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Co-seismic ruptures of the 12 May 2008, M_s 8.0 Wenchuan earthquake, Sichuan: East–west crustal shortening on oblique, parallel thrusts along the eastern edge of Tibet

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Abstract

The M_s 8.0, Wenchuan earthquake, which devastated the mountainous western rim of the Sichuan basin in central China, produced a surface rupture over 200 km-long with oblique thrust/dextral slip and maximum scarp heights of ~10 m. It thus ranks as one of the world's largest continental mega-thrust events in the last 150 yrs. Field investigation shows clear surface breaks along two of the main branches of the NE-trending Longmen Shan thrust fault system. The principal rupture, on the NW-dipping Beichuan fault, displays nearly equal amounts of thrust and right-lateral slip. Basin-ward of this rupture, another continuous surface break is observed for over 70 km on the parallel, more shallowly NW-dipping Pengguan fault. Slip on this latter fault was pure thrusting, with a maximum scarp height of ~3.5 m. This is one of the very few reported instances of crustal-scale co-seismic slip partitioning on parallel thrusts. This out-of-sequence event, with distributed surface breaks on crustal mega-thrusts, highlights regional, ~EW-directed, present day crustal shortening oblique to the Longmen Shan margin of Tibet. The long rupture and large offsets with strong horizontal shortening that characterize the Wenchuan earthquake herald a re-evaluation of tectonic models anticipating little or no active shortening of the upper crust along this edge of the plateau, and require a re-assessment of seismic hazard along potentially under-rated active faults across the densely populated western Sichuan basin and mountains.

1. Introduction

Great earthquakes having thrust ruptures within continents have been only rarely observed. Outside of regions adjacent to subduction plate boundaries, such as Taiwan, Japan, New Zealand, or Alaska, environments prone to large thrust earthquakes in the heart of continents such as Central China, India, Pakistan, Central Asia, Iran, Peru, Bolivia, and Argentina are associated with active plateau or mountain building, usually as a result of crustal shortening, and mostly as a consequence of continental collision. Yet, co-seismic ruptures unambiguously related to great thrust events in such areas have seldom been rigorously described. None of the famous Himalayan events of the late 19th and early 20th centuries (1897, 1905, 1934, 1950), for instance, are believed to have produced surface ruptures (e.g., Bilham et

al., 2001; Lavé et al., 2005). Similarly, most of the large thrust earthquakes that occurred in the Tien Shan or Qilian Shan during roughly the same period have poorly documented surface breaks, although rare stretches of such ruptures were found decades later in a few cases (e.g., Avouac et al., 1993; Gaudemer et al., 1995).

The 12 May 2008, M_s 8.0, Wenchuan earthquake thus provides a rare opportunity to study the rupture geometry, dynamics and crustal loading processes of a great intraplate thrust earthquake. Its occurrence also has implications that may help to resolve debates over competing models of regional active tectonics and uplift mechanisms for the Tibetan plateau (England and Houseman, 1986; Peltzer and Tapponnier, 1988; Avouac and Tapponnier, 1993; Royden et al., 1997; Meyer et al., 1998; Metivier et al., 1998; Clark and Royden, 2000; Tapponnier et al., 2001; Cook and Royden, 2008).

The earthquake struck the Longmen Shan margin of the Tibetan plateau, causing tragic loss of life and disastrous damage to infrastructure along the densely populated western edge of the Sichuan basin. It is the most devastating earthquake in China since the 1976 Tangshan earthquake, perhaps with even greater total economic damage yet with fewer fatalities. Strong shaking during the Wenchuan earthquake triggered numerous landslides on the steep slopes, some of which dammed rivers forming lakes across the rugged topography of the Longmen Shan range, aggravating damage and natural hazard. The tragedy is a sad reminder that seismic vulnerability has risen sharply over the past few decades due to combined economic and population growth and insufficient understanding and awareness of seismic hazard, a situation faced in many other highly seismic parts of the world (e.g., Jackson, 2006).

Rapid and exhaustive investigation of earthquake surface rupture puts essential constraints on the rupture mechanism, and helps to resolve the non-uniqueness in initial finite fault models of rupture dynamics (e.g., Ji and Hayes, 2008; Sladen, 2008; Chinese Earthquake Information Center, 2008; Nishimura and Yagi, 2008), as well as the future hazards to a region that hosts tens of millions of people (Parsons et al., 2008; Toda et al., 2008). Field observations of surface breaks and related features immediately after an earthquake are also important for documenting natural processes affecting the preservation of earthquake surface rupture. As verified in the field, unambiguous evidence of surface rupture (fresh fault- or fold-scarps, in particular) can be altered or even erased in a matter of days or weeks due to not only to the survival pressure of the local population, but also to natural degradation factors. Fault scarps

were already erased in some places we documented in this paper by large debris flows triggered by the heavy rains in the following summer season, which has implications for preservation of surface ruptures, and active fault studies in general, in regions with similar settings of high-relief topography and wet climate.

2. Neotectonics of the Longmen Shan margin of the plateau

In contrast with the low and flat Sichuan basin, the Longmen Shan defines the sharp and steep middle part of the eastern plateau margin, with deeply incised tributaries of the Yangtze River flowing oblique or perpendicular to the margin. The steepest part of the Longmen Shan margin is in the south, where mean elevation increases from ~500 m in the Sichuan basin to ~3000 m over 50 km distance plateau-ward, and then to ~3500 m over another 30–50 km farther northwest (Fig. 1a inset). The mean topographic gradient across the southern Longmen Shan is thus steeper than that in the middle of the Himalaya arc, but is comparable to the Tarim-west Kunlun margin.

The over 400 km-long NE-trending active Longmen Shan thrust fault system is a reactivated Mesozoic imbricated fold and thrust belt that separates the Songpan–Ganzi terrain to the west from the Yangtze block to the east (e.g., Tapponnier and Molnar, 1977; Xu et al., 1992; Burchfiel et al., 1995; Chen et al., 1995). The fault system consists of a series of active parallel thrusts, among which the Wenchuan, Beichuan, and Pengguan faults are considered to be seismogenic (Fig. 1; e.g., Tapponnier and Molnar, 1977; Tang and Han, 1993; Deng et al., 1994; Chen et al., 1994; Deng et al., 2003; Ma et al., 2005; Chen et al., 2007; Densmore et al., 2007; supplement S1). The Dayi and several anticline-bounding thrusts within the western Sichuan basin, though less appreciated and levels of activity less understood, also form parts of the thrust system (e.g., Deng et al., 1994; Jia et al., 2006; Hubbard and Shaw, 2009).

Historical seismicity within the Longmen Shan thrust system proper is characterized by moderately sized earthquakes, including five M_6 – 7 earthquakes since the 14th century from historical seismicity catalogs (M_6 in 1327, $M_{6-6.5}$ in 1657, M_6 in 1941, $M_{6.4}$ in 1958, and $M_{6.4}$ 1970), and no earthquakes larger than 7 were recorded in the last millennium. But several earthquakes with $M \geq 7$ occurred in the peripheral regions, for example, two $M_{7.2}$ 1976 Songpan earthquakes and 1933 $M_{7.5}$ Diexi in the Min Shan area to the north, in addition to those on the

active left-lateral Kunlun and Xianshuihe faults (Tang and Han, 1993; Division of Earthquake Monitoring and Prediction, China Seismologic Bureau, 1995, 1999).

Although folds and blind thrusts in the Longmen Shan region have long been recognized and mapped, their exact age and, more importantly, the amount of Cenozoic deformation and ongoing movement on such features, relative to that absorbed during the Late Triassic to Cretaceous, has remained unclear, with the prevailing view that they were mostly structures of pre-Cenozoic tectonic episodes (e.g., Xu et al., 1992; Dirks et al., 1994; Burchfiel et al., 1995; Chen and Wilson, 1996; Li et al., 2003; Jin et al., 2007). Such a view, and henceforth the contrast between high topography and the correlative lack of recent, large low-angle thrust faults, thick foreland deposits, and low present-day horizontal shortening, have served as the basis for proposing the lower crustal channel flow model, the dominant model for the Cenozoic growth of the Longmen Shan and southeastern Tibet (e.g., Royden et al., 1997; Clark and Royden, 2000; Kirby et al., 2002; Clark et al., 2005).

3. Observations of surface rupture

Shortly after the event, fault-plane solutions showed that the main shock had a thrust mechanism with a right-lateral slip-component (U.S. Geological Survey's National Earthquake Information Center, 2008). Various initial finite-fault source models derived from waveform inversions all favored a NE-propagating rupture on the NE-striking, 33° NW-dipping nodal plane, in keeping with the orientation and structure of the Longmen Shan thrust belt (e.g., Ji and Hayes, 2008; Sladen, 2008; Chinese Earthquake Information Center, 2008).

3.1. *General features of rupture geometry in map view*

Field mapping, initiated 2 weeks following the event, shows that the earthquake ruptured principally two main, NE-trending thrusts: the Beichuan and Pengguan thrusts of the Longmen Shan system (Fig. 1). But the frontal Dayi thrust, and the Wenchuan fault, the westernmost fault of the system, were probably not activated, though preliminary InSAR analysis indicates the possibility of motion or enhanced damage along these faults (de Michele et al., 2008; and see

supplement S1 for a description of more intense liquefaction along mapped blind thrusts in the basin).

The main surface break, on the Beichuan fault, is over 200 km long from the town of Yinxiu (or Xuankou on the parallel branch) in the south to near Guanzhuang in the north (Fig. 1c). The actual rupture is probably longer, but we could not assess its potential southwest continuation because there are few roads in the mountainous epicentral zone. In the north, although the northernmost unambiguous evidence of surface rupture on the Beichuan fault is near Shikan (Fig. 1c; 32.23869° N, 104.88022° E) with 2–3 m high scarp, the northernmost observable surface break was found at Guanzhuang (Fig. 1c; 32.39018° N, 105.14597° E), where we measured vertical and right-lateral offsets of 0.3 and 0.2 m, respectively, shown by the detached staircase outside of the hydro-power plant (a more detailed description of the site is provided in supplement S2).

One prominent feature of the Wenchuan earthquake is the partitioning of the co-seismic rupture on at least two parallel thrust faults. Basin-ward from the Beichuan thrust, a ~70 km-long surface rupture formed along the middle section of the Pengguan fault. For both the Pengguan and Beichuan faults, surface rupture is continuous in the middle section of the rupture, but becomes spotty and discontinuous at both the northern and southern ends, with observable fault scarps separated by kilometers. For example, we found no unambiguous fault scarp between km 85 and km 90 on the Pengguan fault, despite large vertical slip amounts at these locations, 3.3 m and 1.3 m high, respectively. In addition, at both ends of the surface rupture and where the faults were mapped, cracks or fissures with nominal offsets are subjected to arguable interpretations in terms of tectonic or non-tectonic origin, which leads to the different reported numbers of total length of surface rupture (e.g., Xu et al., in press; Li et al., 2009; Lin et al., 2009; supplement S3 includes a detailed description of the uncertainty in field mapping). In any case, surface rupture can be 50–100 km shorter than that at depth, indicated by both the aftershock distribution and seismological finite-fault inversions (e.g., Huang et al., 2008; Ji et al., 2008).

Overall, the surface ruptures along the Beichuan and Pengguan thrusts are fairly straight, in keeping with the geomorphic expression of these faults. In particular, the section of the Beichuan fault between 50 and 100 km northeast of the epicenter has the most prominent rectilinear fault trace on satellite images and in the geomorphology of the entire fault zone (Fig. 2a). This section of the fault bounds the southeastern margin of the Pengguan massif, which has

the highest peak and steepest terrain along the rupture, and also lies immediately west of the mapped surface rupture along the Pengguan fault (Fig. 1). The surface rupture along the Pengguan thrust is also quite straight overall, striking N50–60 °E, with only small local changes in azimuth. Our mapping of surface rupture, mostly limited by road access, however, may not capture the full extent of the small-scale geometrical complexities.

Perhaps the most notable geometric complexity in surface rupture is in the epicentral region, where northeastward propagation started (e.g., Ji and Hayes, 2008). In this area, at least three thrust faults ruptured, which might reflect branching in the initial phase of up-dip and NE-propagation (Bowman et al., 2003; King et al., 2005). They include two branches of the Beichuan fault, one crossing the town of Yingxiu, and the other Xuankou (Fig. 3a), and the Pengguan fault, which ruptured with patches of high slip at depth but with arguable surface break (e.g., Ji et al., 2008, Lin et al., 2009). The two branches of the Beichuan fault merge near Hongkou. North of this junction, the rupture on the Beichuan fault forms one single strand, though locally there are geometrical irregularities and kilometer-scale steps, notably near Xiaoyudong (~km 45), Gaochuan (~km 100), and Leigu (~km 135), in the form of three marked bends or doglegs (Fig. 1c).

The two bends, near Xiaoyudong and Gaochuan (~km 100, Fig. 1c) respectively, divide the rupture on the Beichuan fault into three main sections, whereas the one near Leigu is prominent with larger sinuosity in map view geometry at smaller scale. The southern bend, near Xiaoyudong, is where the thrust-slice between the Beichuan and Pengguan faults is cut by the 8 km-long, N50 °W-striking Xiaoyudong cross-fault, which moved left-laterally with SW side-up thrusting (Figs. 1 and 3c,d). The Xiaoyudong fault appears to disrupt also the Pengguan rupture into northern and southern segments, Hanwang and Guanxian segments respectively, with a ~4 km step in map view (Figs. 1 and 3a). Field mapping shows that, towards the southeast, this short NW-striking fault veers clockwise by more than 90 ° to connect, in kinematic continuity, with the Guanxian segment of the Pengguan fault. Near Gaochuan (~km 100, Fig. 1c), the Beichuan fault orientation locally swings to ≈EW, between its two ≈N50 °E-striking middle and northern sections. This bend of the Beichuan fault rupture roughly faces the step and dogleg bend of the Pengguan and Dayi foreland thrusts and coincides with a geologically mapped NW-trending tear fault which, even though did not break during the Wenchuan earthquake, in geometry resembles a mirror image of the Xiaoyudong fault. This corroborates the inference that the Beichuan and

Pengguan faults might merge at depth (e.g., Liu et al., 1994; Jia et al., 2006; Hubbard and Shaw, 2009), and suggests a common geometrical control of both by deep, transverse basement features.

3.2. *Outcrops of the fault plane and morphology of the fault scarp*

The expression of the surface rupture is generally in the form of free-faced scarps, with fissures and open cracks sub-parallel to or at small angles to the fault strike, or monoclinial half folds with varying slopes (Fig. 4), as previously documented for other thrust and oblique-slip earthquakes (e.g., Florensov and Solonenko, 1963; King and Vita-Finzi, 1981; Philip and Meghraoui, 1983; Crone et al., 1992; Kurushin et al., 1997; CGS, 1999). Sometimes minor back thrusts are present in the hanging wall. The rupture width and wavelength of monoclinial flexure scarps can vary along strike over short distances (Fig. 5a), but are usually less than 30 m. Near the end of the thrust segments, likely in part due to decrease of the vertical throw, the fault zone can become particularly wide and diffuse (Fig. 4d). Warping there may extend a few ten meters or more away from the fault, and is commonly more prominent on the up-thrown than down-thrown side.

Field investigation shows that the Beichuan fault dips at surface moderately to steeply to the northwest. Thanks to co-seismic exhumation, direct observation of the superficial fault dip angle was possible in some locations, for example near Hongkou (Fig. 6a and b), Leigu and north of Beichuan (Fig. 6c and d). At two former locations, the fault plane itself in bedrock, which is clearly exposed, with gouge and/or slickensides, in overhanging but still coherent position, has a dip of 75–80° to the NW (Fig. 6a, b). In view of the overall relationship between the fault trace and the topography, we suspect that such a steep dip at shallow depth characterizes the Beichuan fault along at least the southern half, if not most of the rupture length. Locally however, for example, north of Beichuan, the fault dips to the SE with NW side up (Fig. 6c), for a 5 km-long reach along the fault, which suggests the fault plane is overturned only at a very shallow level near the surface.

Exposure of the gouged or slickensided fault plane was not observed along the Pengguan surface rupture. Nevertheless, from trenches excavated after the earthquake (Ran et al., 2008), the fault dips ~30–60° to the NW, 15–30° shallower than the Beichuan fault. At depth, the dip

ought to become close to the 33° average dip angle of the NE-striking nodal plane of the focal mechanism, possibly even less, as required by finite fault model inversion of coseismic deformation (Ji et al., 2008). The fact that, despite their relatively steep surface dips, the two thrusts, especially the Pengguan fault, become more shallow-dipping at depth is corroborated by subsurface interpretation of the Longmen Shan imbricate thrust fault system derived from seismic sections (e.g., Jia et al., 2007; Hubbard and Shaw, 2009). Such near-surface steepening of thrust fault dip angle has long been established in fold and thrust belt tectonic environments (e.g., Boyer and Elliott, 1982), including along active continental thrusts in the Tien Shan and NE Tibet (Avouac et al., 1993; Meyer et al., 1998; Van der Woerd et al., 2001).

3.3. *Slip variations along the rupture*

Vertical throw (scarp height) and horizontal offset measurements were collected along accessible stretches of the ruptures through a combination of tape measurements and local total station surveys. In general, such measurements were feasible mostly where the ruptures cut across flat, manmade features such as roads, farm fields, etc., rather than on steep slopes, where they became difficult to follow and much more challenging to document quantitatively.

Co-seismic strike-slip components of offset can be difficult to measure on oblique thrusts due to horizontal shortening. If a piercing line is oblique to the fault, such shortening will lead to over- or underestimating the lateral offset, depending on the orientation of the line relative to fault strike. Fig. 5b shows one example on the Pengguan fault, with the piercing line obliquity relative to the fault scarp resulting in an apparent, erroneous sense of lateral offset: ~0.4–0.5 m of apparent left-lateral slip on what is actually a pure thrust break (see Supplement S3 for detail). Therefore, field reports of the strike-slip components for oblique thrusting ruptures should provide as much as possible of the information on fault plane geometric parameters and the offset piercing line obliquity, which are necessary for evaluating the true lateral offsets and uncertainties.

Fig. 1c shows along-strike variations of measured scarp heights along segments of the three faults that ruptured. On the Beichuan fault, local maxima in scarp heights, 5–6 m near

Hongkou and ~10 m near Beichuan, were found at km 35 and 140, respectively (Figs. 1c and 7). The locally ~10 m maximum scarp height occurs in a short section of the fault, where the plane locally reverses to 60–70° SE dipping. The reversed fault dip at shallow depth is probably inherited from the geological mapped SE-dipping fault, which developed parallel to bedding within the SE-dipping Devonian carbonates in the northwestern limb of the Tangwanzhai syncline (a more detailed analysis of this site is presented by Li et al., 2009). This high value of scarp height is perhaps a local anomaly, because it decreases sharply to 5–6 m within 1–2 km. Geomorphology shows that this local phenomenon is a cumulative feature, by the counter slope to a flat strip of land on the NW-facing slope, where the village houses were unfortunately built along the fault to take advantage (sadly) of the low slope angle (Fig. 7b, c).

The northernmost 100 km of the rupture are characterized by a distinctive, progressive tapering of the vertical offset, from about 6 m to zero over that distance, suggestive of a “dog-tail” rupture termination (Ward, 1997). Unfortunately, offset measurements along the middle section were few, due to a combination of difficulties of access, burial by many massive landslides, and a fault trace cutting slopes too steep to permit straightforward surveying. Nevertheless, limited data in this section of the fault suggests that there were large along-strike fluctuations in scarp height.

Slip on the steeply NW-dipping Beichuan fault is generally thrusting with a right-lateral component. In the southern and middle sections of the rupture, the strike-slip component is slightly smaller than dip-slip thrusting at a given location (table S1 and Fig. 8). For example, near Hongkou, the right-lateral component is 40–80% of the vertical. Fig. 9a and b show that here a terrace riser indicates 3 ± 1 m right-lateral offset and 4.85 ± 0.6 m in the vertical. Since this is within a distance of 30 m from a fault plane exposing cross-cutting slickenside striations of two to three different rake angles (40° and 75–80° plunge), those striations most likely have been formed during the Wenchuan earthquake alone. Such a phenomenon has been previously documented during the 1995 Kobe earthquake (Otsuki et al., 1997; Spudich et al., 1998).

Only farther north, and starting perhaps near Leigu (~km 135) and Beichuan (Fig. 1c) does the dextral strike-slip component become almost equal to, or slightly larger than, the vertical offset at many individual localities (Fig. 9c,d), consistent with the dominantly $45 \pm 5^\circ$ rake angle striations exposed near Beichuan (Fig. 6d). Towards the north, within the uncertainties of our measurements and despite the sampling bias due to offset marker

availability, strike-slip offsets and vertical throws appear to have correlated spatial variations along strike; both decrease in synch to ~0.3 m at the rupture's northern end.

The Pengguan fault rupture shows predominant NW-side-up thrusting. The largest vertical offset, ~3–3.5 m, is observed near the northern end of the surface rupture, and in general the scarp height decreases both north- and south-wards of the rupture midpoint. The most distinctive minimum (<0.5 m) in scarp height is at the intersection with the NW-trending Xiaoyudong fault. As the Pengguan fault appears to dip less steeply than the Beichuan fault, it should have accommodated more co-seismic horizontal shortening for a given vertical throw. With a dip of 30 ° at depth, conservation of mass implies that horizontal shortening should be ~2 times the amount of vertical throw along this thrust (Avouac et al., 1993; Lave and Avouac, 2001). The transverse, NW-striking Xiaoyudong fault shows SW side-up co-seismic thrusting with a large left-lateral strike-slip component. The scarp is highest at the northwestern end of the rupture, and decreases to less than 0.5 m where the fault merges with the Guanxian section of the Pengguan fault (Fig. 3c). The Xiaoyudong cross-fault displays a clear component of left-lateral strike-slip in addition to the SW side-up sense of vertical throw, suggesting a local present day E–W shortening.

4. Characterization of the Wenchuan earthquake rupture

4.1. Significant crustal-scale oblique slip partitioning on parallel thrusts

The great Wenchuan thrust event, with its >200 km-long multi-stranded rupture, illustrates a hitherto rarely documented case of co-seismic slip partitioning on multiple, crustal scale thrusts that are thought to merge into a single plane below the Longmen Shan range (e.g., Liu et al., 1994; Jia et al., 2006; Hubbard and Shaw, 2009). Co-seismic slip partitioning of rupture on multiple faults, recently observed along a 70 km section of the 2001 Kokoxili earthquake strike-slip rupture (King et al, 2005; Klinger et al., 2005), is now demonstrated to occur also during thrust events. The difference is, however, that coseismic slip partitioning during the Wenchuan earthquake is at the crustal scale, likely branching off at ~10 km depth (Ji et al., 2008), and by judging from the spacing between the two parallel ruptures on the surface, and thus is much deeper than the <2 km depth branching in the Kokoxili earthquake. Another

possible example of deeper branching and partitioning is the 1957 Gobi–Altay earthquake in which evidently simultaneous oblique rupture on the Bogd fault and thrust rupture of the Gurvan Bulag fault occurred (Florensov and Solonenko, 1963; Kurushin et al., 1997).

Co-seismic slip partitioning has been explained as a consequence of up-dip elastoplastic propagation from a fault or shear zone with oblique slip at depth in previous static regional stress field modeling (Bowman et al., 2003; King et al., 2005). Recent dynamic rupture propagation modeling (Oglesby et al., 2008) indicates that a structural barrier at the base of two intersecting fault planes is needed to cause enough stress perturbation to initiate slip partitioning, and usually causes strong partitioning of strike-slip on the steeper fault and dip slip on the shallower fault. However, during the Wenchuan rupture, the up-dip propagation of oblique thrusting did not result in complete partitioning, which would have resulted in pure thrust on the Pengguan fault and pure strike-slip on the Beichuan fault. Thrusting is dominant on the Beichuan fault, to the west of and parallel to the Pengguan surface rupture (Fig. 8). The Wenchuan earthquake thus offers a rare case for understanding the dynamic co-seismic slip partitioning process. The mechanism for an incomplete slip partitioning in this event awaits future explanation; perhaps the dips of the Beichuan and Pengguan faults near their intersection at depth are not too different, such that slip partitioning was only partial.

Field discovery of slip partitioning on multiple parallel thrust faults demonstrates that the single-fault assumption used in the fast response seismic waveform inversions would be overly simplified for this earthquake, and required modification to handle the natural complexity of the fault zone in this case. Initial finite fault models shortly after the earthquake, which had not yet incorporated the slip partitioning effect, indicated a strong north–south difference in the rake of coseismic slip vector along the fault (e.g., Ji and Hayes, 2008). In contrast with these early models, our field observations indicate that the sense of slip is actually rather consistent along individual faults. In particular, on the Beichuan fault, thrusting and shortening is prominent in the north, with the horizontal to vertical displacement ratio increasing only slightly to 1–2 from less than 1 in the south (Fig. 8). The modified two-parallel-plane finite-fault solution of Ji et al. (2008) is broadly consistent with field observations, in that two maxima in surface slip coincide with that in the inversion. However, a detailed comparison is still premature. The surface faulting data provide important constraints that can help improve the accuracy of finite-fault models, and

can help to guide the necessary addition of complexity to better match surface faulting observations.

The incomplete slip partitioning between the Beichuan and Pengguan faults results in a considerable amount of thrusting accommodated on the high-angle to nearly vertical NW-dipping Beichuan fault. Over the long-term, this may be responsible for the abrupt steepening in topography across the Beichuan fault, and fast exhumation of the Pengguan massif (Kirby et al., 2003; Godard, 2007), while at the same time maintaining the straight plan view geometry typical of strike-slip faults (Fig. 2).

4.2. *An out-of-sequence thrusting event*

The Wenchuan earthquake also provides a clear example of active out-of-sequence thrusting within a large fold and thrust belt (e.g., Morley, 1988). Although the Beichuan and Pengguan faults most likely developed earlier than more frontal thrusts, they remain active in the hinterland of the Longmen Shan belt. To the east, within the Sichuan basin, foreland thrusts underlie NNE-trending anticlines whose emergence above the flat plains is reflected by long, linear, low relief hills. On the numerous gas and oil exploration seismic lines that image subsurface structures in the basin, such thrust ramps, which are inferred to be active, appear to sole into a shallow decollement at 2–4 km depth before merging with the Pengguan fault, attesting to thin-skinned shortening in the southwestern Sichuan basin (e.g., Liu et al., 1994; Jia et al., 2006; Hubbard and Shaw, 2009). It is likely that the anticlines in the southwestern Sichuan basin are actively growing, because they show positive relief above the flat basin surface (Fig. 1a; Hubbard and Shaw, 2009). Accordingly, transverse rivers become narrower where they cross the anticlines. Thrusts underlying the Longquan Shan, Xiong Po and Qiong Xi anticlines, in particular, show evidence of activity in the late Pleistocene–Holocene (Deng et al., 1994; Tang and Han, 1993; Tang et al., 1996; Jia et al., 2007). In any event, the geometry of the fold and thrust system demonstrates that the Tertiary shortening front has migrated well eastward of the Pengguan fault. The stacking due to motion on the younger thrusts along the basin edge could contribute to the steepening the now high angle thrusts visible in the mountain hinterland, as common in other thrust belts.

Together with two other large, recent thrust events—the 1999 Chi-chi, Taiwan earthquake (Kao and Chen, 2000) and the 2005, Muzaffarabad, Kashmir earthquake (Avouac et al., 2006)—the Wenchuan earthquake suggests that out-of-sequence thrusting may be common in fold-and-thrust belts. One proposed mechanism for out-of-sequence thrusting involves enhanced erosion within the steepest part of the mountain range while maintaining a critical wedge geometry (e.g., Davis et al., 1983; Hodges et al., 2004; Wobus et al., 2005; Avouac et al., 2006). In the case of the southern Longmen Shan, the persistence of hinterland, out-of-sequence thrusting might be linked to the activation of a NW-propagating, Late Cenozoic regressive erosion wave (Godard, 2007; Liu-Zeng et al., 2008), in keeping with sediment infill flushing from a formerly internally-drained Sichuan basin (Richardson et al., 2007).

Other mechanisms might involve changes in boundary conditions such as a decrease in the shortening rate after an Oligocene–Miocene phase of rapid mountain-building. This could occur as the principal locus of tectonic deformation was transferred from central Tibet/Songpan and the Kunlun fault to northern Tibet, the Altyn Tagh fault and the Qilian Shan in the Late Miocene (Lacassin et al., 1996; Meyer et al., 1998; Tapponnier et al., 2001). Tectonic and geological studies, particularly to the south near the border between Sichuan and Yunnan, have long indicated that the climax of tectonic deformation in the southeastern part of Tibet, including both left-lateral strike-slip and large-scale crustal thrusting and folding, occurred before the mid-Miocene (e.g. Horton et al., 2002; Spurlin et al., 2005; Lacassin et al., 1996), which implies a significant decrease of local shortening rates, possibly from a couple cm/yr to a few mm/yr in the Late Miocene. Such a slowdown, coupled with enhanced erosion, might have caused “hinterland thrust retreat”, accounting for predominant out-of-sequence thrusting at the present time. A third possible mechanism could be a change to having more oblique component of slip across the thrust fault stack. If the oblique motion tends to mechanically favor movement on the steeper faults to accommodate both the thrust and strike-slip, perhaps the shallower-dipping faults in the foreland would be disfavored through time. Or perhaps in the rare big events, hinterland thrusts would be activated with more of a mix of strike-slip and thrust, whereas in more frequent smaller events, outboard thrusts in the foreland would be activated with more thrust. Though these mechanisms have yet to be tested, the Wenchuan earthquake clearly calls for a more detailed investigation of the potential seismic activity of hinterland thrusts, in the Longmen Shan and elsewhere, and of the mechanical implications of similar out-of-sequence thrusting.

4.3. *Present-day ESE shortening direction oblique to the Longmen Shan*

Our field mapping shows that in the northern part of the rupture, the dextral and thrust offsets generally vary in synch along the fault, increasing or decreasing together. Our measurements of dextral components are sparse, and may not completely sample small-scale variations due to fault orientation change, however, the overall trend in our measurements indicates that the present day maximum horizontal principal stress is ESE. This is consistent with the main-shock focal mechanism, and the rake of slickenside striations.

Multiple stress proxies, including focal mechanisms and slip vectors of past earthquakes in the region, also show that the P-axis histogram reaches a maximum between 85 and 105 °E (Xie et al., 2004). In the southernmost half of the Wenchuan rupture, where the dextral component is less than that in the north, one might infer slightly more NW-SE shortening. However, as shown in Fig. 1, the frontal part of the fold-and-thrust belt fans out counterclockwise into the southwestern Sichuan basin. The Longquan Shan, the most conspicuous ramp anticline, trends north-northeastward, oblique to the range, and may kinematically accommodate more ESE shortening. In addition, the NS-trending Min Shan to the north is bounded on two sides by the Min Jiang and Huya active faults, where two 1976 M_s 7.2 Songpan earthquakes occurred, exhibiting mainly thrusting and left-lateral components on a NS-trending plane (Jones et al., 1984; Zhao et al., 1994). Both features are most likely the result of ESE-directed thrusting. The orientation of contemporary shortening along the Longmen Shan margin of the Tibetan plateau is thus markedly oblique to the Longmen Shan margin.

The Wenchuan earthquake therefore highlights the present-day ~E–W shortening and oblique thrusting across the Longmen Shan belt, which had not previously been fully appreciated. For example, kinematic and geodetic modeling of present-day movements of eastern Tibet had been done under the assumption of a Longmen Shan fault-perpendicular shortening, and without acknowledgement of a significant strike-slip component (Avouac and Tapponnier, 1993; Zhang et al., 2004). In the GPS velocity field, the right-lateral shearing instead appears in a zone 100–200 km to the NW of, and parallel to, the Longmen Shan thrust belt (Shen et al., 2005). This recognition motivated a discovery at that position of an active strike-slip-dominant fault, the Longriba fault, with 5.4 mm/yr of right-lateral and minor 0.7 mm/yr of uplift rates (Xu

et al., 2008). ESE-shortening in the Longmen Shan region is kinematically compatible with the left-lateral strike-slip Kunlun fault in the north. England and Molnar (1990), however, dismissed this kinematic link and instead they discussed the E–W shortening in the context of N–S directed right-lateral simple shear. However, their model implies that the Longmen Shan, being parallel to the Indian–Eurasia relative motion, should be mostly right-lateral. Densmore et al. (2007) inferred also that on the Longmen Shan thrusts, the strike-slip to vertical throw ratio was at least 5–10. The Wenchuan earthquake rupture suggests that they may have over-estimated the dominance of a strike-slip component in Late Quaternary time, as did Burchfiel et al. (1995) in their kinematic inference of Cenozoic deformation. One remaining question is whether or not the Wenchuan type of event mechanism is representative of slip accumulation on the fault over the long-term.

5. Discussion

5.1. Implications for regional tectonic models

The great magnitude, long rupture length, strong crustal shortening and disastrous consequences of the Wenchuan earthquake were not well anticipated. Before the earthquake, the dominant view for regional deformation had been the model of lower crustal channel flow without large scale shortening in the upper crust. The Wenchuan earthquake was a rare great oblique thrust event, with a crustal fault plane down to 20 km depth, beneath the eastern topographic rim of Tibet, as delineated by numerous aftershocks (e.g., Huang et al., 2008). This, and the fact that the two superficial faults that ruptured in the event (especially the shallower-dipping Pengguan fault, and perhaps also shallow blind ramps in the foreland) showed predominantly thrust motion, challenges the widely held perception of a lack of present day upper crustal shortening along the western edge of the Sichuan basin. Indeed, the GPS velocity field now shows strong crustal shortening in coseismic deformation across the Longmen Shan thrust fault system (Working group of CMONC, 2008). For instance, two stations in the northern section of the rupture near Beichuan and Nanba (Fig.1c) and 0.8 km and 1.2 km from the Beichuan fault on the footwall, moved 2.23 m and 1.15 m in fault-perpendicular, and 1.75 m and 0.74 m in fault-parallel directions, respectively (Working group of CMONC, 2008).

The Wenchuan earthquake thus calls for a re-evaluation of the lower crustal channel flow model for orogenesis along this margin of the high plateau. Direct or indirect geophysical and geological evidence questioning aspects of this model have been accumulating before and after the earthquake (e.g., Godard, 2007; Liu-Zeng et al., 2008; Robert et al., 2008; Yao et al., 2008; Yin et al., 2008; Hubbard and Shaw, 2009).

Whether the viscous piling of lower crustal material can lead to thrusting in the upper crust is not clear. Pushing from underneath, as envisioned in the lower crustal channel flow model, may result in mostly extensional rather than compressional surface stress at the frontal edge of the uplifting region of the Longmen Shan front. In this model, flow of ductile lower crustal rocks away from the central plateau, impeded by the strong crust of the Yangtze Craton beneath the Sichuan basin, would pump up topographic relief in the Longmen Shan by inflating its lower crust. Thus, the crust of the mountain range would thicken due to the viscous addition of exotic Tibetan lower crust, rather than by stacking of Sichuan upper crust slices through brittle thrusting. This “channel flow” model predicts predominant vertical motion at the plateau margin, with little horizontal shortening of the upper crust, if any. The passive response of the upper crust to upward pushing from underneath should instead be primarily normal faulting near the topographic break, if surface stress is the second derivative of surface uplift by isostatic lower crustal inflation (e.g., Nimmo, 2005). Yet neither active fault mapping nor earthquake focal mechanisms (Tapponnier and Molnar, 1977; Tang and Han, 1993; Xie et al., 2004; Cui et al., 2005; Xu and Zhao, 2006) indicate significant normal faulting in the Longmen Shan. In short, the lower crustal channel flow model, by overly emphasizing the role of deep processes in regional deformation and minimizing that of the elastic upper crust, is inherently inadequate and fails to provide a viable framework for understanding either the kinematics or dynamics of active faulting, or for evaluating regional seismic hazard.

5.2. *Implications for regional seismic hazard*

The Wenchuan earthquake was somehow unexpected because the standard view of the present tectonics of the Longmen Shan thrust belt involved a very slow deformation rate scenario, and hence low seismic hazard estimates (State Seismological Bureau, 1992; National Standards of China, 2001). This understanding of relatively low hazard had been further

enhanced by the occurrence of mostly moderately sized (<7) earthquakes as was known from historical seismicity catalogs (Division of Earthquake Monitoring and Prediction, China Seismologic Bureau, 1995, 1999).

Quantitative studies of active faulting and paleoseismic trenching on the Beichuan and Pengguan faults were few before the Wenchuan earthquake. Those undertaken suggested slip rates on order of 1 mm/yr or less on individual faults, and very long recurrence intervals, of several thousands to ten thousand years, between events (Tang and Han, 1993; Zhao et al., 1994; Ma et al., 2005; Zhou et al., 2007; Densmore et al., 2007). While clearly insufficient to constrain elastic inter-seismic loading on the large thrust faults across the eastern rim of Tibet, GPS measurements have been repeatedly interpreted as showing a slow convergence rate of less than 3 mm/yr across the entire width of the Longmen Shan margin of the plateau (Chen et al., 2000; Zhang et al., 2004; Shen et al., 2005). Note that the inference that the Longmen Shan margin of the Tibet plateau might be over the peak of its principal phase of crustal shortening and topographic uplift (Lacassin et al., 1996; Tapponnier et al., 2001; Liu-Zeng et al., 2008) provides a plausible reason for present slip rates being somewhat lower than they once might have been, and thus for repeat times of great earthquakes in the Longmen Shan thrust belt being longer than along other margins of the plateau, most notably in the Himalayas. Even with an arguable 3 mm/yr shortening rate, the Longmen Shan region is still more active than some continental regions where multiple $M \geq 8$ earthquakes have occurred in historical time, such as in Mongolia.

The fresh scar of the earthquake rupture now reveals the exact location of the active fault traces, which were hitherto difficult to pinpoint in much of this mountainous region of deep incision, dense vegetation and with multiple-stranded inherited faults. Patches of young deposits, such as alluvial fans, that usually provide clear records of Quaternary faulting are rare and small, and rapidly rejuvenated by very active erosion. The few that are preserved are commonly cultivated and modified yearly by human action.

Curiously, on the Beichuan fault, the sites that were the target of the most detailed and quantitative studies of slip rate and paleo-earthquake sequences are in fact located on strands that did not rupture during the 12 May 2008 event, or that display unrepresentatively small offsets. This appears to be the case, for instance at the paleoseismic investigation site of Zhou et al. (2007) and at the slip rate determination sites near Gaoyuan village, Baishuihe and Donglinshi of Densmore et al. (2007) (Figs. 3c and S3). Similarly, the surface rupture on the Pengguan fault,

near Tongji, did not occur on the strand that was mapped both geologically and geomorphologically (yellow line in Fig. 3a). It is possible that previous active fault studies missed the most relevant targets by focusing on unrepresentative locations, leading to an under-estimation of seismic hazard along the Longmen Shan thrust belt as a whole. It is also possible that a complex, inherited network of parallel faults or fault branches might provide multiple paths for upward rupture propagation, increasing the randomness of potential surface break locations, such that over the long term, extrapolation from studies on a few faults might not capture the actual frequency of large earthquake occurrence. Our field observations show that, in most places along the Beichuan fault, the rupture follows closely, but sometimes with a shift of a couple of hundred meters distance from geologically mapped fault traces. However, along the surface rupture of both the Beichuan and Pengguan faults, geomorphic features representing cumulative displacement from multiple events are recognizable. These indicate that randomness in rupture location from event to event over Late Quaternary time scale is actually not likely to be the main reason for the observed discrepancy.

Whatever the case, such issues call for a complete re-evaluation of seismic hazard through more thorough determinations of Quaternary slip rates and paleoseismic investigations across the multi-stranded Longmen Shan thrust system. Indeed, the Wenchuan earthquake rupture now highlights new sites with evidence of repeated large offsets, which provide interesting targets for future work. Perhaps more importantly, it is now mandatory to perform such thorough studies, with reliable dating techniques, to better quantify seismic hazard on the thrusts that bound the Longquan Shan, Xiong Po, and Qiong Xi anticlines, which reportedly show evidence of Quaternary activity (e.g., Tang et al., 1993; Deng et al., 1994; Huang and Tang, 1995; Tang et al., 1996; Jia et al., 2007) and might pose a threat to the greater metropolitan area of Chengdu, home to over 10 million habitants, as well as on other active faults along the densely populated eastern margin of the Tibetan plateau. Without knowledge of their activity and paleoseismic recurrence data, analysis of triggered seismic hazard from stress transfer associated with the Wenchuan rupture alone (e.g., Parsons et al., 2008; Toda et al., 2008) would be of minimal practical use.

6. Conclusion

In summary, field mapping performed soon after the 12 May 2008 Wenchuan earthquake shows prominent, often spectacular, surface ruptures on several sub-parallel faults of the Longmen Shan thrust system. Chiefly, surface rupture involved movement on the steeply NW-dipping Beichuan oblique thrust fault, which experienced dominant up-thrusting with roughly one to two times amounts of right-lateral slip of the NW-up hanging-wall, and also the more shallowly NW-dipping Pengguan fault, which experienced pure thrust faulting. The partitioning of slip on multiple thrust faults implies that shallowly dipping thrusts basinward may be active and responsible for the steepening of the higher angle thrusts in the mountain hinterland. This >200 km long, mostly out-of-sequence thrust rupture with large throws of up to nearly 10 m, demonstrates that the ongoing upper crustal deformation in the Longmen Shan and hence across the entire eastern rim of the Tibet plateau is dominated by ~E–W shortening, oblique rather than perpendicular to the axis of the massif.

Like that of most mountain ranges, the growth and maintenance of the Longmen Shan topography was likely produced by movement on a large, deep crustal mega-thrust: the NW-dipping interface between the Songpan Ganzi terrane and Yangze block. Other than the reactivation of inherited, Mesozoic and more ancient deformation zones, and the fact that shortening likely slowed down since the Miocene, there may have been nothing radically unusual in this process, variants of which appear to have been at work along other present or past rims of Tibet. Clearly, the occurrence of this great earthquake calls for a reassessment of models that anticipate little or no crustal shortening and emphasize instead tunneled, horizontal channel flow and inflation of the lower crust. Such models were devised to explain older data that should now be reconsidered, because the new data and surface slip in the 12 May 2008 Wenchuan earthquake seem to indicate that perhaps such a specialized model is no longer required. A quantitative re-evaluation of seismic hazard on thrust ramps directly beneath the densely populated Sichuan basin is also urgently needed.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2009.07.017.

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List of Figures

Fig. 1. Map view of surface rupture of 12 May 2008 Wenchuan earthquake and other faults of the Longmen Shan thrust fault system in Sichuan, China, modified from Tapponnier and Molnar (1977), Tang et al. (1993), Deng et al. (1994, 2003) and Xu et al. (2003). a) Map of active faults in the Longmen Shan and western Sichuan basin, superimposed on SRTM DEM, also shown are aftershocks $M_s \geq 5.0$ (until 19 August, 2008; Chinese Earthquake Information, 2008), historical seismicity of $M_s \geq 4$ (Division of Earthquake Monitoring and Prediction, China Seismologic Bureau, 1995, 1999). Surface rupture is shown in red. Star shows the NEIC epicenter location of 30.986°N , 103.364°E , with focal mechanism ([http:// neic.usgs.gov](http://neic.usgs.gov)). Focal mechanism of the 1976 Songpan earthquake (Jones et al., 1984). Shown in the lower right is the average topographic profile within a swath of ~ 100 km width. b) Simplified geological map of the Longmen Shan area (adapted from Chengdu Institute of Geology and Mineral Resources, 2004), with surface rupture highlighted in red. c) Map view geometry of the surface rupture and along-fault variation of scarp height on the Beichuan and Pengguan faults. Distance along the fault is as referred to the projection of the epicenter onto the fault. Also shown are the locations of the corresponding offset measurement points.

Fig. 2. a) Landsat image of the middle section of the Beichuan fault, showing relatively straight fault trace in map view. Arrows point to location of fault, red dots indicate Wenchuan earthquake offset measurement sites. See locations in Fig. 1a. b–d) are field photos of fault scarp along the Beichuan fault, showing prominent vertical throw, despite straight fault trace in map view. b) Fault scarp cut through a resort parking lot. The road in the photo was sloping before the earthquake. c) Fault scarp cuts through a concrete road in Qingping, and uplift ~ 3.7 m. Offset of white middle line indicates a right-lateral strike-slip of ~ 0.85 m. d) Fault cuts across a major inter-town paved road through the village in Gaochuan, with ~ 2.2 m vertical throw. The roadside aqueduct was bent, indicating at least ~ 1.4 m shortening. Photos e) and f) show scarps on the Pengguan fault. e) Fault cut through and uplifted the river bed. The current river

channel narrows and incises. f) Rupture cut through a man-made flood-control bank, near pt 1046.

Fig. 3. Close-up map view of surface rupture in the areas of Hongkou and Xiaoyudong, where relatively broad valleys allow detailed mapping of surface rupture geometry. See location in Fig. 1a. a) Surface rupture of Wenchuan earthquake (red lines) in the region of Yingxiu and Xiaoyudong, superimposed on Landsat images. Yellow line marks the trace of prior mapping of the Pengguan fault, which did not break during this earthquake. b) The section of Beichuan fault near Hongkou, where slip was partitioned onto a mostly right-lateral northern branch and thrust with SE-side up on the southern strand. Star shows the site of Densmore et al. (2007) near Gaoyuan. c) Google Earth image with field investigation points showing the geometry of the NW-trending thrust and left-lateral Xiaoyudong cross-fault where it merges with the NE-trending Pengguan fault segment. Black dots are field GPS point locations. Also shown are vertical offsets as a function of distance along the fault. d) Field photos of fault scarp along the Xiaoyudong fault. The irrigation aqueduct shows a SW-side-up uplift of ~1 m and left-lateral offset of ~1.7 m. Location in Fig. 3c. e) Pengguan fault cut through and caused warping in the rice paddies, uplifting ~1.65 m. Location in Fig. 3a. f–g) are photos of fault scarp on the Beichuan fault near Gaoyuan locations in Fig.3b. f) Fault cut through the Baisha river, and exposed boulders in pre-earthquake river channel (whitish in color) uplifted by ~4.6 m. g) Fault scarp through Kiwi orchard, with SE side uplifted by ~1.6 m.

Fig. 4. Photos showing typical outcrop of (a) and (b) sharp free-faced fault scarps on the Pengguan fault near Bailu town, or (c) gentle monoclinal fault scarps, where the fault tip stops at shallow depth beneath the ground surface. Photo taken in Pingtong town, on the Beichuan fault. See Fig. 1c for location of towns relative to the surface rupture. (d) Near the end of a rupture segment, the rupture zone is generally wider than that in the center. Photo taken south of Nanba town.

Fig. 5. Surface rupture on the Pengguan fault, trending $\sim N55^{\circ} E$ at this locality, cuts diagonally through a school yard in Bailu town. (a) Over a 20 m distance, 4 m wide narrow sharp free-faced fault scarp changes to a 15 m-wide round monoclinical scarp. Horizontal shortening is clearly shown by the over-shooting of concrete slabs. Two black arrows point to the location of rupture through valleys and saddles, which are geomorphic expressions of long-term activity on the Pengguan fault. (b) The orientation of concrete blocks, indicated by the gap between blocks, is $N50^{\circ} W$. This slightly oblique orientation relative to the fault zone, when horizontal shortening is present, produces an apparent strike-slip component of slip.

Fig. 6. Field photos of fault plane outcrops a) at km 35 northeast of the epicenter, near Hongkou ($31.14527^{\circ} N$, $103.69208^{\circ} E$), where b) slickenside striations occurred on the $74\text{--}80^{\circ} NW$ -dipping fault plane. Later striations with $75\text{--}80^{\circ}$ rake angle cut those with $\sim 40^{\circ}$ plunge. c) Outcrops of fault plane north of Beichuan ($84397^{\circ} N$, $104.475217^{\circ} E$;) show d) the striations of $45 \pm 5^{\circ}$ rake angle.

Fig. 7. Photos showing the ~ 10 m vertical throw on a short stretch of counter slope fault scarp with locally overturned SE dip, a few kilometers northeast of Beichuan. a) The fault cuts through the yard of Mr. Zhou Jizhong, and the uplifted portion of the yard was $\sim 0.5\text{--}0.8$ m lower before the earthquake, therefore the total uplift is ~ 10.5 m. b) and c) Similarly, ~ 100 m to the SW of Mr. Zhou's house, the ~ 10 m high fault scarp cuts through a groove, and uplifted a linear ridge from a sloping to the NE shallow valley. A certain amount of pre-existing topography is likely here (2 m in maximum for the entire valley based on a local resident's recollection). d) Looking toward SW, the rupture cuts through a flat counter-slope strip of land, along which villagers built their houses. Cumulative displacement on this SE-dipping stretch of fault is clear in the geomorphology.

Fig. 8. Comparison of scarp height and horizontal offset on the Beichuan fault and Xiaoyudong cross-fault. Right-lateral component on the Beichuan fault within the first 50 km from the epicenter, was only observed on a short section where slip is partitioned

on two parallel strands: one almost purely strike-slip strand and the other purely thrust, but with the SE side-up, opposite to the general throw (see Fig. 3b).

Fig. 9. Examples of sites where both vertical and strike-slip offsets can be determined at the same location, indicating the changing ratio of strike-slip and vertical components along the fault. a) Field photo and b) total station survey of offset terrace riser near Hongkou (km 35.7) indicate that right-lateral offset is 40–80% of the vertical offset at this location. Further to the north along the fault, c) field photo of fault scarp near Leigu (km 135.5), view toward northeast, d) map view and e) vertical profile of total station survey points along a footpath trail indicate that it is offset ~6 m right-laterally and ~5 m vertically by the fault.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

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Fig. 8.

Fig. 9.