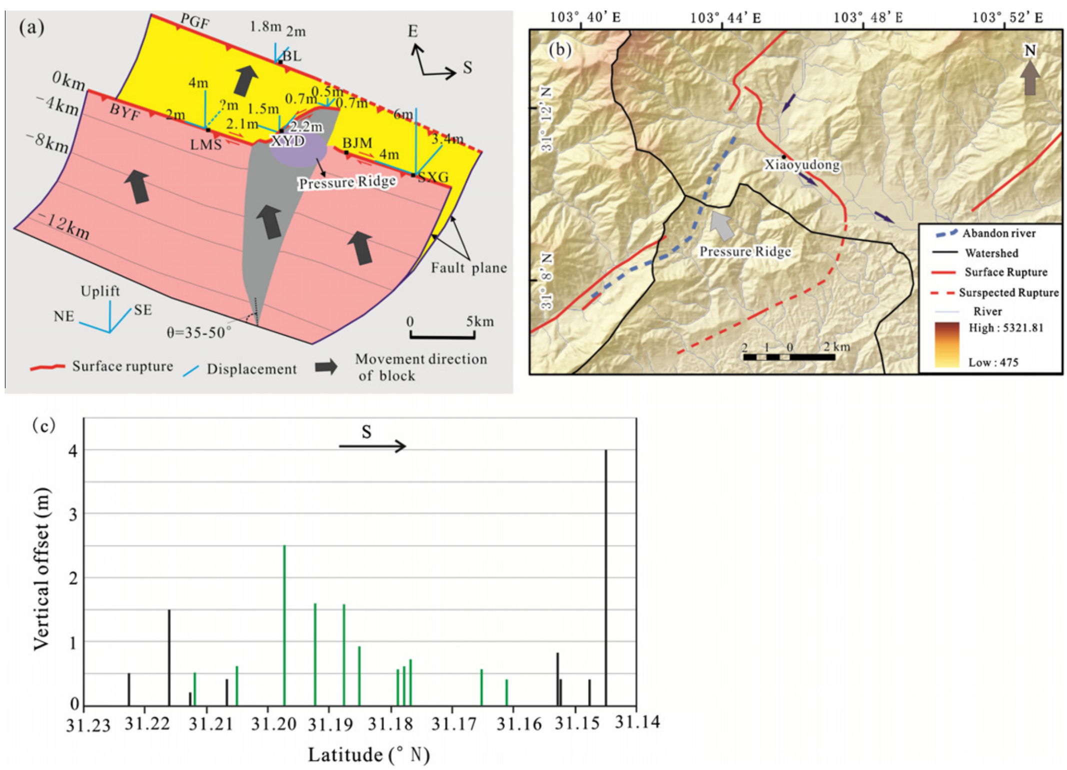

Fig. 9. (a) Mechanism model for the Xiaoyudong fault rupture (the fault planes are after Hubbard et al., 2010). (b) Geomorphologic features in the Xiaoyudong area. (c) Vertical offset of the Xiaoyudong rupture and the Beichuan-Yingxiu rupture in the Xiaoyudong area along latitude.

Our stepover model for the Xiaoyudong area (Fig. 9a) cannot only account for the Xiaoyudong rupture and the 'deformation gap' of the Beichuan-Yingxiu rupture in this area, but is also supported by some geomorphologic evidence. Fig. 9b shows that a secondary highland was formed in the Paleozoic–Mesozoic sedimentary rock area of the Xiaoyudong restraining stepover area and a local watershed has appeared there. This is the exact location of the pressure ridge. More interestingly, an abandon river with NE strike is found in this area (Fig. 9b); this river was likely induced by course change of the Jian River due to the uplift of the block in the Xiaoyudong stepover in the past.

4.2. Slip partitioning and simultaneous rupturing of two parallel faults

The term 'slip partitioning' is generally thought to describe oblique motion along a fault system that is accommodated on two or more faults by different mechanisms; it may represent a minimum energy condition (Michael, 1990). Bowman et al. (2003) suggested that partitioning can be explained by the upward elastoplastic propagation of oblique slip from a fault or shear zone at depth. The strain field ahead of the propagating fault separates into zones of predominantly normal, reverse, and strike-slip faulting. All these explanations reflect that only oblique motion could cause slip partitioning, whereby a fault is separated into a steep strike-slip fault and a thrust or normal fault with a low dip angle. The Wenchuan earthquake displays the features of slip partitioning. However, slip partitioning only describes the combined features of faulting within the fault system due to oblique motion, it does not describe how these faults could have ruptured simultaneously during a shock. Prior to the Wenchuan earthquake, the phenomenon of two faults rupturing simultaneously in an oblique fault system had only been observed in the 1957 Gobi-Altay earthquake (Bayarsayhan et al., 1996) and the 2001 Kunlunshan earthquake (King et al., 2005; Klinger et al., 2005). This aspect is the more interesting and important question in the rupturing process. What happened to cause these two parallel faults to rupture the surface simultaneously once rupturing had propagated to the northeast of the Xiaoyudong area?

During the Wenchuan earthquake, the same level of regional oblique stress would have been acting upon the hanging wall of the Beichuan-Yingxiu fault in the Xiaoyudong area (Fig. 9a, 10a); however, the different dip angles of the Beichuan-Yingxiu fault on both sides of the Xiaoyudong meant very different stress conditions (Fig. 10a). Fig. 10 shows how the horizontal stress F_n perpendicular to the rupture would have influenced on the footwall of the Beichuan-Yingxiu fault. F_{a1-1} and F_{b1-1} are the shearing strengths which cause the thrust slip of the Peng-Guan rupture, south and north of Xiaoyudong rupture respectively. The F_{b1-1} which equal to $F_n \sin(\theta_1) \cos(\theta + 90° - \theta_1)$ is bigger than the F_{a1-1}, which equal to $F_n \sin(\theta_2) \cos(\theta + 90° - \theta_2)$, as angle θ_1 is bigger than angle θ_2.

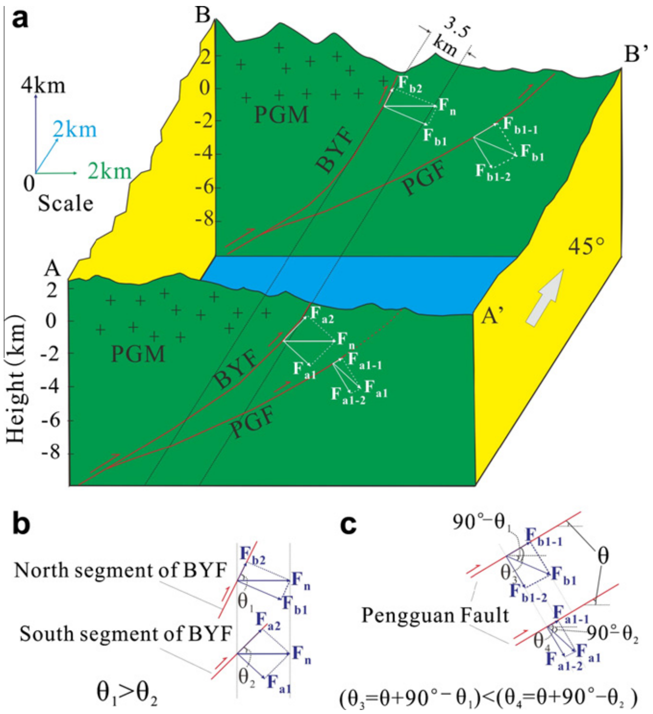

Fig. 10. Model explanation for two parallel faults being ruptured simultaneously (the position of profile A-A' and B-B' shown in the Fig. 8-b).

The results indicate that the stress parallel to the fault plane of the Peng-Guan fault is larger at the northern side than that of the south side in the Xiaoyudong area. In the southern side, stress F_{a1-1} is so small that the fault was unable to rupture the ground's surface even if rupturing occurred at depth (Wang et al., 2008). By contrast, in the north stress F_{b1-1} was large enough for the Peng-Guan fault to rupture the ground's surface.

By supposing $\theta = 30^\circ$, $\theta_2 = 45^\circ$and $\theta_1 = 60^\circ$, then $F_{b1-1} = F_n \sin 60^\circ \cos 60^\circ$ and $F_{a1-1} = F_n \sin 45^\circ \cos 75^\circ$, thus $F_{b1-1}/F_{a1-1} = 2.37$. This indicates that a 15° change of the dip angle of the Beichuan-Yingxiu fault at both sides of the Xiaoyudong restraining stepover creates conditions, whereby stress along the Peng-Guan fault surface doubles. This analysis can readily explain why the two faults ruptured the surface simultaneously after initial rupturing propagated northeast of the Xiaoyudong area.

5. Conclusion

This paper systematically documents co-seismic ruptures in the Xiaoyudong area that accompanied the 2008 Mw 7.9 Wenchuan earthquake based on field investigations, and discusses the mechanisms of the unique rupture phenomena.

The results suggest that the primary cause of the complex ruptures in the Xiaoyudong area is the 3.5 km wide Xiaoyudong restraining stepover on the Beichuan-Yingxiu fault. The Xiaoyudong fault is not a tear fault as was previously thought by some researchers, but a frontal reverse fault induced by the oblique compression of the stepover. Consideration for stress conditions indicates that stress along the Peng-Guan fault plane doubles due to the change in dip angle of the Beichuan-Yingxiu fault on both sides of the Xiaoyudong stepover. This condition resulted in two faults simultaneously rupturing the ground's surface north of the Xiaoyudong area. These results are helpful in deepening our understanding of the dynamic processes that produced surface ruptures during the Wenchuan earthquake.The results suggest that attention needs to focus on the influence of the dextral slip component, the change of the control fault's attitude, and property differences in rocks on either side of a fault when discussing formation mechanisms of surface ruptures.

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References

Bayarsayhan, C., Bayasgalan, A., Enhtuvshin, B., Hudnut, K.W., Kurushin, R.A., Molnar, P., Olziybat, M., 1996. 1957 Gobi-Altay, Mongolia, earthquake as a prototype for southern California's most devastating earthquake. Geology 24, 579–582.

Bowman, D., King, G., Tapponnier, P., 2003. Slip Partitioning by elastoplastic propagation of oblique slip at depth. Science 300, 1121–1123.

Burchfiel, B.C., Chen, Z., Liu, Y., Royden, L.H., 1995. Tectonics of the Longmen Shan and adjacent regions. International Geology Review 37, 661–735.

Burchfiel, B.C., Royden, L.H., van der Hilst, R.D., Hager, B.H., Chen, Z., King, R.W., Li, C., Lu, J., Yao, H., Kirby, E., 2008. A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, People's Republic of China. GSA Today 18, 4–11.

Chen, S., Wilson, C.J.L., 1996. Emplacement of the Longmen Shan Thrust–Nappe Belt along the eastern margin of the Tibetan Plateau. Journal of Structural Geology 18, 413–430.

Chen, Z., Burchfiel, B.C., Liu, Y., King, R.W., Royden, L.H., Tang, W., Wang, E., Zhao, J., Zhang, X., 2000. Global positioning system measurements from eastern Tibet and their implications for India/Eurasia intercontinental deformation. Journal of Geophysical Reasearch 105 (87), 16215–16227.

Chen, G.H., Xu, X.W., Zheng, R.Z., Yu, G.H., Li, F., Li, C.X., Wen, X.Z., He, Y.L., Ye, Y.Q., Chen, X.C., Wang, Z.C., 2008. Quantitative analysis of the co-seismic surface rupture of the 2008 Wenchuan earthquake, Sichuan, China along the Beichuan-Yingxiu fault. Seismology and Geology 30, 723–738 (in Chinese).

Chen, G.H., Xu, X.W., Yu, G.H., An, Y.F., Yuan, R.M., Guo, T.T., Gao, X., Yang, H., Tan, X.B., 2009. Co-seismic slip and slip partitioning of multi-faults during the Ms8.0 2008 Wenchuan earthquake. Chinese Journal of Geophysics 52, 1384–1394 (in Chinese).

Deng, Q.D., Chen, S.F., Zhao, X.L., 1994. Tectonis, seismicity and dynamics of Longmenshan Mountains and its adjacent regions. Seismology and Geology 16, 389–403 (in Chinese).

Deng, Q., Chen, G., Zhu, A., 2011. Discussion of rupture mechanisms on the seismogenic fault of the 2008 Ms8.0 Wenchuan earthquake. Science China (Earth Sciences) 54 (9), 1360–1377.

Densmore, A.L., Ellis, M.A., Li, Y., Zhou, R.J., Hancock, G.S., Richardson, N., 2007. Active tectonics of the Beichuan and Pengguan faults at the eastern margin of the Tibetan Plateau. Tectonics 26, 1–17.

Division of Earthquake Monitoring and Prediction, China Seismologic Bureau, 1999. Catalog of Chinese Historical Strong Earthquakes 1912–1990 Ms ⩾ 4.7. China Seismology Press, pp. 637. (in Chinese).

Division of Earthquake Monitoring and Prediction, State Seismologic Bureau, 1995. Catalog of Chinese Historical Strong Earthquakes 2300 BC-1911. China Seismology Press, pp. 514. (in Chinese).

Dong, S.W., Zhang, Y.Q., Wu, Z.H., Wu, Z.H., Yang, N., Ma, Y.S., Shi, W., Chen, Z.L., Long, C.X., An, M.J., 2008. Surface rupture and co-seismic displacement produced by the Ms 8.0 Wenchuan Earthquake of May 12th, 2008, Sichuan, China: Eastwards growth of the Qinghai-Tibet Plateau. Acta Geologica Sinica 82, 938–948.

Duman, T., Emre, O., Dogan, A., Ozalp, S., 2005. Step-over and bend structures along the 1999 Duzce earthquake surface rupture, North Anatolian fault, Turkey. Bulletin of the Seismological Society of America 95, 1250–1262.

Escalona, A., Mann, P., 2006. Tectonic controls of the right-lateral Burro Negro tear fault on Paleogene structure and stratigraphy, northeastern Maracaibo Basin. AAPG Bulletin 90 (4), 479–504.

He, H.L., Sun, Z.M., Wei, Z.Y., Dong, S.P., Gao, X., Wang, S.Y., Wang, J.Q., 2008. Rupture of the Ms8.0 Wenchuan earthquake along Baishahe river. Seismology and Geology 30, 658–673 (in Chinese).

He, H., Wei, Z., Chen, C., Shi, F., 2011. On-site determination of slip vectors along the Longmenshan fault during the Mw 7.9 Wenchuan, China, earthquake of May 12, 2008. Journal of Asian Earth Sciences 41, 274–282.

Hubbard, J., Shaw, J.H., 2009. Uplift of the Longmen Shan and Tibetan plateau, and the 2008 Wenchuan ($M = 7.9$) earthquake. Nature 458, 194–197.

Hubbard, J., Shaw, H., Klinger, Yann., 2010. Structural setting of the 2008 Mw 7.9 Wenchuan, China, earthquake. Bulletin of the Seismological Society of America 100 (5B), 2713–2735.

Jia, D., Li, Y., Lin, A., Wang, M., Chen, W., Wu, X., Ren, Z., Zhao, Y., Luo, L., 2010. Structural model of 2008 Mw 7.9 Wenchuan earthquake in the rejuvenated Longmen Shan thrust belt, China. Tectonophysics 491, 174–184.

King, R.W., Shen, F., Burchfiel, B.C., Royden, L.H., Wang, E., Chen, Z.L., Liu, Y.P., Zhang, X.Y., Zhao, J.X., Li, Y.L., 1997. Geodetic measurement of crustal motion in southwest China. Geology 25 (2), 179–182.

King, G., Klinger, Y., Bowman, D., Tapponnier, P., 2005. Slip-Partitioned surface breaks for the Mw 7.8 2001 Kokoxili Earthquake, China. Bulletin of the Seismological Society of America 95, 731–738.

Kirby, E., Reiners, P.W., Krol, M.A., Whipple, K.X., Hodges, K.V., Farley, K.A., Tang, W., Chen, Z., 2002. Late Cenozoic evolution of the eastern margin of the Tibetan Plateau: inferences from 40Ar/39Ar and (U–Th)/He thermochronology. Tectonics 21, 1–20.

Klinger, Y., Xu, X., Tapponnier, P., van der Woerd, J., Lasserre, C., King, G.C.P., 2005. High-resolution satellite imagery mapping of the surface rupture and slip distribution of the Mw 7.8, November 14, 2001 Kokoxili earthquake (Kunlun faut, Northern Tibet, China). Bulletin of the Seismological Society of America 95, 1970–1987.

Li, Y., Zhou, R.J., Densmore, A.L., Ellis, M.A., 2006. Geomorphic evidence for the late Cenozoic strike-slipping and thrusting in Longmenshan Mountain at the eastern margin of the Tibetan Pllateau. Quaternary Science 26, 40–52 (in Chinese).

Li, Y., Zhou, R.J., Densmore, A.L., Yan, L., Richardson, N., Dong, S.L., Ellis, M.A., Zhang, Y., He, Y.L., Chen, H., Qiao, B.C., Ma, B.L., 2008. Surface rupture and deformation of the Yingxiu-Beichuan fault by the Wenchuan earthquake. Acta Geologica Sinica 82, 1688–1706 (in Chinese).

Li, Y., Huang, L.Q., Densmore, A.L., Zhou, R.J., Yan, L., Zhang, Y., Richardson, N., Dong, S.L., Qiao, B.C., Ellis, M.A., He, Y.L., Chen, H., Ma, B.L., 2009. Surface rupture of Xiaoyudong fault caused by Wenchuan earthquake and its geological significance. Quaternary Sciences 29, 502–512 (in Chinese).

Lin, A., Ren, Z., Jia, D., Wu, X., 2009. Co-seismic thrusting rupture and slip distribution produced by the 2008 Mw 7.9 Wenchuan earthquake, China. Tectonophysics 471, 203–215.

Liu, J., Zhang, Z., Wen, L., Xing, X.C., Xu, Q., Hu, G.Y., Tapponnier, P., Zeng, L.S., Ding, L., Liu, Y.L., 2008. The Ms 8.0 Wenchuan earthquake co-seismic rupture and its tectonic implications-an out-of-sequence thrusting event with slip partitioned on multiple faults. Acta Geologica Sinica 82, 1707–1722.

Liu-Zeng, J., Zhang, Z., Wen, L., Tapponnier, P., Sun, J., Xing, X., Hu, G., Xu, Q., Zeng, L., Ding, L., Ji, C., Hudnut, K.W., Van der Woerd, J., 2009. Co-seismic ruptures of the 12 May 2008, Ms 8.0 Wenchuan earthquake, Sichuan: East–West crustal shortening on oblique, parallel thrusts along the eastern edge of Tibet. Earth and Planetary Science Letters 286, 355–370.

Liu-Zeng, J., Wen, J., Sun, J., Zhang, Z., Hu, G., Xing, X., Zeng, L., Xu, Q., 2010. Surface slip and rupture geometry on the Beichuan fault near Hongkou during the Mw 7.9 Wenchuan earthquake, China. Bulletin of the Seismological Society of America 100 (5B), 2615–2650.

Ma, B.Q., Su, G., Hou, Z.H., Shu, S.B., 2005. Late quaternary slip rate in the central part of the Longmenshan fault zone from terrace deformation along the Mingjiang river. Seismology and Geology 27, 234–242 (in Chinese).

Michael, A.J., 1990. Energy constraints on kinematic models of oblique faulting: Loma Prieta versus Parkfield-Coalinga. Geophysical Research Letters 17, 1453–1456.

Ran, Y.K., Chen, L.C., Chen, J., Wang, H., Chen, G.H., Yin, J.H., 2010. Paleoseismic evidence and repeat time of large earthquakes at three sites along the Longmenshan fault zone. Tectonophysics 491, 141–153.

Research group of Crustal Movement Observation Network of China, 2008. The Co-seismic displacement field of the 2008 Ms 8.0 Wenchuan Earthquake measured by GPS, Science in China 38(10), 1195–1206.

Shen, Z., Sun, J., Zhang, P., Wang, Y., Wang, M., Burgmann, R., Zeng, Y., Gan, W., Liao, H., Wang, Q., 2009. Slip maxima at fault junctions and rupturing of barriers during the 2008 Wenchuan earthquake. Nature Geosciences 2, 718–724.

Tang, R.C., Han, W.B., 1993. Active Faults and Earthquakes in Sichuan Province. Seismological Press, pp. 368 (in Chinese).

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., 1982. Propagating extrusion tectonics in Asia: New insights from simple experiments with platicine. Geology 10, 611–616.

Tapponnier, P., Zhiqin, X., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., Jingsui, Y., 2001. Oblique stepwise rise and growth of the Tibet Plateau. Science 294, 1671–1677.

Wang, W.M., Zhao, L.F., Li, J., Yao, Z.X., 2008. Rupture process of the M8.0 Wenchuan earthquake of sichuan. China. Chinese Journal of Geophysics 51, 1403–1410 (in Chinese).

Xu, X., Wen, X., Ye, J., Ma, B.Q., Chen, J., Zhou, R.J., He, H.L., Tian, Q.J., He, Y.L., Wang, Z.C., Sun, Z.M., Feng, X.J., Yu, G.H., Chen, L.C., Chen, G.H., Yu, S.E., Ran, Y.K., Li, X.G., Li, C.X., An, Y.F., 2008. The Ms 8.0 Wenchuan earthquake surface ruptures and its seismogenic structure. Seismology and Geology 30, 597–629 (in Chinese).

Xu, X.W., Yu, G.H., Chen, G.H., Ran, Y.K., Li, C.X., Chen, Y.G., Chang, C.P., 2009a. Parameters of coseismic reverse- and oblique-slip surface ruptures of the 2008 Wenchuan earthquake, eastern tibetan plateau. Acta Geologica Sinica 83, 801–840.

Xu, X.W., Wen, X.Z., Chen, G.H., Tian, Q.J., Chen, J., He, H.L., He, Y., Yu, S., Ye, J., Zhou, R.J., Yu, G.H., Chen, L., Li, Z., Li, C.Y., An, Y.F., Klinger, Y., Hubbard, J., Shaw, J.H., 2009b. Co-seismic reverse- and oblique slip surface faulting generated by the 2008 Mw 7.9 Wenchuan earthquake. China. Geology 37, 515–518.

Xu, X.W., Chen, G.H., Yu, G.H., Sun, X.Z., Tan, X.B., Chen, L.C., Sun, J.B., Chen, Y.G., Chen, W.S., Zhang, S.P., Li, K., 2010. Reevaluation of surface rupture parameters of the 5 12 Wenchuan earthquake and its tectonic implication for Tibetan uplift. Chinese Journal of Geophysics 53 (10), 2321–2336 (in Chinese).

Yu, G., Xu, X., Klinger, Y., Diao, G., Chen, G., Feng, X., Li, C., Zhu, A., Yuan, R., Guo, T., Sun, X., Tan, X., An, Y., 2010. Fault-scarp features and cascading rupture model for the Mw 7.9 Wenchuan Earthquake, eastern Tibetan Plateau, China. Bulletin of the Seismological Society of America 100, 2590–2614.