Surface Rupture of the 2008 Wenchuan, China, Earthquake in the Qingping Stepover Determined from Geomorphologic Surveying and Excavation, and Its Tectonic Implications

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Abstract The Wenchuan $M_w$ 7.9 earthquake of 12 May 2008 caused the rupture of the Longmen Shan thrust belt, which bounds the eastern margin of the Tibetan plateau, and generated a very complex surface rupture. The Beichuan–Yingxiu fault (BYF) was the main seismogenic fault and formed two distinctively different surface rupture zones separated by the Qingping and Gaochuan stepovers. Real-time kinematic (RTK) surveying of alluvial terrace sequences indicates that terraces T1-T3 and river floodplain T0 have the same vertical displacement associated with the Wenchuan earthquake. Trench excavation and optical stimulated luminescence (OSL) dating of alluvial deposits indicate that only the deformation of the Wenchuan earthquake was recorded in the Qingping stepover since at least $\sim$20 ka. Other deformations since $\sim$20 ka probably occurred in other places or did not reach the surface. This can be meaningful to analyze the completeness of paleoearthquakes in trench excavation on thrust faults.

The width of the Qingping stepover is $\sim$1 km and it is not strong enough to form a barrier to arrest the propagation of rupture in the 2008 Wenchuan earthquake. The Gaochuan stepover is $\sim$7 km wide and it is a barrier to separate the two surface rupture zones associated with the Wenchuan earthquake along the BYF. The empirical relationship of rupture displacement and stepover dimensions on strike-slip faults is probably suitable for the large thrust fault zone with a strike-slip component. This may be beneficial to the study of cascade rupture sections and seismic hazard assessment on large thrust faults.

Introduction

The earthquake surface rupture behavior is the key link for understanding transformation from elastic strain accumulation to permanent tectonic deformation in the crust (Xu, Yu, et al., 2008). It contains basic information about the deformation pattern, amplitude of motion, movement state, and earthquake faulting process in the continental crust. In the assessment of large earthquake hazards, detailed evidences of fault segmentation such as fault stepovers and bend structures, determine the rupture pattern and models of the potential rupture source. The maximum magnitude of the earthquake or recurrence of future earthquakes on single fault or multifault ruptures correlates to these patterns and model sources.

On 12 May 2008, an exceptionally large earthquake ($M_w$ 7.9) awakened the seemingly sleeping Longmen Shan fault zone, a northeast trending boundary fault between the Songpan–Ganzi and Sichuan basin blocks, at the eastern margin of the Tibetan plateau (Xu, Wen, et al., 2009). This catastrophe caused millions of landslides, the loss of many thousands of lives, and large property loss (Zhang et al., 2008) and caused the most complicated surface rupture zone of thrust faulting in the world (Xu, Yu, et al., 2009).

The Beichuan–Yingxiu fault (BYF) is the main seismogenic fault of the Wenchuan earthquake (Xu, Wen, et al., 2009). Postearthquake trenching for paleoseismological examinations in the towns of Yingxiu, Leigu, and Pingtong show the recurrence of large earthquakes along the BYF (Dong et al., 2008; Ran et al., 2010). Because these trenches are located within the fault subsegment of the BYF, further study is needed to define the characteristics of large earthquakes in the boundary regions of fault segments.

Longmen Shan Fault Zone and Earthquake Surface Rupture Features

On the eastern margin of the Tibetan plateau, the Longmen Shan rises 6,000 m above the Sichuan basin, exhibiting greater relief than anywhere on the plateau (Burchfiel et al., 2008; Royden et al., 2008; Fig. 1a). The Longmen Shan fault zone bounds the east side of the plateau. It consists of three
northwest-trending faults, which, from west to east, are the Wenchuan–Maoxian fault (WMF), the Beichuan–Yingxiu fault (BYF), and the Pengxian–Guanxian fault (PGF) (Burchfiel et al., 2008; Xu, Ji, et al., 2008; Zhang et al., 2008; Fig. 1b).

The results of field investigation, Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) indicate that the $M_w 7.9$ Wenchuan, China, earthquake ruptured two large thrust faults along the Longmen Shan fault zone and formed a 240-km-long surface rupture zone along the BYF and an additional 72-km-long surface rupture zone along the PGF (Fig. 1b,c; Hao et al., 2009; Shen et al., 2009; Xu, Wen, et al. (2009); Zhang et al., 2010). The surface rupture zones are characterized by fault-related geomorphic features such as fault scarps, linear drainages, shutter ridges, offset drainages, and topography changes (Chen et al., 2009; Xu, Wen, et al. (2009); Xu, Yu, et al. 2009; Lin et al., 2009, 2010; Zhang et al., 2010).

The middle rupture zone along the BYF that is the main rupture associated with Wenchuan earthquake can be divided into two distinct geometric segments. These segments oriented southwest to northeast are the Hongkou–Qingping and Beichuan–Nanba segments (Hao et al., 2009; Xu, Wen, et al. (2009)). These two surface rupture segments are about 101 and 133 km long, respectively, and are separated by the right step Qingping and Gaochuan stepover structures (Fig. 1c).

The Hongkou–Qingping surface rupture segment that is located in steep barrancos and mountains and strikes N35°–45° E generated a dominant thrust fault slip with maximum offset of 6.2 m and accompanied minor dextral slips (~2 m). The Beichuan–Nanba surface rupture segment, which formed the maximum vertical offset of ~6.5 m caused by deformation localization at Beichuan County, is expressed with an approximately equivalent dextral and vertical offset.

Figure 1. Surface rupture zone associated with the 2008 Wenchuan earthquake along the BYF and GJF. Surface rupture zone data of Wenchuan earthquake modified from Xu, Wen, et al. (2009). (a) Topography of the Tibetan plateau; (b) tectonics of the longmenshan region; (c) surface rupture zone associated with the 2008 Wenchuan earthquake. The base map is the hill shade image of the SRTM 90 m digital elevation data. See (b) for the location. (d) The distribution of the displacement along the BYF. SCB, Sichuan basin; BYF, Yingxiu–Beichuan fault; GJF, Guanzxian–Jiangyou fault; WMF, Wenchuan–Maoxian fault; QCF, Qingchuan fault; MJF, Minjiang fault; HYF, Huya fault. Locations: LX, Lixian County; YX, Yingxiu; DJY, Dujiangyan County; XYD, Xiaoyudong; WC, Wenchuan County; MX, Maoxian County; QP, Qingping; LG, Leigu; BC, Beichuan County; and QC, Qingchuan County.
displacements to the south of this segment (Shen et al., 2009; Xu, Yu, et al., 2009). In the northernmost part of this segment, the dextral slip is dominant (∼3 m) and the vertical slip is below ∼2 m (Fig. 1d; Xu, Wen, et al. (2009)).

Tectonic and Geologic Setting at Qingping

The town of Qingping is located in the valley of Mianyuan River (Fig. 2a). Interpretation of pre-earthquake aerial photographs and SPOT satellite images indicates that active fault traces are characterized by shutter ridges, scarps, and linear valleys (Fig. 2). At the village of Wangjiaping and its adjacent areas, the BYF is located on the northwest hillside of the Qishu gully (Fig. 2b). Along the fault strike, a fault valley is formed, and the shutter ridges are offset. In addition, many paleolandslides are distributed along the fault trace. To the east of the village of Wangjiaping and to the west of Mianyuan River, the fault forms linear valleys. This fault does not spread along the original trace, and another fault further east along the Zoumaling gully generated a linear valley (Fig. 2b). These features reveal that the BYF was active during the Quaternary period. The town of Qingping is located in a stepover, here named Qingping stepover, with the width of ∼1 km (Fig. 1c).

In the Qingping stepover, the main lithologic characters are Devonian–Carboniferous carbonatite and Cambrian shale. Field investigation indicates that the bedrock bedding striking ∼N45°W is perpendicular to the strike of fault trace and has a large dip angle (∼50° or more) that reveals a strong tectonic compression process in the northwest-southeastern direction.

Surface Rupture at Qingping

In the north of the village of Qipanshi, there are four terraces (T4-T1), and the flood plain (T0) along the Mianyuan River whose heights above the present riverbed are 53, 28, 18.5, 11, and ∼1 m, respectively (Figs. 3 and 4). The village of Qipanshi is located on the terrace T2, and the village of Sanxingmiao is located on the terrace T1 (Fig. 3).

The 2008 Wenchuan earthquake produced a surface rupture at the town of Qingping. From post-earthquake detailed field investigation, there is a surface rupture at P1

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Figure 2. Characteristics of active fault traces and river terraces at the town of Qingping and its adjacent regions (see Fig. 1 for the location). (a) Pre-earthquake SPOT satellite image (5-m resolution) overlain on the 30-m hillshade image. (b) Tectonic geomorphology and river terraces of the Mianyuan River, interpreted from (a) according to the features of offset shutter ridges, scarps, and linear valleys. The base map is the 1:500,000 geologic map (Sichuan Province). G. represents the gully.
(Fig. 3), west of Luociliangzi Mountain, which formed a reverse slope due to a new fold with northwest uplift accompanied with landslides and collapses. There is no investigation point between P1 and P2 because of a high hill and dense trees. The surface rupture was found at P2. We infer this surface rupture could traverse across the Luociliangzi Mountain (Fig. 3). Drunk trees and a hanging-wall collapse scarp at P6 and a pressure ridge at P7 reveal the Wenchuan earthquake surface rupture. The rupture trace associated with the Wenchuan earthquake is inferred between P6 and P7 (Fig. 3).

The Wenchuan earthquake displaced the terrace sequence from the flood plain (T0) to terrace T3. According to a local villager (Xiangwei Zheng, personal commun., 2008), these geomorphologic surfaces were almost flat before the Wenchuan earthquake. Real-time kinematic (RTK) surveying lines, established perpendicular to the strike of the coseismic surface scarp (Fig. 3), indicate the flood plain (T0) of the Mianyuan River was deformed in the southern village of Qipanshi (Fig. 3). Terrace T2 was deformed, its scarp is 294 cm-high (P3 in Figs. 3 and 4c,e), and the scarp height on terrace T3 is 310 cm (P2 in Figs. 3 and 4d,e). The horizontal offset of terraces and floodplain is very small (Fig. 4b).

Deformation of Alluvial Sediments

Shallow excavations have been useful for describing the internal structure of the fault scarp (Yeats et al., 1997; McCalpin, 2009). In order to study the deformation of alluvial sediments in the 2008 Wenchuan earthquake, a 13-m-long and 5-m-deep trench was excavated on the surface of terrace T2 across the rupture scarp (Figs. 3 and 5). The southwest wall of the trench was mapped in detail. The trenching defined eight sediment units (Fig. 5). Unit 1 consists of recent blackish 20-cm-thick cultivated soil (mainly sand with pebbles and often grass roots) that covers the surface of terrace T2 and presently is farmland. Other units represent alluvial deposits. Unit 2 is a brownish cobble layer filled with sand and silty sand. Unit 3 is a gray gravel-bearing silt. Units 3 and 2 represent a coarse to fine sediment sequence in this alluvial deposit. Unit 4 is grayish-brown coarse sand, filled with pebbles. Unit 5 is yellowish-brown gravel-bearing silt. Unit 6 is medium-grain grayish-brown sand with horizontal beddings. Unit 7 consists of gray gravel-bearing coarse sand, and Unit 8 consists of grayish-brown horizontally bedding coarse sand, filled with pebbles.

On terrace T2, the fault scarp reflects only warping on the surface. In the trench, the zone of faulting is about 2-m-wide and is complex (Fig. 5b). Units 6 to 8 are on the hanging wall of the fault and dragged by the fault plane f3. An extensional packed wedge was formed along with the movement of the fault plane f3 (Fig. 5b). On the footwall, Unit 6 and the bottom of Unit 4 are not exposed in the trench. Unit 5, a silt lens in the coarse sand-gravel layer (Unit 4), was dragged and dislocated by the fault plane f1 (Fig. 5b), indicating the direction of thrust faulting. However, the vertical offset of Unit 5, 1.4 m, is smaller than that of the surface on terrace T2. Under the biggest boulder in Unit 3, the gravels of Unit 4 exhibit long-axis orientation along the slip plane f1 (Fig. 5b). Units 1 to 3 are expressed as a fold and have a similar
deformation with a vertical offset of \( \sim 2.6 \text{ m} \). Far from the fault zone and its vicinity, the deposits are in a common alluvial sedimentary sequence and are not deformed (Fig. 5b). This demonstrates the deformation of the Wenchuan earthquake is confined to the limited fault zone.

Ages of Terrace Sequence at Qingping

Three optically stimulated luminescence (OSL) samples were collected in the trench on terrace T2 in order to date the terrace T2 (Fig. 5b). Sample dating was conducted in the
Luminescence Dating Laboratory, Institute of Geology, China Earthquake Administration. Under weak red light, fine quartz grains (4–11 μm) were separated, and the purity was tested by the infrared stimulated luminescence (IRSL) scanning until an IRSL/OSL ratio was less than 3%. The equivalent dose was determined using fine-grained quartz (4–11 μm) on a Daybreak 1100B reader with the sensitivity corrected multiple aliquot regenerative-dose protocol (SMAR) initially developed by Zhou and Shackleton (2001). Following the experimental procedures of Wang et al. (2006), Lu et al. (2007), and Wang et al. (2010), uranium and thorium contents were determined with a Daybreak 582 thick source alpha-counter. The potassium content was measured with a flame photometer.

A sample (QP-1) collected from the fine-medium sand lens between Unit 2 and Unit 3 revealed an age of 68.3 ± 2.9 ka (Fig. 5b). Two samples (QP-2 and QP-3) were collected from a silt lens (Unit 5) and in the coarse sand layer (Unit 4) and were separated by the fault f2. Their ages are 22.9 ± 3.1 and 24.9 ± 3.1 ka, respectively (Fig. 5b). According to ages of later Quaternary river terrace sequence in the middle segment of Longmen Shan, which is published in the journals (see Table 1), terraces T1-T3 are generally ~10, 15–20, and ~30 m high above the present riverbed.
Table 1

<table>
<thead>
<tr>
<th>River</th>
<th>Site</th>
<th>Terrace</th>
<th>Height above the Riverbed (m)</th>
<th>Age (ka)</th>
<th>Method</th>
<th>Reference</th>
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<tr>
<td>Fu River</td>
<td>Pingtong town, Beichuan County</td>
<td>T1</td>
<td>12</td>
<td>14 ± 0.80</td>
<td>OSL</td>
<td>Ren et al. (2009)</td>
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<td></td>
<td>Nancha town</td>
<td>T1</td>
<td>7.5</td>
<td>12 ± 0.03</td>
<td>OSL</td>
<td></td>
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<tr>
<td>Min River</td>
<td>Songpan</td>
<td>T2</td>
<td>19</td>
<td>22.78 ± 0.34</td>
<td>^14C</td>
<td>Kirby et al. (2000)</td>
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<tr>
<td></td>
<td>Guangdianzi town, Chengdu</td>
<td>T1</td>
<td>3–4</td>
<td>3</td>
<td>^14C</td>
<td>Li et al. (2006)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T2</td>
<td>7–10</td>
<td>20.2 ± 1.6</td>
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<tr>
<td></td>
<td></td>
<td>T3</td>
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<td>30.8 ± 2.5</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>T4</td>
<td>34–38</td>
<td>55.8 ± 2.4</td>
<td>TL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>4–6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td>Wenchuan County</td>
<td>T2</td>
<td>20</td>
<td>20.36 ± 1.73</td>
<td>TL</td>
<td></td>
<td>Ma et al. (2005)</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>38</td>
<td>50.8 ± 3.9</td>
<td>TL</td>
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<td>Li et al. (2006)</td>
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<td>Yinxiu</td>
<td>T2</td>
<td>15</td>
<td>16.49 ± 0.98</td>
<td>TL</td>
<td>Ren et al. (2009)</td>
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<tr>
<td></td>
<td>T3</td>
<td>25–30</td>
<td>51.33 ± 4.36</td>
<td>TL</td>
<td></td>
<td>Ma et al. (2005)</td>
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<td>Baisha River *</td>
<td>Luojia village, Dujiangyan</td>
<td>T2</td>
<td>15</td>
<td>18.51 ± 1.57</td>
<td>TL</td>
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<tr>
<td></td>
<td>T3</td>
<td>34</td>
<td>57.85 ± 4.92</td>
<td>TL</td>
<td></td>
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<tr>
<td>Jian River</td>
<td>Longmen Shan town</td>
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<td>22</td>
<td>23.3 ± 1.8</td>
<td>TL</td>
<td>Zhou et al. (2007)</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>40</td>
<td>12.2 ± 3.9</td>
<td>10^Be</td>
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<td>Densmore et al. (2007)</td>
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</table>

*Baisha River is a tributary of Min River. See Figure 1c for the location of rivers.

respectively; and their ages are ~10, ~20, and ~50 ka, respectively (Table 1).

Because the rivers across the middle Longmen Shan region underwent the similar tectonic and climatic environment, ages of their terraces are probably coeval. Terrace T2 at Qingping is 18 m high above the present riverbed and is probably equivalent to the regional terrace T2. So we infer that the age of QP-1 is unreliable, partly because the luminescence signal of the sediments of the fine-medium sand lens might not have been bleached sufficiently (Wallinga, 2002). The results of QP-2 and QP-3 are correct. Terrace T2 was formed after the deposition of Unit 5. The age of terrace T2 is ~20 ka. We also infer that the age of terrace T3 at the town of Qingping is ~50 ka.

Tectonic Implications of Surface Rupture at Qingping

The result of RTK surveying on river terraces indicates that terrace T1–T3 and flood plain (T0) have an equivalent vertical offset that represents a vertical displacement of ~3 m related to the Wenchuan earthquake at the town of Qingping. Trench excavation on the terrace T2 shows that Units 1–3 have a same deformation with the height of ~2.6 m, revealing that the three alluvial layers have undergone the same deformation history since the formation of Unit 3 and were merely warped in the 2008 Wenchuan earthquake.

The RTK measurement of deformation on terrace T2 is 294 cm. The deformation of terrace deposits (Units 1–3) indicates that the displacement of terrace T2 is about 265 cm. There are possibly two reasons for this difference. One possible reason is that the coseismic deformation of terrace T2 is also expressed with several small pressure ridges (~10–20-cm-high) besides main fold scarp (Fig. 4c).

Another reason is that there was a ~30-cm-high preexisting scarp on the surface of Unit 4 before the deposition of Unit 3.

Because of the limitation of the excavation environment such as narrow space, big gravel, and sand-gravel layers that collapse easily, the trench is not deep enough to discover the Unit 6 on the footwall. We do not know whether Units 6–8 also have the vertical displacement equivalent to Units 1–3. The surface rupture before the formation of Unit 3 may have been removed by the erosion of the Manyuang River.

In the historical record, at least 1700 to 2300 yr, large earthquakes have never been reported in the Chengdu and Longmen Shan region (Wen et al., 2009). Pre-earthquake trenches along the BYF show a recurrence interval of at least 2000 yr (Li et al., 2006). Post-earthquake trench excavation and ^14C dating in Leigu and Yinxiu along the BYF indicate that recurrence interval of large earthquakes is 2300 to 3300 yr (Dong et al., 2008, Ran et al., 2010). Recurrence interval estimated by the method of seismic moment rate is 2600 ~ 3800 yr (Ren et al., 2009). From these study data, we conclude that large earthquakes may repeat with the interval of ~3000 yr along the BYF.

Trench excavations in the towns of Leigu and Yinxiu indicate large earthquake recurred along the BYF (Dong et al., 2008, Ran et al., 2010). The surface rupture associated with the 2008 Wenchuan earthquake at the Qingping stepover provides an exceptional example. Units 1–3 have recorded the deformation history since at least ~20 ka. During this long period, several large earthquakes occurred along the BYF. Only the Wenchuan earthquake, however, deformed the surface at the location of the Qingping trench. This reveals that the fault could be reactivated by the Wenchuan earthquake. The deformation between the Wenchuan earthquake and ~20 ka might occur in other places or did not reach the surface. This demonstrates that it can be meaningful to
analyze the completeness of paleoearthquakes in trench excavations on thrust faults.

Fault stepovers are the boundaries of fault segmentation in seismic hazard assessment on a large fault zone. The town of Qingping is located in a stepover with the width of ∼1 km (Fig. 1c). Surface rupture investigation shows the Qingping stepover is not wide enough to arrest the propagation of surface rupture during the Wenchuan earthquake because the jog was not strong enough to act as a barrier. The Gaochuan stepover, to the northeast of Qingping stepover, is about ∼7 km, and its length influenced the fault movement as a transition zone along the BYF (Fig. 1c). To the south of Gaochuan stepover, surface rupture is dominant vertical with a small dextral slip. To the north of Gaochuan stepover, surface ruptures exhibit vertical and dextral slip. Xu, Wen, et al. (2009) conjectured that dip angle to the north of Gaochuan stepover is obviously bigger than that to the south in the deep crust. The seismic data inversion of rupture process indicates that the Wenchuan earthquake consists of two rupture events (Parsons et al., 2008; Wang et al., 2008; Zhang et al., 2009; Zhao et al., 2010). The first event is expressed with the pure reverse rupture along the west of Gaochuan stepover. Eastward propagation of the rupture triggered the second event along the Beichuan–Nanba segment with the dextral slip accompanied by the vertical component.

Stepover tectonics is regarded as the boundary of fault segments. For strike-slip faults, the width of stepover is an important parameter to determine whether the rupture can propagate across the stepover (Zhang et al., 1999; Duman et al., 2005). According to the empirical relationship of rupture displacement and stepover dimensions (Letts et al., 2002), the width of ∼1 km could not impede the propagation of rupture with the displacement of ∼3 km, and fault stepovers with the width of greater than 4~5 km can arrest up to 5 m or more of fault displacement. The empirical relationships are probably suitable to the thrust fault zone with a strike-slip component. This can be helpful to determine whether a fault stepover can be a termination of cascade ruptures in large thrust fault belts accompanied with strike-slip movement.

Conclusions

Trench excavations in the towns of Leigu and Yingxiu indicate large earthquakes recurred along the BYF (Dong et al., 2008; Ran et al., 2010). The surface rupture associated with the 2008 Wenchuan earthquake at the Qingping stepover provides an exceptional example. RTK surveying of alluvial terrace sequence and excavation of the trench across the surface rupture in the village of Qipanshi, the town of Qingping indicate that only the deformation of the Wenchuan earthquake was recorded at Qingping stepover in the past ∼20 ka. Other deformations since ∼20 ka probably occurred in other places or did not reach the surface. This can be meaningful in analyzing the completeness of paleoearthquakes in trench excavation on thrust faults.

The width of the Qingping stepover is ∼1 km, and it is not strong enough to form a barrier to arrest the propagation of rupture. But the Gaochuan stepover is ∼7 km wide, and it is a barrier to separate the two surface rupture zones along the BYF associated with the Wenchuan earthquake. Two rupture segments have distinctively different movements. The dimension of fault stepover structure in thrust fault belts with a strike-slip component can be regarded as a parameter to determine cascade rupture on large thrust faults.

The empirical relationship of rupture displacement and stepover dimensions on strike-slip faults is probably suitable for the large thrust fault zone with strike-slip component. This may be beneficial to the study of cascade rupture and seismic hazard assessment on large thrust faults.

Data and Resources

The shade image comes from the Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation Data that can be downloaded from the Consultative Group for International Agriculture Research (CGIAR) Consortium for Spatial Information (http://srtm.cgiar.org/index.asp; last accessed August 2008). The 30 m hillshade was generated from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) that can be downloaded from the Ministry of Economy, Trade, and Industry (METI) of Japan (http://www.gdem.aster.ersdac.or.jp/; last accessed September 2009). The 1:50,000 topographic map of the town of Qingping and 1:500,000 geologic map (Sichuan province) are published by the Chinese government.

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