Journal of Structural Geology 32 (2010) 781–791

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Structural analysis of the coseismic shear zone of the 2008 M_w 7.9 Wenchuan earthquake, China

Aiming Lin [a,b,*], Zhikun Ren [a], Yasuhiro Kumahara [c]

[a] Graduate School of Science and Technology, Shizuoka University, Shizuoka 422-8529, Japan
[b] Institute of Geosciences, Faculty of Science, Shizuoka University, Shizuoka 422-8529, Japan
[c] Faculty of Education, Gunma University, Gunma 371-8510, Japan

ARTICLE INFO

Article history:
Received 17 September 2009
Received in revised form
18 April 2010
Accepted 12 May 2010
Available online 20 May 2010

Keywords:
2008 M_w 7.9 Wenchuan earthquake
Longmen Shan Thrust Belt
Coseismic shear zone
Cataclastic rocks
Tibetan Plateau

ABSTRACT

Field investigations reveal that the surface rupture of the 2008 M_w 7.9 Wenchuan earthquake, China, occurred along a pre-existing shear zone in the Longmen Shan Thrust Belt. Structural analyses of the coseismic fault zone and fault rocks show that i) the main coseismic shear zone consists of a fault core that includes a narrow fault gouge zone of <15 cm in width (generally 1–2 cm) and a fault breccia zone of <∼3 m in width, and a wide damage zone of >5 m in width that is composed of cataclastic rocks including fractures and subsidiary faults; ii) the foliations developed in the fault core and damage zones indicate a dominantly thrust slip sense, consistent with that indicated by the coseismic surface rupture; and iii) coseismic slip was largely localized to within a narrow fault gouge zone of <2–3 mm in width. The structural characteristics of the coseismic shear zone and cataclastic rocks indicate that the location of coseismic slip zone associated with the 2008 Wenchuan earthquake was controlled by a pre-existing shear zone and that the main active fault of the Longmen Shan Thrust Belt has moved as a thrust since the formation of cataclastic rocks along the fault during the late Miocene or early Pliocene.

1. Introduction

The magnitude (M_w) 7.9 Wenchuan earthquake, China, occurred on 12 May 2008 in the Longmen Shan (*Shan* is Chinese for mountain) region, the transition zone between the Tibetan Plateau and the Sichuan Basin, producing a 285-km-long surface rupture zone along pre-existing active faults (Lin et al., 2008, 2009; Lin and Ren, 2009). Many preliminary field investigations, carried out immediately after the earthquake, report that the coseismic surface rupture was dominated by thrusting, folding, and landsliding across pre-existing active faults of the Longmen Shan Thrust Belt (Dong et al., 2008; Lin et al., 2008, 2009; Xu et al., 2008; Zhang et al., 2008; Ren and Lin, 2010; Jia et al., 2009).

Although many studies have investigated on the ground deformation features and seismic mechanism of the Wenchuan earthquake, and the deep structure of the Longmen Shan Thrust Belt, in the year following the Wenchuan earthquake, the nature of the seismogenic fault zone, including the internal deformation structure of the fault zone and faulting behavior, remains unclear because of a lack of geological data regarding the coseismic fault zone. This limitation hinders further assessment of the nature of coseismic rupture, the relationship between the pre-existing active faults and the coseismic shear zone, and the nature of seismic hazards in the densely populated region around the Longmen Shan Thrust Belt.

In previous decades, to understand the nature of coseismic fault zones, many studies have focused on the internal deformation structures of coseismic shear zones and on fault rocks within these zones, which have triggered large earthquakes. For example, the Nojima Fault triggered the 1995 M_w 7.2 Kobe earthquake (e.g., Shigetomi and Lin, 1999; Lin, 2001) and the Chelungpu Fault triggered the 1999 M_w 7.6 Chi-Chi (Taiwan) earthquake (Lin et al., 2005; Ujiie, 2005). These previous studies have provided insight into the nature of seismogenic faults and the deformation structures of coseismic shear zones.

The present study reports the analytical results of meso- and microscopic structures of the coseismic shear zone developed in the main fault zone of the Longmen Shan Thrust Belt, which triggered the 2008 M_w 7.9 Wenchuan earthquake, based on observations of fault rocks in outcrops and trenches. The seismotectonic implications of these results are then discussed. Field investigations were initiated immediately following the Wenchuan earthquake, and continued for 1 year, during which time the samples of fault

* Corresponding author. Institute of Geosciences, Faculty of Science, Shizuoka University, Shizuoka 422-8529, Japan. Tel./fax: +81 54 238 4792.
E-mail address: slin@ipc.shizuoka.ac.jp (A. Lin).

0191-8141/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2010.05.004

rock were collected. These timely investigations, conducted so soon after the seismic event, and the analysis of fresh samples of fault rocks taken from exposures of the fault plane along which coseismic surface ruptures occurred, provide ideal materials with which to study the nature of rupturing and the active faulting history of a seismogenic fault zone.

2. Geological setting

The study region lies in the Longmen Shan Thrust Belt, developed along the boundary zone between the Tibetan Plateau and the Sichuan Basin. The area is characterized by high elevations of up to 7556 m above sea level (Mt. Gongga) and topographic relief of more than 5 km over distances of less than 50 km (Fig. 1) (Burchfiel et al., 1995, 2008). The northeast-trending Longmen Shan Thrust Belt is dominated by thrust faults and fold structures developed mainly within pre-Mesozoic basement over a distance of ∼500 km and a width of 30–50 km (Jia et al., 2006, 2007, 2009).

The belt is dominated by four major thrust faults: the Wenchuan–Maowen, Yingxiu–Beichuan, Guanxian–Anxian, and Qingchuan faults (Deng et al., 1994; Jia et al., 2006; Li et al., 2006) (Fig. 1). Field investigations and trench surveys reveal that these faults have been active throughout the late Quaternary, with slip rates of up to 1.0–1.5 mm/yr (Li et al., 2006; Densmore et al., 2007). The 2008 M_w 7.9 Wenchuan earthquake produced a 285-km-long surface rupture zone, with dominantly thrusting slip along the pre-existing Yingxiu–Beichuan, Guanxian–Anxian, and Qingchuan faults (Fig. 1; Lin et al., 2009). Seismic inversion results also show a dominantly thrust mechanism for the 2008 Wenchuan earthquake and a long coseismic rupture of up to ∼300 km, which propagated along the northeast-trending fault (e.g., CENC, 2008; Chen et al., 2008; Ji, 2008; Nishimura and Yagi, 2008). The

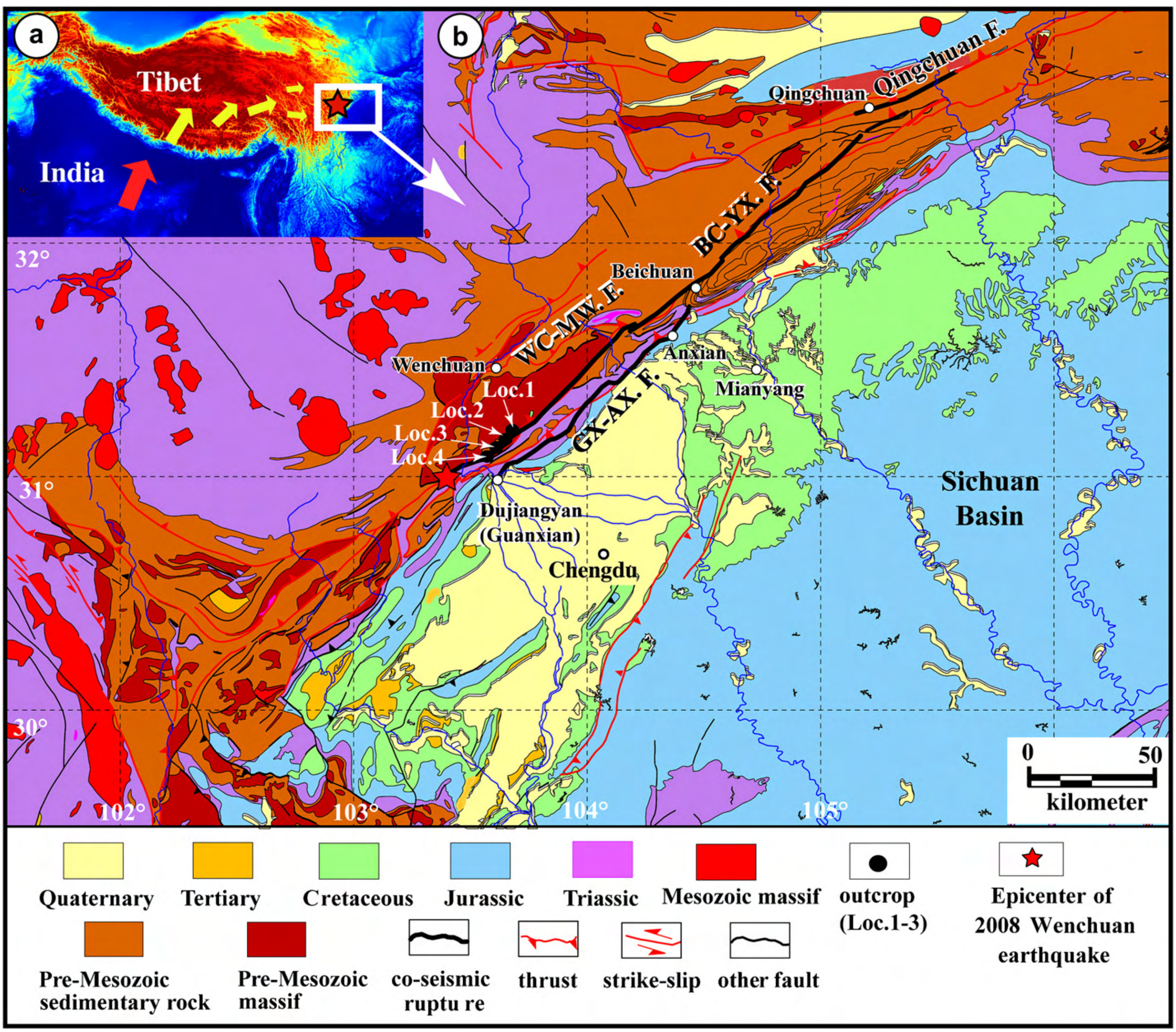

Fig. 1. Index maps of the study area, showing geologic structures and the distribution of coseismic surface ruptures. (a) Landsat image of the Tibetan Plateau and north India, showing the location of the study area. Yellow arrows indicate the eastward movement direction of the Tibetan Plateau. Red arrow indicates the movement direction of the Indian Plate. (b) Geological map of the study region, showing the geologic structures of the Longmen Shan region (modified from BGMRSP, 1991). The distribution of coseismic surface ruptures is modified from Lin et al. (2009). Red star indicates the epicenter of the 2008 Wenchuan earthquake, as determined by the China Earthquake Networks Center (CENC, 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

maximum coseismic displacements observed in the field are up to 6.5 m in the vertical (typically 1–3 m) (Lin et al., 2009). The rupture length and maximum vertical displacement produced by the Wenchuan earthquake are the largest among all intracontinental thrust-type earthquakes reported to date.

3. Structural analysis of the coseismic shear zone

The surface ruptures related to the Wenchuan earthquake are defined mainly by distinct thrust faults including fault scarps and fold structures, and numerous extensional fractures, distributed in a zone of <50 m in width (generally <20 m) along pre-existing active faults (Lin et al., 2008, 2009). The coseismic fault scarps duplicated on pre-existing fault scarps were easily observed in alluvial deposits during field investigations immediately following the earthquake; however, the coseismic shear zone is not generally exposed. To understand the internal structure of the fault zone related to the coseismic rupture, three outcrops (Locs. 1–3) and one trench (Loc. 4) were examined that cross coseismic fault scarps and that show clear exposure of a prominent fault plane that separates basement and alluvial deposits along the Yingxiu–Beichuan Fault, a main active fault in the southern segment of the Longmen Shan Thrust Belt (Figs. 2–4). The fault planes that accommodated the main coseismic slip of the Wenchuan earthquake were observed in the outcrops and the trench; they strike N35–40°E and dip to the northwest at 36–85° (Figs. 2–4). Numerous striations on the coseismic fault plane indicate a slip sense dominated by thrusting (Fig. 4).

A shear zone is observed within basement rocks in the hanging wall of the coseismic fault. The shear zone generally consists of a fault core, which includes a narrow fault gouge zone of <15 cm (generally <2–3 cm) in width and a fault breccia zone of 0.5–3 m in width, and a damage zone mainly consisting of a thick cataclastic rock zone of >5 m in width, including fractures and some thin fault gouge and breccia zones developed along subsidiary faults (Figs. 2–4 and 5a). The fault gouge and breccia zones are unconsolidated, resembling clay and matrix-supported deposits, respectively.

To observe the structure of the shear zone, the exposure walls were smoothed using a sickle (Figs. 2–4 and 5a). It is generally easy to smooth the exposure walls of outcrops of cataclastic rocks, even those that formed from basement rocks due to the weathering and weakening of the water-rich fault-damage zone and fault-core zone in basement rocks. Foliations are developed in the fault-core zone (including the incohesive fault gouge and fault breccia) and the cohesive cataclasite (Figs. 3 and 5). The foliations are generally defined by subsidiary faults and fractures and angular to sub-rounded fragments aligned parallel or subparallel to the main fault plane, indicating a thrust shear sense, as also indicated by the coseismic surface rupture (Figs. 3 and 5a, b). These fragments are commonly asymmetrical, resembling the pressure shadows developed in S–C mylonitic rocks. The foliated fault breccia zone (generally <1 m in width) is generally bounded by fault gouge on one side and the non-foliated fault breccia zone on the other. The damage zone includes both foliated and non-foliated cataclasitic rocks. The foliation in foliated cataclasitic rocks are generally defined by microshear bands (visible cracks) along which fine-grained material occurs, and fragments have a preferred orientation. The foliated cataclasitic rocks are generally distributed throughout a narrow zone of <2 m, bounded by the fault breccia zone. In contrast, the non-foliated cataclasitic rocks occur in a large zone of >5 m in width, generally bounded by the foliated cataclastic rock zone. Some dark gouge veins were observed along subsidiary faults; these are locally injected along an orientation oblique to the foliation within the shear zone (Fig. 3c and d). No mylonitic rocks were observed in the outcrops or surrounding area along the main active fault zones in the study region.

4. Meso- and microstructures of fault rocks

To observe the meso- and microstructures of fault rocks, oriented samples were collected in the field, from which cut and polished slabs were prepared in the X–Z, Y–Z, and X–Y orientations (X–Z, Y–Z, and X–Y planes of the finite strain ellipsoid) (Figs. 5 and 6). Microstructures were then observed under the microscope using oriented thin sections (Fig. 7). The fault gouge zone, which is gray to dark gray in color, is clearly observed in the slabs, and is generally bounded by the fault breccia zone (Figs. 5 and 6). The fault gouge–breccia zone generally consists of interlayered, gray to dark gray, thin gouge layers (Fig. 5). A thin gouge layer of <2–3 mm in width, bounded by the main fault plane on which the 2008 coseismic slip occurred, is different in color to the bounding gouge layer or fault breccia zone; this is observed in all polished slabs (Figs. 5 and 6). It is proposed that this thin gouge layer bounded by the fault plane is the main *slip zone* of the Wenchuan earthquake, and that the foliation in this layer was generated by coseismic shearing during the earthquake (see Section 5 for details).

S–C fabrics are observed in both the fault gouge and fault breccia zones, and are defined mainly by variations in color, the preferred orientation of fragments (S-surfaces), microshears (C-surfaces) developed parallel to the main fault plane and shear bands (C′-surface) [using the terminology of Lin (1999) for S–C cataclastic rocks] (Figs. 5 and 6). S–C fabrics developed in the cataclastic rocks of coseismic shear zones are also observed along the Nojima Fault, related to the 1995 M_w 7.2 Kobe earthquake (Lin, 2001), and along the Chelungpu Fault, related to the 1999 M_w 7.6 Chi-Chi (Taiwan) earthquake (Lin et al., 2005). The S-surfaces in the present study are defined by aggregates of fine-grained clasts that are generally asymmetric in shape, the C-surfaces are generally defined by subsidiary faults or microshears, and C′-surfaces are defined by shear bands which are oblique to C-surfaces (Figs. 5 and 6). The orientations of S–C fabrics indicate a thrust shear sense, as also indicated by examinations of the outcrop and trench surfaces and the coseismic offset along the surface rupture (Figs. 2 and 3).

Microstructurally, the S–C fabrics are defined by the microshears (C-surface) parallel to the main fault plane, shear bands (C′-surface) oblique to C-surface with angles of 10–30°, and the alignment of clasts and fine-grained mineral aggregates that possess an asymmetric shape similar to the pressure shadows observed in mylonitic rocks (Fig. 7). The core of each asymmetric aggregate consists of coarser clasts than those in the margins, which are generally occupied by fine-grained clasts. The proportion of fine-grained matrix (clasts) increases in the microshears (C foliation) located between the layered zones and in the shear bands (C′ foliation). These asymmetric textures in both the foliated cataclasite and fault gouge, and breccia zones indicate that the main thrust sense is consistent with that observed in the trench walls and in outcrop (see Figs. 3–5).

5. Discussion

5.1. Timing of the initiation of the main active faults

Fault rocks commonly record primary evidence of faulting and the deformation processes of seismic slip and aseismic creep at all depths from the near-surface to deep levels in the crust; consequently, it is necessary to analyze fault rocks to understand not only the nature of fault zones, but also the entire history of fault movement (Sibson, 1975; Lin, 1999, 2008). Fault rocks that formed

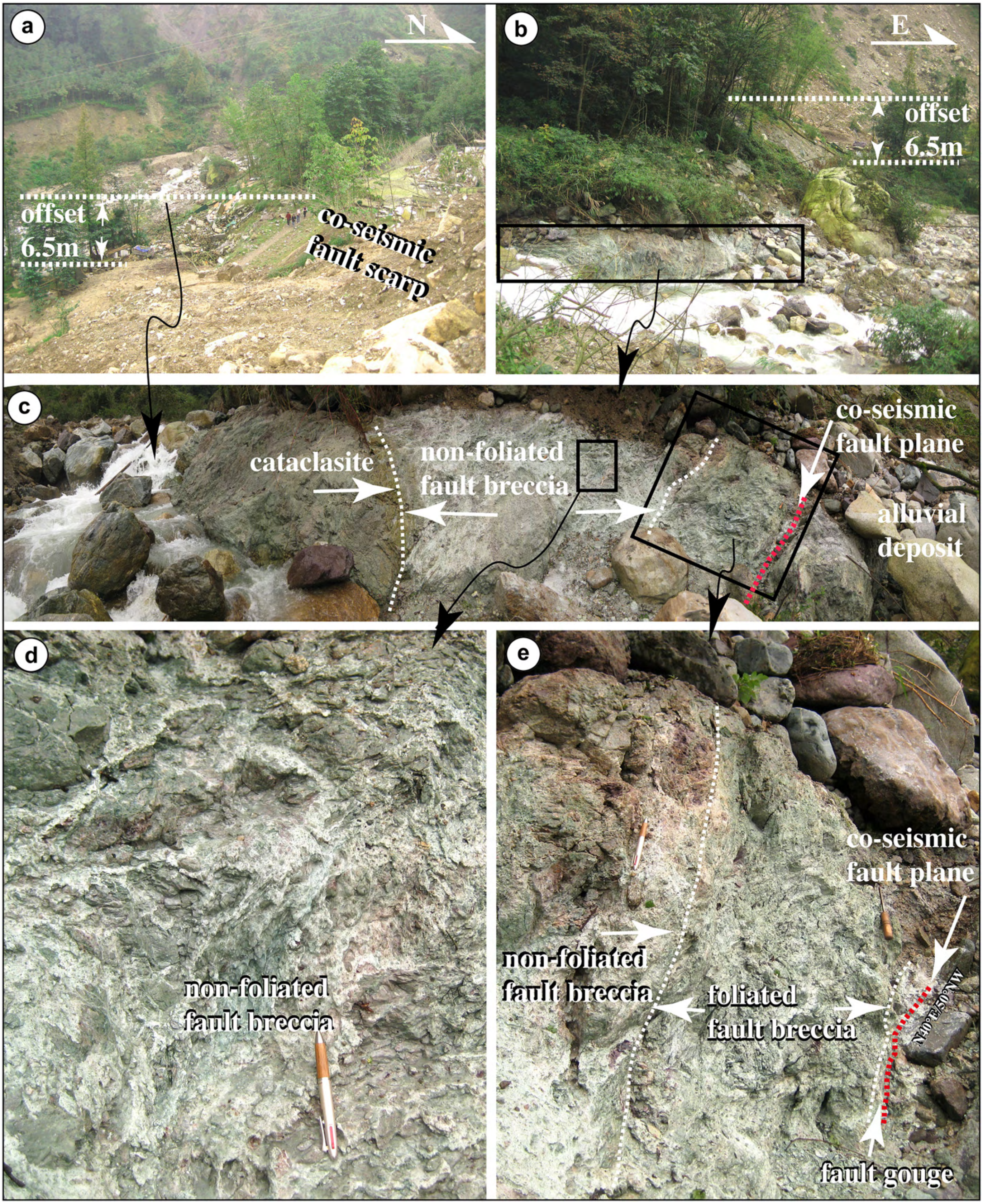

Fig. 2. Photographs of coseismic fault scarps associated with the Wenchuan earthquake and cataclastic rocks in the outcrop at Loc. 1. (a–b) Coseismic fault scarp with a vertical offset of 6.5 m, developed upon an alluvial terrace during the Wenchuan earthquake. (c) Coseismic shear zone consisting of cataclasite, fault gouge, and breccia, bounded by alluvial deposits. (d–e) Close-up views of the non-foliated and foliated fault breccia zones shown in (c).

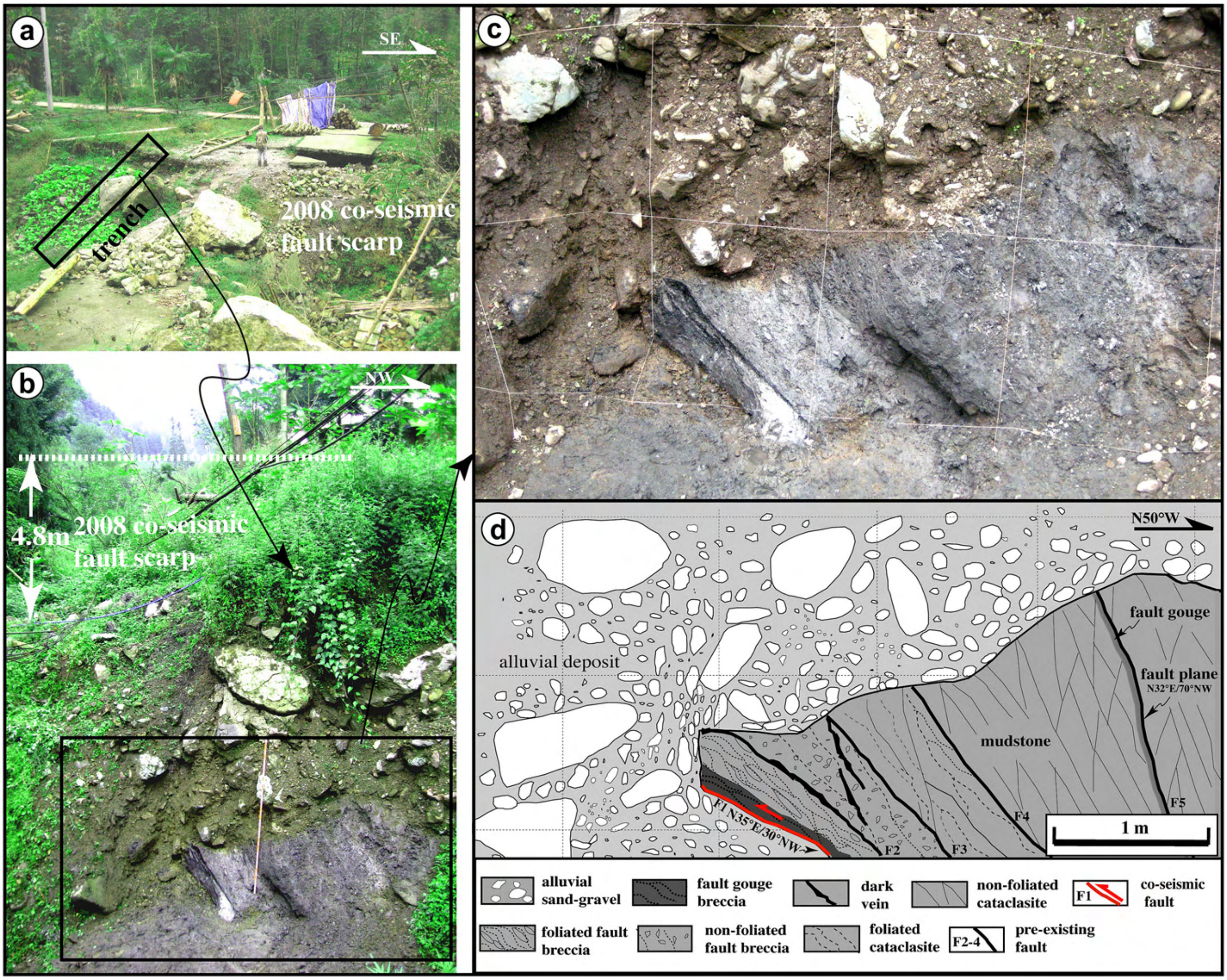

Fig. 3. Photographs and sketch of the coseismic fault scarp and shear zone of the Wenchuan earthquake, as observed at a trench excavated at Loc. 2. (a) Coseismic fault scarp with a vertical offset of 4.8 m, as developed upon an alluvial terrace during the Wenchuan earthquake. (b) Trench excavated across the coseismic fault scarp shown in (a). (c) Close-up view of the trench wall shown in (b). (d) Sketch of (c), showing the occurrence of a shear zone developed in the mudstone.

within seismogenic fault zones at various depths by ancient seismic faulting are exhumed by denudation and uplift; if fault movement continues throughout this process of exhumation, a variety of fault rocks, formed under varying conditions, become exposed at the surface (Scholz, 1990; Lin, 1999, 2008). Accordingly, it is possible to gain an insight into the processes of deformation and faulting operating throughout the faulting history by studying the structures of exposed fault rocks.

Cataclastic rocks generally originate in brittle-dominated regimes at shallow depths: incohesive cataclastic rocks, including fault gouge and breccia, form at <4 km depth and cohesive cataclastic rocks form at 4–10 km, whereas mylonitic rocks form in the ductile-dominated regime at greater depths of ~10–15 km, assuming a geothermal gradient of 30 °C/km (Sibson, 1975).

Based on thermochronological and topographical data, it is inferred that the eastern margin of the Tibetan Plateau is no older than the late Miocene or early Pliocene (5–12 Ma) (Kirby et al., 2000, 2002). This means that the present eastern margin of the Tibetan Plateau, which forms the steep topographical boundary between the Tibetan Plateau and the Sichuan Basin, with a topographic relief of over 5000 m, formed during the late Miocene or early Pliocene with an average incision rate of 1–2 mm/yr (Kirby et al., 2002). Trench and field surveys have revealed that the average vertical slip rate of the main active faults within the Longmen Shan Thrust Belt is ~1–3 mm/yr, similar to that of the incision rate inferred from topographical data (Densmore et al., 2007). If mylonitic rocks had developed in the main shear zone of the Longmen Shan Thrust Belt, they would be exposed at the surface after a period of no more than ~10 Ma, given uplift and exhumation at average rates of denudation and vertical slip of 1–2 mm/yr. Accordingly, the lack of mylonitic rocks within the main shear zone of the Longmen Shan Thrust Belt suggests a short faulting history along the Yingxiu–Beichuan Fault. The presence of zones of incohesive fault gouge and breccia of up to 3 m in width suggests the short tectonic history of active faults within the Longmen Shan Thrust Belt. Based on these observations, it is concluded that the cataclastic rocks were developed within the main shear zone of the Longmen Shan Thrust Belt, accompanying the formation of the topographical boundary between the Tibetan Plateau and the Sichuan Basin during the late Miocene or early Pliocene (5–10 Ma).

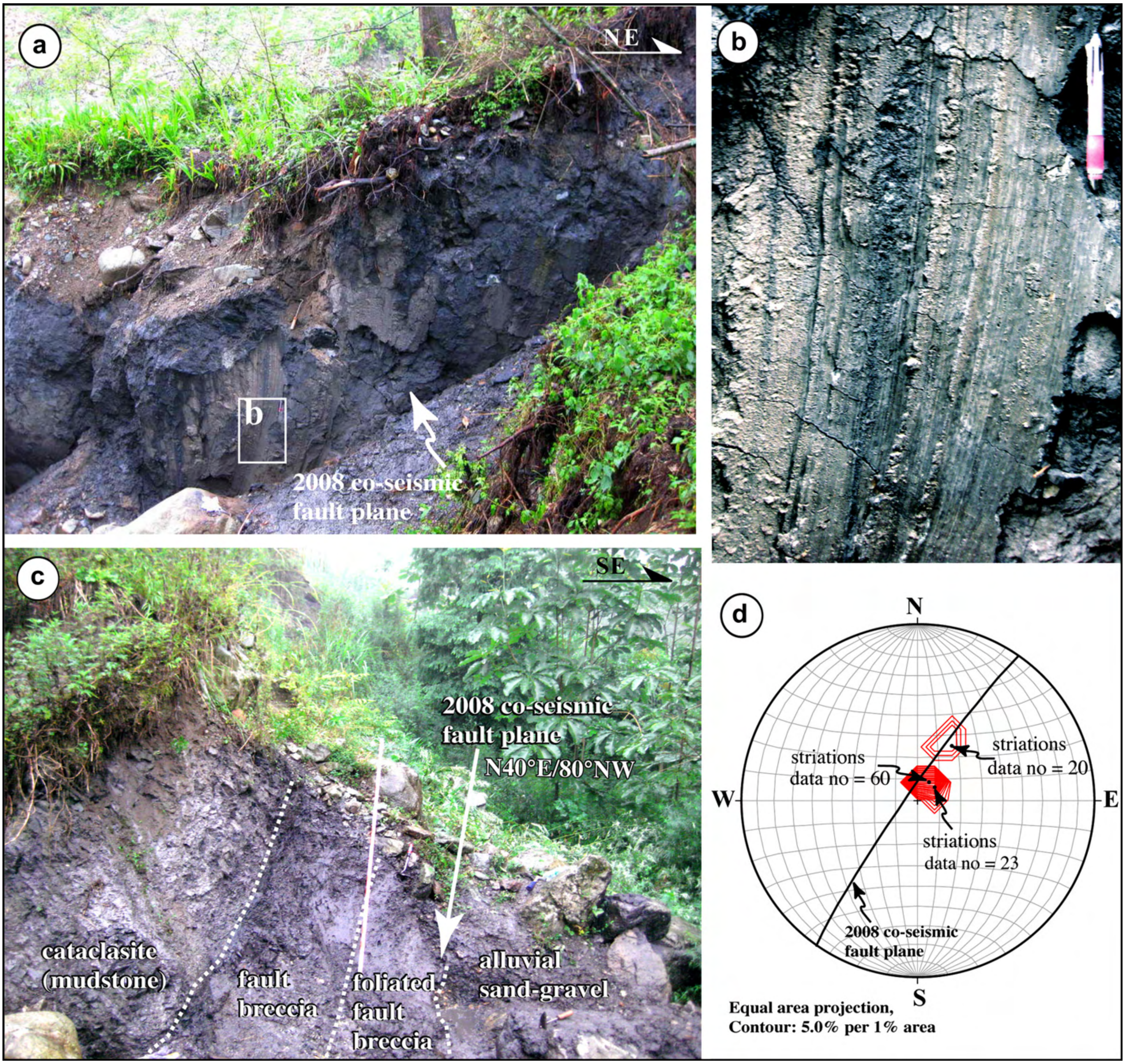

Fig. 4. Photographs of the coseismic fault plane and shear zone. (a) Coseismic fault plane of the Wenchuan earthquake, as developed within mudstone at Loc. 3. (b) Striations generated on the coseismic fault plane shown in (a). (c) Shear zone exposed across the coseismic fault scarp, continuous with the fault scarp shown in (a). (d) Equal-area stereographic projection showing the orientations of striations upon on the coseismic fault plane shown in (a–b).

5.2. Coseismic slip sense

The orientations of S–C fabrics within cataclastic rocks reflect the geometry of the strain field in the brittle shear zone, which is commonly subjected to simple shear parallel to the zone. Accordingly, the orientation of S–C fabrics is commonly used as a criterion in deducing the sense of movement within the fault shear zone, as in mylonitic rocks (e.g., Lin, 1999, 2001, 2008). As stated above, the S–C fabrics within the main shear zone, which consists of cataclastic rocks including fault gouge, breccia, and cataclasite, show a uniformly thrust shear sense. This finding indicates that the main fault has moved as a thrust since the formation of cataclastic rocks in the Longmen Shan Thrust Belt.

Seismic reflection profiles indicate that the Yingxiu–Beichuan Fault is a through-going thrust fault that extends directly from the hypocenter of the 2008 Wenchuan earthquake to the surface ruptures and that may root into a mid-crust detachment (Jia et al., 2009). Topographically, the coseismic surface rupture produced by the Wenchuan earthquake occurred along pre-existing active faults on which vertical offsets have accumulated (Lin et al., 2008, 2009). As stated above, the coseismic fault scarp just occurred within the fault-core zone, bounded by the main fault plane along which the coseismic slip occurred. The accumulated evidence, based on analyses of coseismic shear, fault rocks, and seismic, topographical, and geological data, indicates that the coseismic source fault of the Wenchuan earthquake has slipped as a thrust fault since its onset during the late Miocene or early Pliocene.

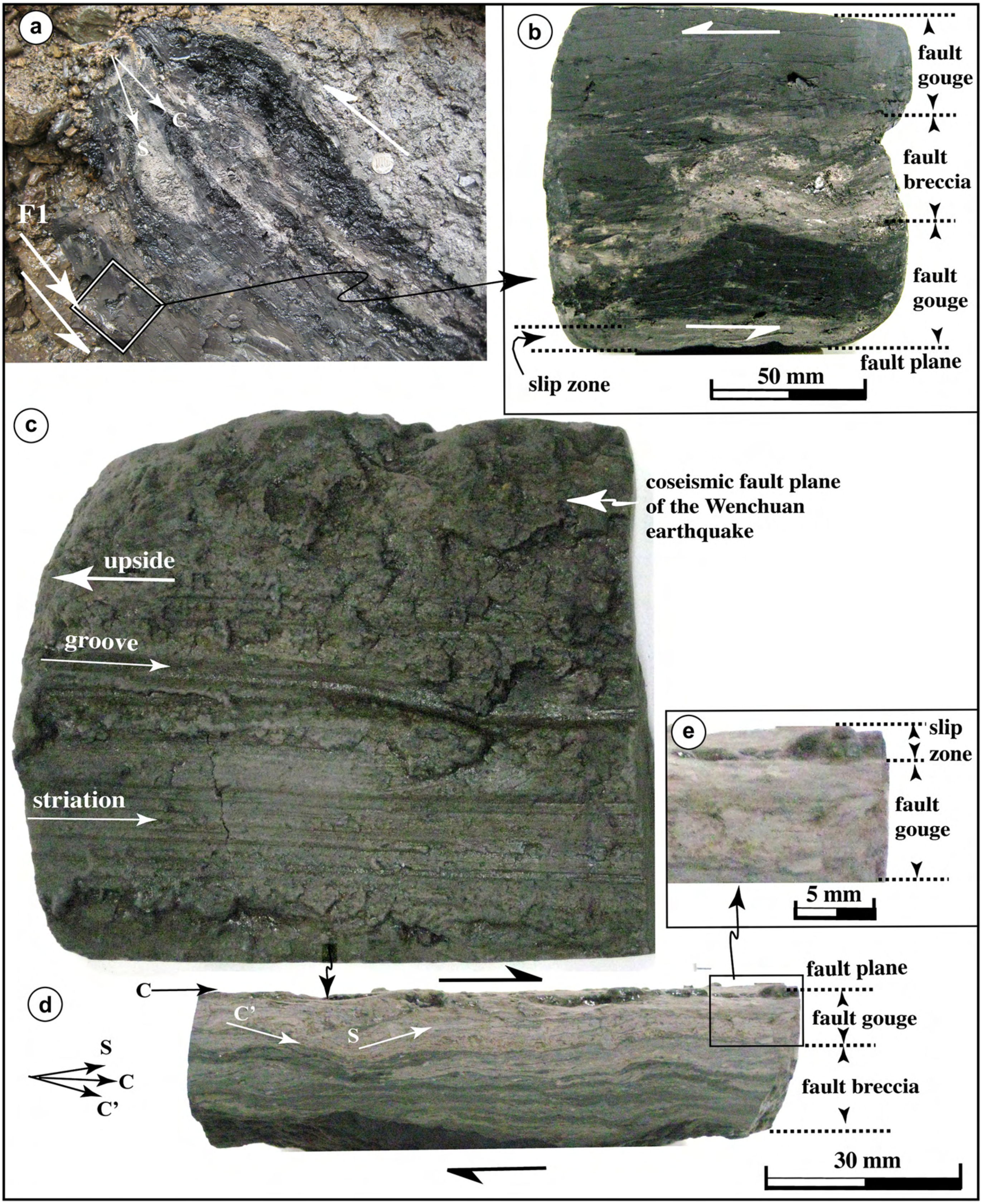

Fig. 5. Photographs of S–C fabric within the coseismic shear zone and striations. (a) Coseismic shear zone of the Wenchuan earthquake, as developed within mudstone at Loc. 2. The shear zone consists of foliated cataclastic rocks, including fault gouge, breccia, and cataclasite. F1: fault plane along which the main coseismic slip occurred, which is bounded by mudstone in the hanging wall (right side) and alluvial deposit in the footwall (left side). (b) Polished X–Z section of a hand sample taken from the shear zone shown in (a). (c) Hand sample showing the striations generated on the coseismic fault plane shown in Fig. 4b. (d) Polished X–Z section of the hand sample shown in (c). (e) Close-up view of the thin fault gouge layer bounded by the fault plane shown in (d).

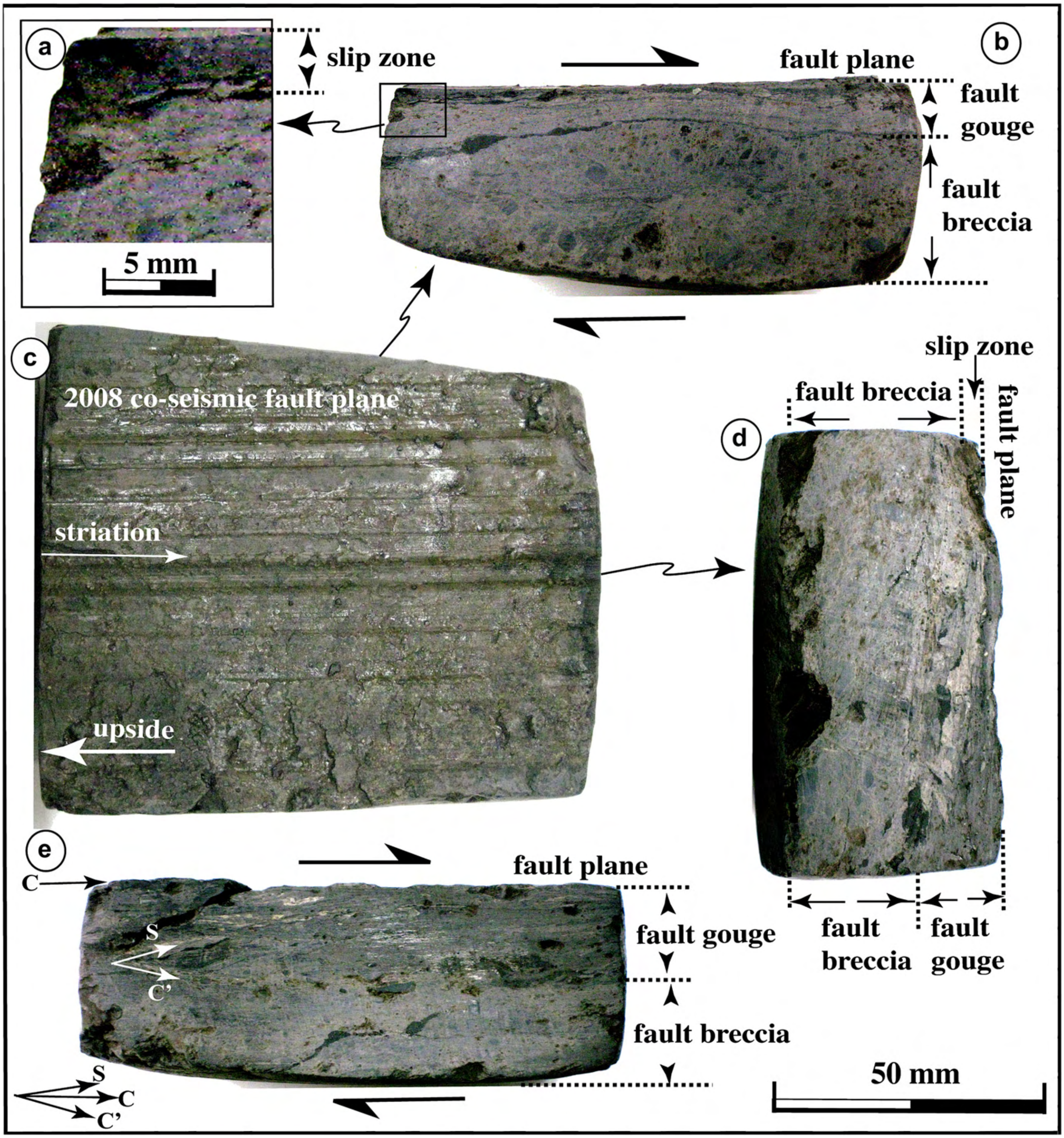

Fig. 6. Photographs of S–C fabrics in and striations on hand samples collected from the outcrop at Loc. 3. (a–b) Polished X–Z slab prepared from a hand sample. (a) Close-up view of (b). (c) Striations upon the coseismic fault plane. (d) Polished Y–Z slab prepared from a hand sample. (e) Polished X–Z slab prepared from a hand sample.

5.3. Width of the coseismic slip zone

It is well known that coseismic surface ruptures produced by individual large-magnitude earthquakes are generally distributed throughout a zone ranging in width from several meters to several tens of meters (e.g., Lin et al., 2001; Yeats et al., 1997), although some such zones are up to 10 km in width (Lin et al., 2002, 2003). Geologic and seismic data reveal that the occurrence of coseismic surface ruptures is controlled mainly by pre-existing fault zones (e.g., Yeats et al., 1997; Lin et al., 2002, 2003). Seismic inversions are generally based on the assumption that the coseismic slip zone is a planar surface. Structural analyses show that damage zones developed in main fault zones generally vary from several meters to hundreds of meters in width (e.g., Gudmundsson et al., 2009) and that coseismic surface ruptures are generally associated with pre-existing damage zones developed along main faults (e.g., Lin et al., 2005). The important issue here is whether the principal slip associated with a moderate to large earthquake is concentrated within a narrow shear zone.

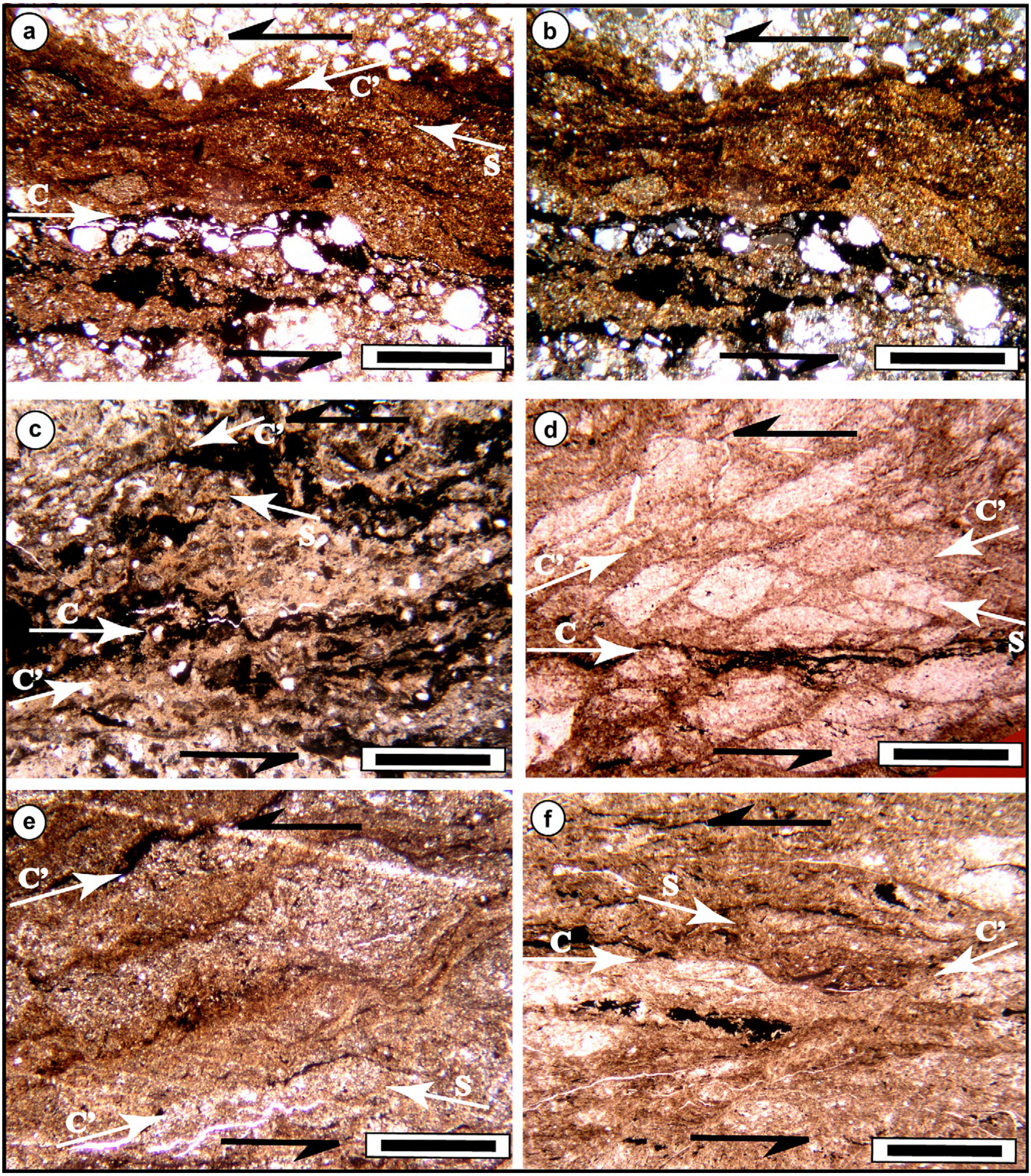

Fig. 7. Photomicrographs showing the textures of fault gouge and foliated fault breccia. (a–b) Fault gouge layer bounded by fault breccia (Loc. 1). (a) Plane-polarized light, (b) crossed-polarized light. (c) Flow structure of the fault gouge (Loc. 2). (d) Foliated fault microbreccia with S–C fabric (Loc. 2). (e–f) Foliated fault gouge with S–C fabric (Loc. 3). S–C fabrics in fault gouge and microbreccia indicate a left-lateral shear sense (shown by long black arrows). Black arrows indicate the shear sense. (c–f) Plane-polarized light. Scale bar: 200 μm.

Sibson (2003) reviewed geological and other evidence that serves to constrain the thickness of the principal slip zone that accommodates the bulk of coseismic shear displacement during an individual rupture event, concluding that the localization of coseismic shearing to a zone of less than 10 cm in width upon planar faults is common throughout the crustal seismogenic zone, with extreme localization to less than 1 cm not uncommon (Sibson, 2003). Heermance et al. (2003) suggested that the coseismic slip during the Chi-Chi earthquake was localized in a narrow zone of 50–300 μm. Based on an analysis of the coseismic shear zone and related fault rocks of the 1999 M_w 7.6 Chi-Chi (Taiwan) earthquake, Lin et al. (2005) reported that the coseismic shear zone is less than 3 mm in width. Similarly, Shigetomi and Lin (1999) reported that the coseismic slip zone that triggered the 1995 M_w 7.2 Kobe earthquake (along the Nojima Fault) is localized in a narrow gouge layer of <3 mm, bounded by the coseismic fault plane. Along this thin gouge layer, the ESR (Electron Spin Resonance) signals decrease sharply across a zone of less than 3 mm in width (Fukuchi and Imai, 1998; Fukuchi, 2003). This finding is explained in terms of annealing associated with frictional heating generated in the thin gouge layer during seismic slip (Fukuchi and Imai, 1998; Fukuchi, 2003). The results of these previous studies indicate that the principal coseismic slip is probably generally localized in a narrow, millimeter-scale gouge zone that develops in shear zones along pre-existing fault zones.

The field occurrence and fabric of the main coseismic shear zone of the Longmen Shan Thrust Belt indicates that the fault gouge zone bounds the coseismic fault plane along which the main coseismic slip occurred during the Wenchuan earthquake. This zone ranges in width from <2–3 mm to 2 cm (generally less than 2–3 mm) and has a sharp contact (accompanied by a change in color) with the adjacent gouge layer or microbreccia layer. This finding indicates that this thin, fault-plane-bounded gouge layer probably formed as a result of coseismic slip during the Wenchuan earthquake. Based on the fabric of the fault gouge and the geological evidence presented above, it is concluded that the principal coseismic slip during the Wenchuan earthquake was concentrated in a narrow gouge zone of <2–3 mm in width that is bounded by the coseismic fault plane. The present results support the hypothesis that coseismic slip during large-magnitude earthquakes is concentrated in a narrow, millimeter-scale shear zone along pre-existing fault zones.

6. Conclusions

Based on a structural analysis of fault rocks and the shear zone associated with the 2008 M_w 7.9 Wenchuan earthquake, China, the following conclusions are drawn.

1. The main coseismic shear zone consists of a fault core that includes a narrow fault gouge zone of <15 cm in width (generally 1–2 cm) and a fault breccia zone of <∼3 m in width, and a wide damage zone consisting of cataclastic rocks including fractures and subsidiary faults.
2. Foliations, characterized by S–C fabrics, are developed in the cataclastic rocks, and indicate a dominantly thrust slip sense, consistent with that indicated by the coseismic surface rupture.
3. Coseismic slip was localized in a narrow fault gouge zone of <2–3 mm in width, the location of which was controlled by a pre-existing shear zone.
4. The main active fault of the Longmen Shan Thrust Belt has moved as a thrust since the formation of cataclastic rocks along the fault during the late Miocene or early Pliocene.

Acknowledgements

The author thanks Drs. D. Jia and X. Wu of the Nanjing University for assistance in the field. This work was supported by the Science Project (No. 1818340158) of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

Burchfiel, B.C., Chen, Z., Liu, Y., Royden, L.H., 1995. Tectonics of the Longmen Shan and adjacent regions, central China. International Geological Review 37 (8), 661–735.

Burchfiel, B.C., Royden, L.H., van der Hilst, R.D., Hager, B.H., 2008. A geological and geophysical contex for the Wenchuan earthquake of 12 May 2008, Sichuan, People's Republic of China. GSA Today 18. doi:10.1130/GSATG18A.J.

Bureau of Geology and Mineral Resource of Sichuan Province (BGMRSP), 1991. Regional Geology of Sichuan Province. Geological Publishing House, Beijing.

Chen, Z., Zhao, C., Zhou, L., Shi, Y., 2008. The rupture process of the M_w 8.0 Wenchuan earthquake. http://www.csi.ac.cn/sichuan (accessed 30.05.09).

China Earthquake Networks Center (CENC), 2008. Rupture Process of the 2008 Ms 8.0 Wenchuan Earthquake. http://www.cenc.ac.cn (accessed 26.06.09).

Deng, Q., Chen, S., Zhao, X., 1994. Tectonics, seismicity, and dynamics of the Longmen Shan Mountains and its adjacent regions. Seismological and Geology 16, 389–403 (in Chinese).

Densmore, A.L., Ellis, M.A., Li, Y., Zhou, R., Hancock, G.S., Richardson, N., 2007. Active tectonics of the Beichuan and Pengguan faults at the eastern margin of the Tibetan Plateau. Tectonics 26, TC4005. doi:10.1029/2006TC001987.

Dong, S., Zhang, Y., Wu, A., Ma, Y., Shi, W., Chen, Z., Long, C., An, M., 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.

Fukuchi, T., 2003. Strong ferromagnetic resonance signal and magnetic susceptibility of the Nojima pseudotachylyte in Japan and their implication for coseismic electronmagnetic changes. Journal of Geophysical Research 108, 2312. doi:10.1029/2002JB002007.

Fukuchi, T., Imai, N., 1998. Resetting experiment of E′ centres by natural faulting – the case of the Nojima earthquake fault in Japan. Quaternary Geochronology 17, 1063–1068.

Gudmundsson, A., Simmenes, T.H., Larsen, B., Philipp, S.L., 2009. Effects of internal structure and local stresses on fracture propagation, deflection, and arrest in fault zones. Journal of Structural Geology. doi:10.1016/j.jsg.2009.08.013.

Heermance, R., Shipton, Z.K., Evans, J.P., 2003. Fault structure control on fault slip and ground motion during the 1999 rupture of the Chelungpu fault. Bulletin of the Seismological Society of America 93, 1034–1050.

Ji, C., 2008. Preliminary result of the May 12, 2008 M_w 7.9 eastern Sichuan, China earthquake. http://geol.uscb.edu/faculty/ji/big.earthquakes/2008/05/12/Shichuan.html (accessed 10.06.08).

Jia, D., Wei, G., Chen, Z., Li, B., Zeng, Q., Yang, G., 2006. Longmen Shan fold-thrust belt and its relation to the western Sichuan Basin in central China: new insights from hydrocarbon exploration. AAPG Bulletin 90, 1435–1447.

Jia, Q., Jia, D., Zhu, A., Chen, Z., Hu, Q., Luo, L., Zhang, Y., Li, Y., 2007. Active tectonics in the Longmenshan thrust belt to the eastern Qinghai-Plateau and Sichuan Basin: evidence from topography and seismicity. Chinese Journal of Geology 42, 31–44.

Jia, D., Li, Y., Lin, A., Wang, M., Chen, W., Wu, X., Ren, Z., Zhao, Y., Luo, L., 2009. Structural model of 2008 M_w 7.9 Wenchuan earthquake in the rejuvenated Longmen Shan thrust belt, China. Tectonophysics. doi:10.1016/j.tecto.2009.08.040.

Kirby, E., Whipple, K., Burchfiel, B.C., Tang, W., Berger, G., Sun, Z., Chen, Z., 2000. Neotectonics of the Min Shan, China: implications for mechanisms driving quaternary deformation along the eastern margin of the Tibetan Plateau. Geological Society of American Bulletin 112, 375–393.

Kirby, E., Reiners, P., Krol, M., Whipple, K., Hodges, K., Farley, K., Tang, W., Chen, Z., 2002. Late Cenozoic evolution of the eastern margin of the Tibetan Plateau: inferences from $^{40}Ar/^{39}Ar$ and (U–Th)/He thermochronology. Tectonics 21. doi:10.1029/2000TC001246.

Li, Y., Zhou, R., Densmore, A.L., Ellis, M.A., et al., 2006. Continental Dynamics and Geological Responses of the Eastern Margin of Qinghai–Tibet Plateau. Geological Press, Beijing, 148 pp. (in Chinese with English abstract).

Lin, A., 1999. S–C cataclasite in granitic rock. Tectonophysics 304, 257–273.

Lin, A., 2008. Fossil Earthquakes: The Formation and Preservation of Pseudotachylytes. Springer-Verlag, Berlin/Heidelberg.

Lin, A., 2001. S–C fabrics developed in cataclastic rocks from the Nojima fault zone, Japan and their implications for tectonic history. Journal of Structural Geology 23, 1167–1178.

Lin, A., Ouchi, T., Chen, A., Maruyama, T., 2001. Co-seismic displacements, folding and shortening structures along the Chelungpu surface rupture zone occurred during the 1999 Chi-Chi (Taiwan) earthquake. Tectonophysics 330, 225–244.

Lin, A., Kikuchi, M., Fu, B., 2003. Rupture segmentation and process of the 2002 Mw 7.8 Central Kunlun, China, earthquake. Bulletin of the Seismological Society of America 93, 2477–2492.

Lin, A., Jia, D., Ren, Z., Wu, X.J., 2008. Reports on the coseismic surface rupture and related disasters associated with the M_w 7.9 Wenchuan earthquake, China. Journal of Geography 117 (3), 593–598 (in Japanese with English abstract).

Lin, A., Ren, Z., Jia, D., Wu, X., 2009. Co-seismic thrusting rupture and slip distribution produced by the 2008 M_w 7.9 Wenchuan earthquake, China. Tectonophysics 47, 203–215. doi:10.1016/j.tecto.2009.02.014.

Lin, A., Ren, Z., 2009. The Great Wenchuan Earthquake of 2008: A Photogragic Atlas of Surface Rupture and Related Disaster. Springer, Heidelberg/Dordrecht/London/New York.

Lin, A., Fu, B., Guo, J., Zeng, Q., Dang, G., He, W., Zhao, Y., 2002. Co-seismic strike-slip and rupture length produced by the 2001 Ms 8.1 Central Kunlun earthquake. Science 296, 2015–2017.

Lin, A., Lee, C., Maruyama, T., Chen, A., 2005. Meso- and micro-structures of seismic shear zone related with the 1999 M_w 7.6 Chi-Chi earthquake, Taiwan. Bulletin of the Seismological Society of America 95, 486–501.

Nishimura, N., Yagi, Y., 2008. Preliminary results of coseismic-slip for the 2008 M_W 7.9 Wenchuan earthquake, Southwest China, 2008. http://www.geol.tsukuba.ac.jp/~nishimura/20080512 (accessed 30.06.09).
Ren, Z., Lin, A., 2010. Co-seismic landslides induced by the 2008 M 8.0 Wenchuan earthquake, as revealed by ALOS PRISM and AVNIR2 imagery data. International Journal of Remote Sensing, doi:10.1080/0143116003727770.
Scholz, C.H., 1990. The Mechanics of Earthquake Faulting. Cambridge University Press, New York. 438.
Shigetomi, M., Lin, A., 1999. Seimic events inferred from the layering structures of fault gouge zone and pseudotachylytes in the Nojima fault zone, Japan. Structural Geology 43, 38–42 (in Japanese with English abstract).
Sibson, R.H., 1975. Generation of pseudotachylite by ancient seismic faulting. Geophysical Journal Royal Astronomical Society 43, 775–794.
Sibson, R.H., 2003. Thickness of the seismic slip zone. Bulletin of the Seismological Society of America 93, 1169–1178.
Ujiie, K., 2005. Fault rock analysis from the northern part of the Chelungpu and their relation to earthquake faulting of the 1999 Chi-Chi earthquake, Taiwan. The Island Arc 14, 2–11.
Xu, X., Wen, X., Ye, J., Ma, B., Chen, J., et al., 2008. The Ms 8.0 Wenchuan earthquake surface ruptures and its seismogenic structure. Seismology and Geology 30, 597–629 (in Chinese with English abstract).
Yeats, R.S., Sieh, K., Allen, C.R., 1997. The Geology of Earthquakes. Oxford Univ. Press, Oxford.
Zhang, P., Xu, X., Wen, X., et al., 2008. Slip rate and recurrence interval of Longmen Shan active fault zone, and tectonic implications for the mechanism of the May 12, 2008 Wenchuan earthquake, Sichuan, China. Chinese Journal of Geophysics 51, 1066–1073.