Aiming Lin
Zhikun Ren

The Great Wenchuan Earthquake of 2008: A Photographic Atlas of Surface Rupture and Related Disaster

高等教育出版社
HIGHER EDUCATION PRESS

Springer

Aiming Lin
Zhikun Ren

The Great Wenchuan Earthquake of 2008: A Photographic Atlas of Surface Rupture and Related Disaster

Aiming Lin

Zhikun Ren

The Great Wenchuan Earthquake of 2008: A Photographic Atlas of Surface Rupture and Related Disaster

with 121 figures

高等教育出版社
HIGHER EDUCATION PRESS

Springer

Authors
Prof. Aiming Lin
Graduate School of Science & Technology
Shizuoka University
836 Ohya
Suruga-ku
Shizuoka
422-8529 Japan

Dr. Zhikun Ren
Graduate School of Science & Technology
Shizuoka University
836 Ohya
Suruga-ku
Shizuoka
422-8529 Japan

ISBN 978-7-040-15128-2
Higher Education Press, Beijing

ISBN 978-3-642-03758-0 e-ISBN 978-3-642-03759-7
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2009932898

Cover design: Frido Steinen-Broo, Estudio Calamar, Spain

Printed on acid-free paper
Springer is part of Springer Science+Business Media (www.springer.com)

Preface

The magnitude M_s 8.0 (M_w 7.9) Wenchuan earthquake occurred on 12 May 2008 in the Longmen Shan region of China—the topographical boundary between the Tibetan Plateau and the Sichuan Basin—resulting in extensive damage throughout central and western China. To understand the seismic faulting mechanism and surface deformation features associated with the Wenchuan earthquake, including rupture length, geometric characteristics, and slip distribution of co-seismic surface rupture, our survey group traveled to the epicentral area 2 days after the earthquake and undertook 10 days of fieldwork, during which time we collected fundamental data related to rupture structures and the spatial distribution of offset along faults. Based on the results of this preliminary fieldwork, we carried out additional detailed fieldwork along the co-seismic surface rupture over the following year.

This photographic atlas shows the main deformation characteristics of co-seismic surface rupture and the nature of the earthquake disaster and subsequent relief operations, based on photographs taken during our field investigations. This atlas is intended not only for geologists, seismologists, and engineers as a means of furthering their understanding of the seismic mechanisms and surface rupture deformation characteristics of large intracontinental earthquakes, but also for advanced undergraduates and graduate students as a textbook.

We are grateful to the many organizations and individuals who helped to make this book possible. Thanks are also due to Professor Dong Jia and Dr. Xiaojun Wu of the Nanjing University for their assistance in the field.

Aiming Lin

Zhikun Ren

Shizuoka May 2009

Contents

1. Tectonic Setting of the Wenchuan Earthquake

The Longmen Shan region is characterized by high elevations of up to 4 500 m on average above sea level and topographic relief of more than 5 km over distances of less than 50 km, representing one of the steepest mountain fronts along any margin of the Tibetan Plateau. This eastern margin of the plateau is bound by the Longmen Shan Thrust Belt, which strikes northeast–southwest over a distance of ~500 km. The basement of the thrust belt is dominated by strongly folded and deformed pre-Mesozoic rocks. The Longmen Shan Thrust Belt is dominated by four major thrust faults: the Wenchuan–Maowen, Yingxiu–Beichuan, Guanxian–Anxian, and Qingchuan faults. Seismicity is generally restricted to small events in the area around the belt.

The historic record of earthquakes in this region over the past 1 400 years reveals only four earthquakes of M>6 (M 6.5 in 1657, M 6.2 in 1958, 1970, and 1972), indicating a remarkable lack of large earthquakes of M>6.5 along he belt. However, our trenching surveys and field investigations carried out after the 2008 Wenchuan earthquake reveal a great Tang-Song Dynasty (~AD 800—1000) earthquake that ruptured a >200-km-long thrust fault within the Longmen Shan Thrust Belt, along which co-seismic surface ruptures developed in association with the 2008 Wenchuan earthquake. These observations constrain a millennial recurrence interval for magnitude ~8 earthquakes in this region. Geologic and paleoseismic data demonstrate that the major thrusts of the Longmen Shan Thrust Belt are currently active as the source faults of large earthquakes during the late Holocene.

(Figures 1~4)

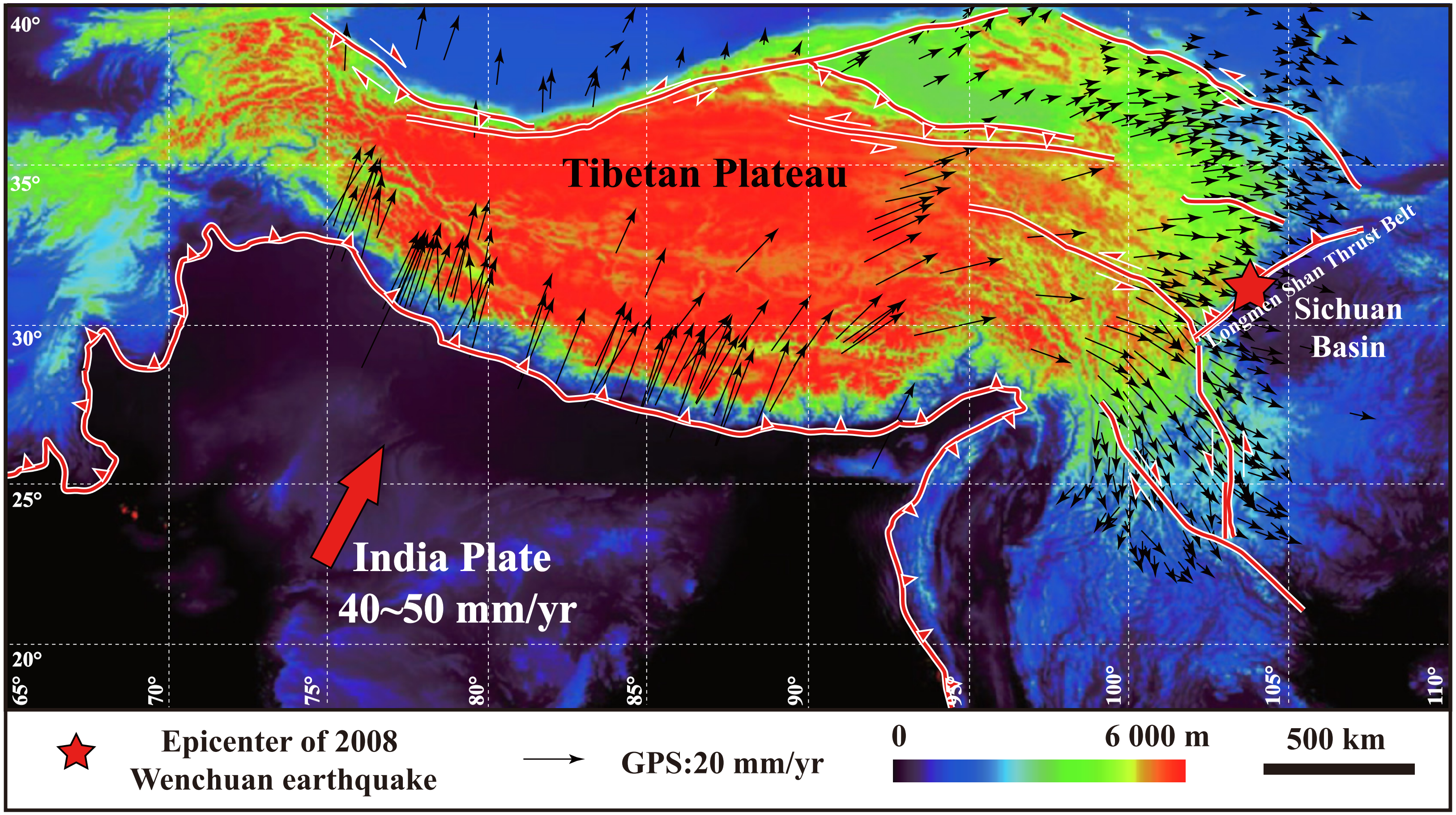

Figure 1 Index map showing the epicenter of the 2008 M_s 8.0 Wenchuan earthquake. The Tibetan Plateau has been uplifted and shortened by collision between the Indian and Eurasian plates at a rate of 40~50 mm/yr,and extruded eastward. The 2008 Wenchuan earthquake resulted from the compressive stress associated with the eastward extrusion of the Tibetan Plateau upon the Longmen Shan Thrust Belt within the eastern marginal zone of the Tibetan Plateau

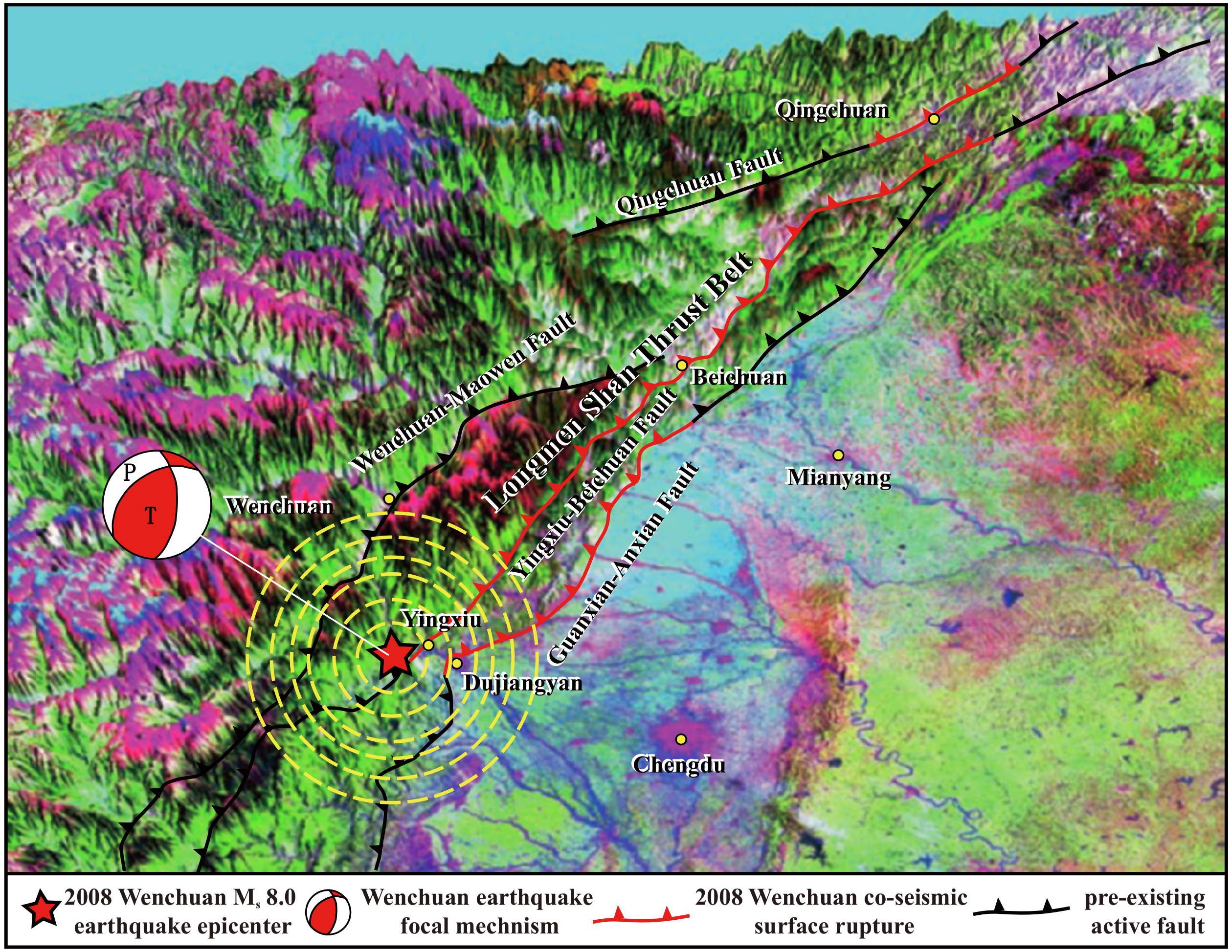

Figure 2 Shaded relief map showing the main topographic features of the Longmen Shan Thrust Belt

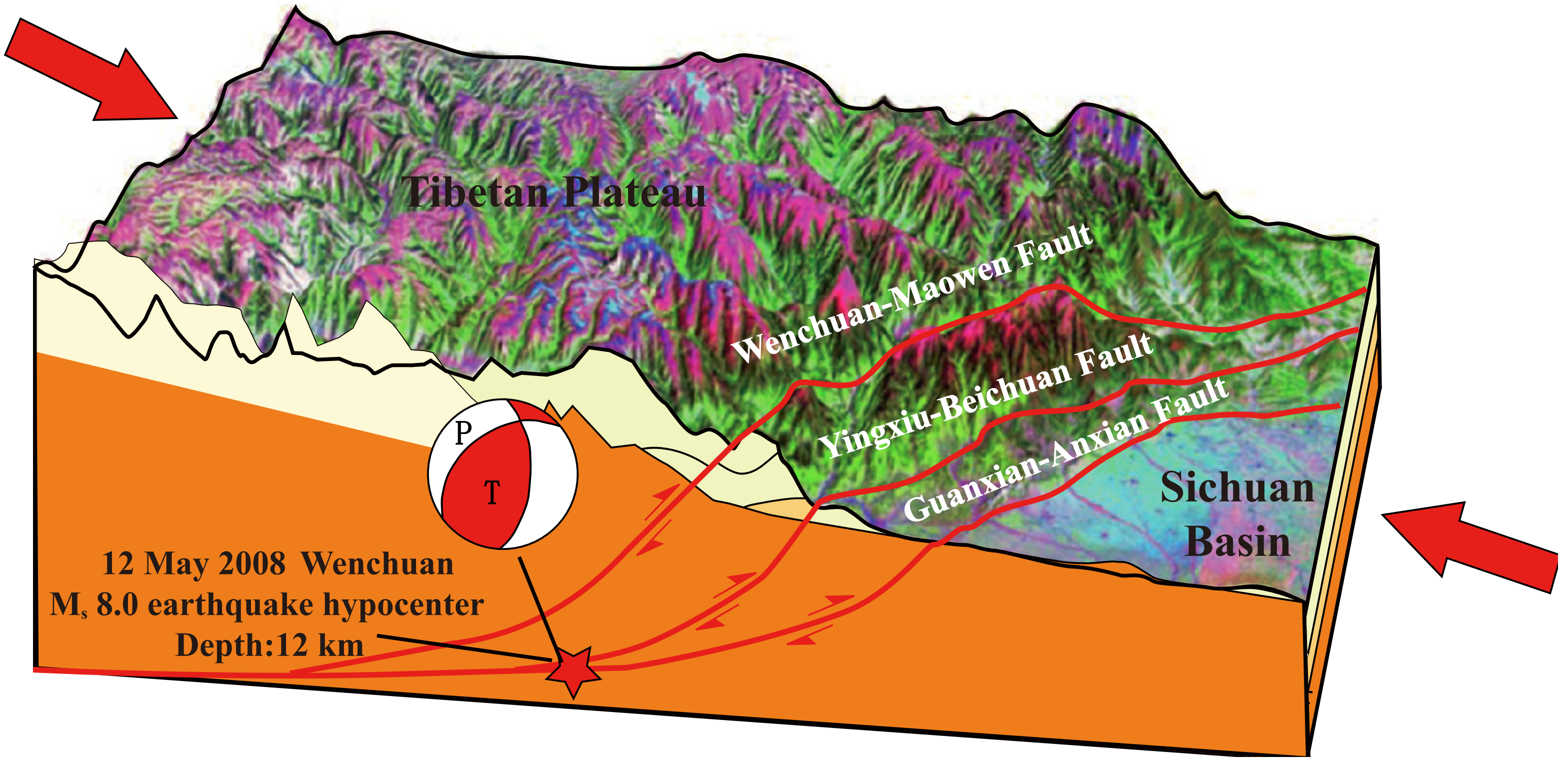

Figure 3 Geologic and topographic section across the Longmen Shan Thrust Belt

Figure 4　Photograph showing fold structures of the Longmen Shan Thrust Belt at Jiangyou

2. Outline of Earthquake and Focal Mechanisms

The Wenchuan earthquake was felt throughout all of China except for Xinjiang Uygur Autonomous Region and Heilongjiang Province, with the strongest shaking being felt in the areas around Sichuan Province. The epicenter of the earthquake was located in Wenchuan County. Seismic rupturing initiated south of the town of Yingxiu, propagated northeastward for ~300 km, and terminated at the town of Shazhou in Qingchuan County. Aftershocks that occurred over the month following the main shock largely concentrated in the zone along the co-seismic surface rupture. Focal mechanism solutions and field investigations reveal that seismic slip was dominated by thrusting, accompanied by a minor component of horizontal slip. The fault upon which the earthquake occurred strikes N40°E and dips to the northwest at 30°. Seismic inversion results reveal an average slip amount of 2~4 m, with a maximum of 6~7 m. These amounts are consistent with those obtained during our field investigations.

(Figures 5~7)

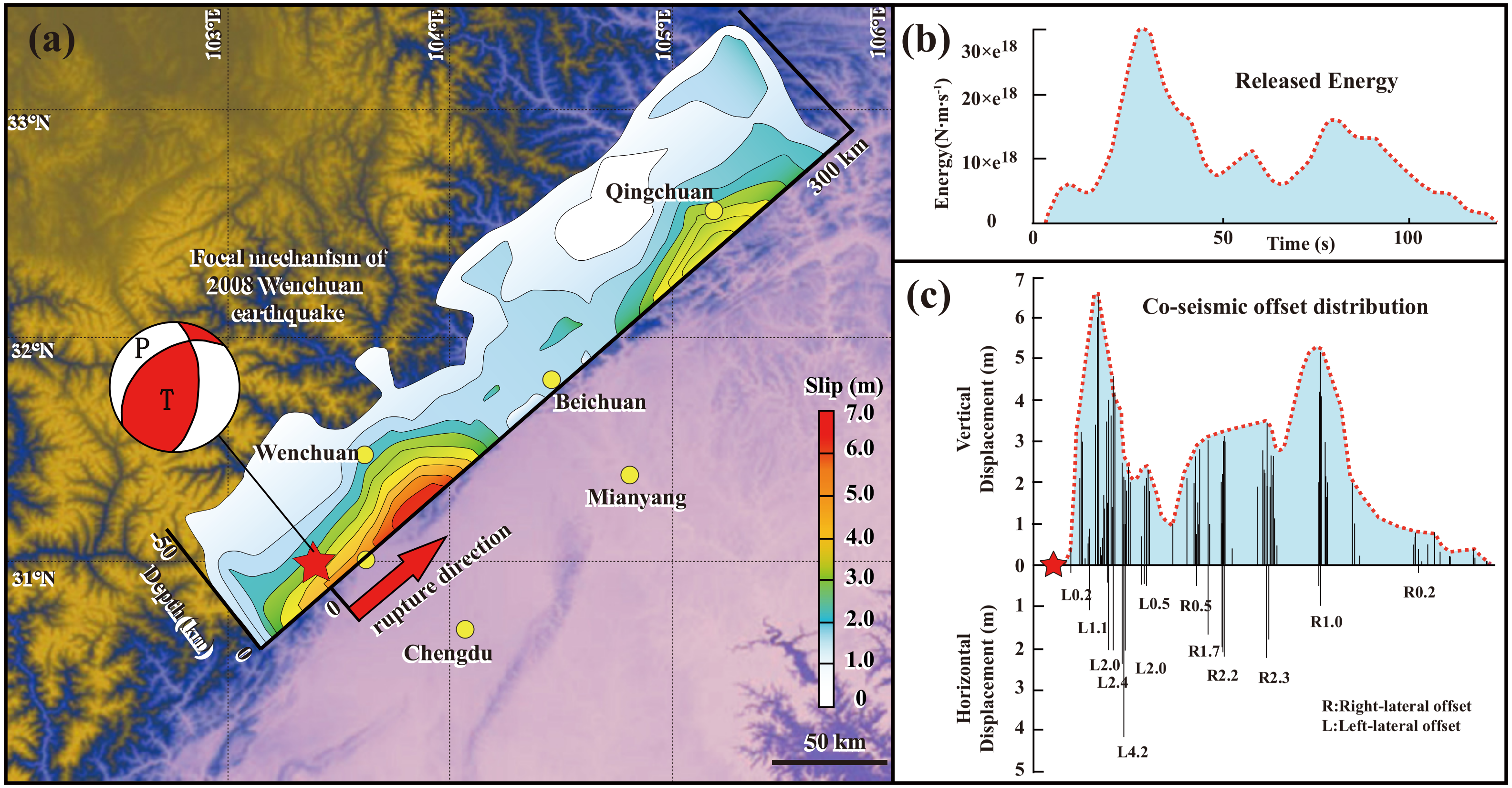

Figure 5 Focal mechanism and seismic slip distribution. (a) Focal mechanism and seismic slip distribution on the fault plane, (b) Released seismic energy, (c) Distribution of slip along the co-seismic surface rupture zone. Note that the distribution pattern of released energy per second is consistent with that of offset distribution along the co-seismic surface rupture. (a),(b) data from Nishimura and Yagi, 2009, (c) data from Lin *et al.*, 2009a

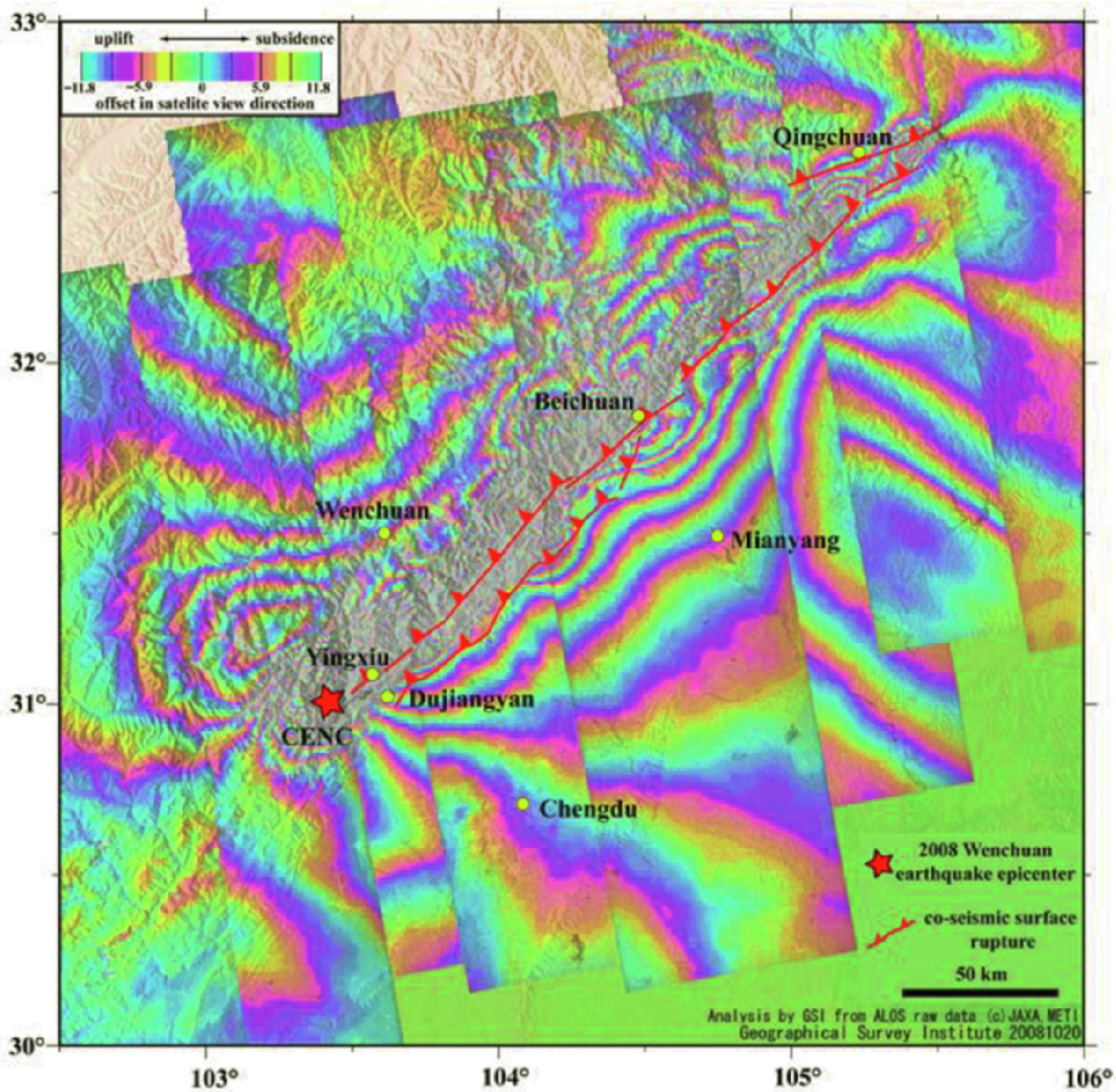

Figure 6 InSar image. InSar image showing a co-seismic surface rupture zone of up to 285 km in length, consistent with that identified in field surveys (Lin *et al*., 2009a). Red line indicates co-seismic surface repture zone. Red star indicates the epicenter of the Wenchuan earthquake. Image courtesy by the Geographical Survey Institute of Japan

Figure 7 Map showing the distribution of felt ground motions associated with the Wenchuan earthquake. Data from CSI (China Seismic Information Network)

3. Outline of Co-seismic Surface Rupture

3.1 Distribution of co-seismic surface rupture

Field investigations reveal that the M_s 8.0 Wenchuan earthquake of 12 May 2008 produced a 285-km-long surface rupture zone along the Longmen Shan Thrust Belt, eastern margin of the Tibetan Plateau, mainly along the pre-existing Yingxiu–Beichuan, Guanxian–Anxian, and Qingchuan faults, which are three of the main active faults within the thrust belt.These faults define a left-stepping en echelon pattern with~10 km clearance. Co-seismic surface ruptures concentrated within a zone of < 50 m in width (generally < 20 m), largely following the strike of pre-existing fault traces within the thrust belt.

Based on the geometry and distribution of deformation structures, the Wenchuan rupture zone can be divided into the northern, central, and southern segments. The northern segment, restricted to the fault trace of the Qingchuan Fault, extends for ~50 km, terminating at the town of Shazhou in the northeast, near the border between the Sichuan and Gansu provinces. The central segment, ~105 km in length, occurs along the northeastern segment of the Yingxiu–Beichuan Fault. The southern segment, ~130 km in length, branches into two parallel sub-rupture zones: one along the southwestern segment of the Yingxiu–Beichuan Fault between the towns of Beichuan and Yingxiu, terminating to the south of Yingxiu town, and another along the Guanxian–Anxian Fault (which forms the topographic boundary between the Longmen Shan Range and the Sichuan Basin), terminating to the south of Dujiangyan City near the epicentral area of the Wenchuan earthquake.

Field investigations demonstrate that (i) the Wenchuan earthquake occurred upon pre-existing active faults of the Longmen Shan Thrust Belt; (ii) the long rupture length and large thrusting slip resulted from compressive stress associated with eastward extrusion of the Tibet Plateau as it accommodates the ongoing penetration of the Indian Plate into the Eurasian Plate; and (iii) present-day shortening strain upon the eastern margin of the Tibetan Plateau is mostly released by seismic slip along thrust faults within the Longmen Shan Thrust Belt.

(Figure 8)

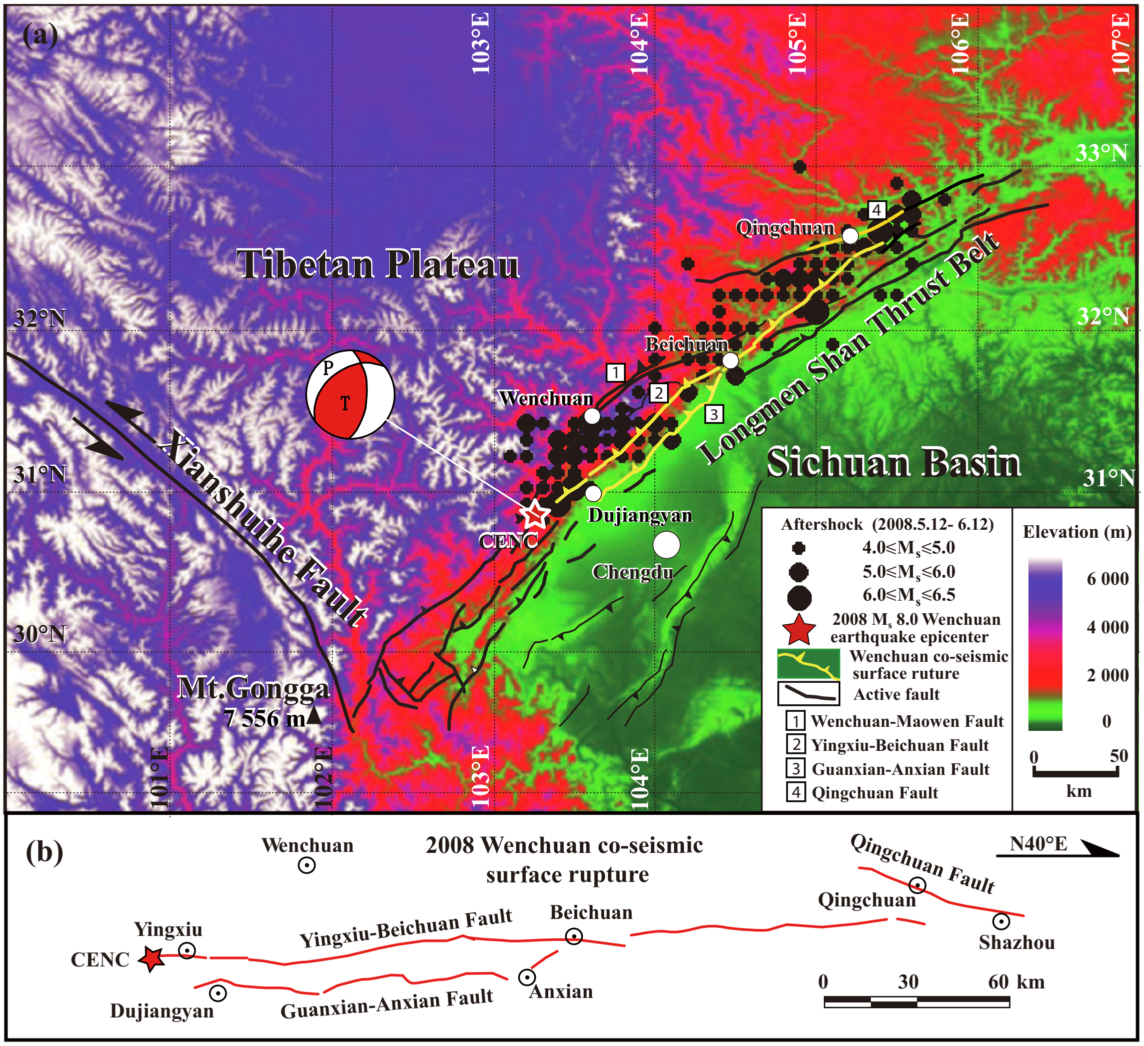

Figure 8 Index map showing the distribution of co-seismic surface ruptures associated with the 2008 Wenchuan earthquake and aftershocks. Co-seismic surface ruptures mainly occurred along pre-existing active faults within the Longmen Shan Thrust Belt, along which aftershocks over the month following the quake also concentrated

3.2 Slip distribution of co-seismic fault

Surface rupture associated with the Wenchuan earthquake is dominated by thrusting slip along the Longmen Shan Thrust Belt, accompanied by a minor component of right-lateral slip along the central and northern segments of the zone, and by a left-lateral component along the southern segment. Co-seismic displacements measured in the field are 0.5~6.5 m in the vertical (typically 1~3 m), accompanied by an average left-lateral component of < 2 m along the 50-km-long southernmost segment of the rupture zone and an average right-lateral component of <1 m along the 150-km-long central and northern segments. Field observations indicate a maximum amount of thrust slip of ~10 m, accompanied by 9 m of shortening across the rupture zone; this finding is consistent with seismic inversion results. The rupture length and maximum vertical displacement are the largest among all intracontinental thrust-type earthquakes reported to date.

(Figures 9~10)

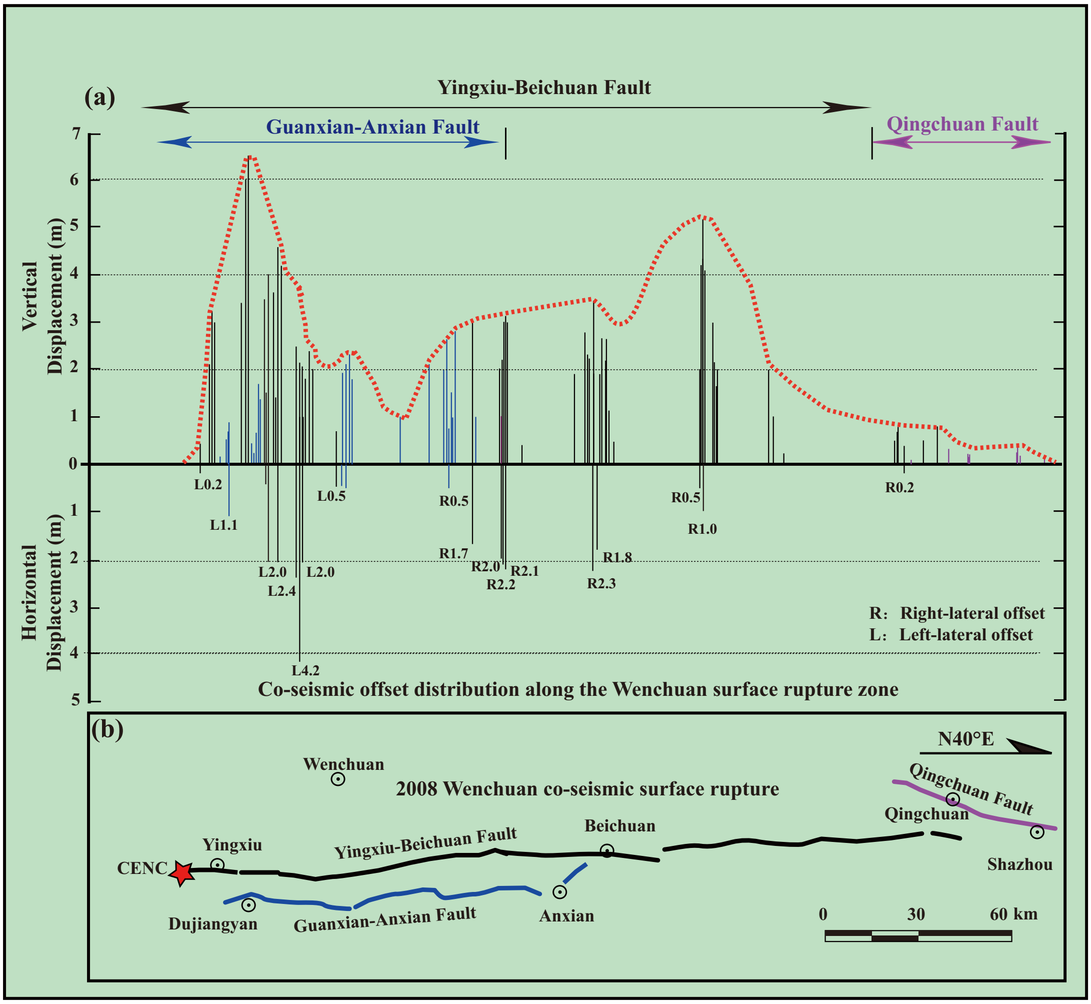

Figure 9 Distribution of co-seismic surface displacement along the 2008 Wenchuan rupture zone (modified from Lin *et al*., 2009a). Colors in (a) correspond to those in (b)

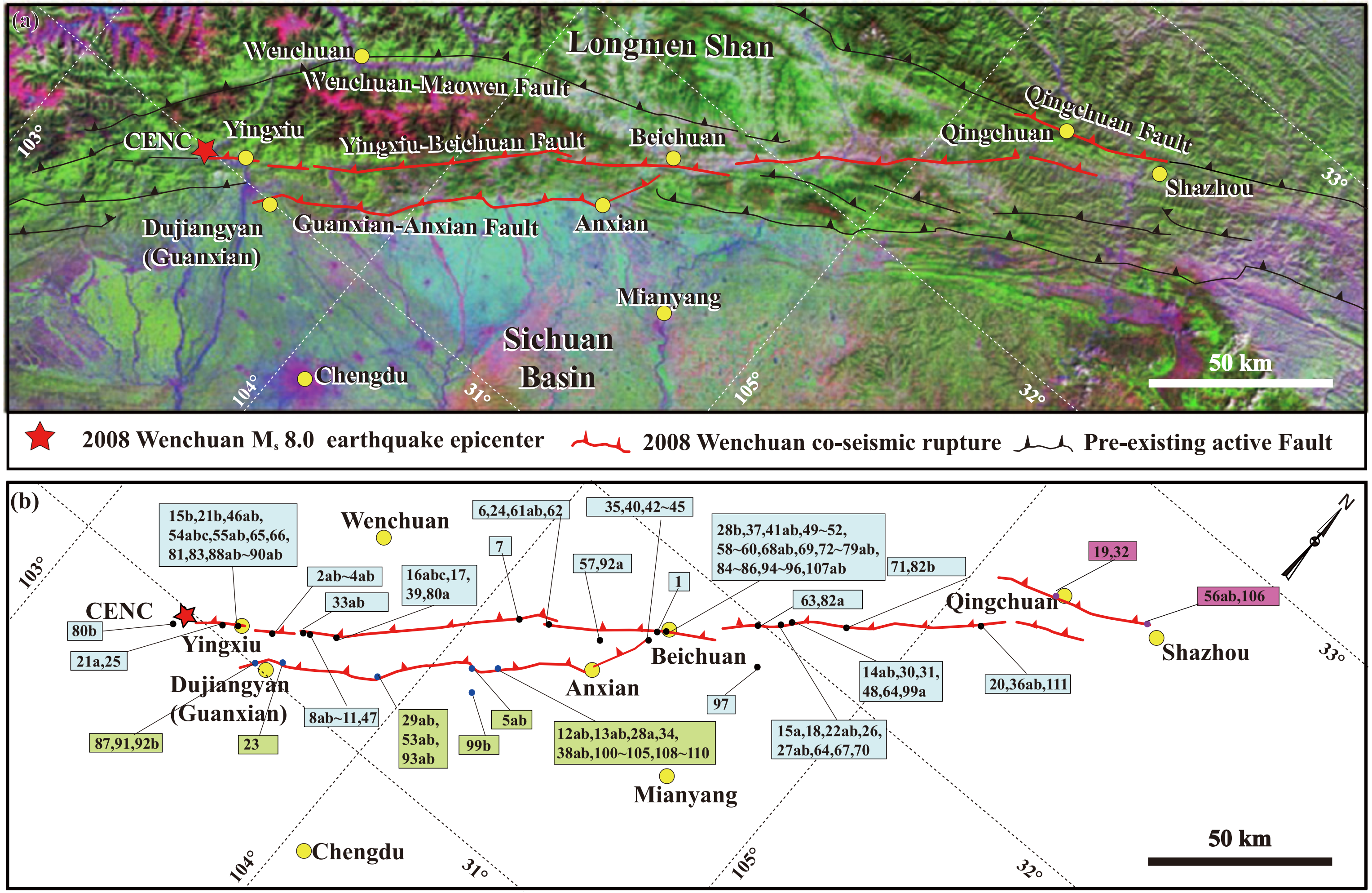

Figure 10 Landsat image (a) showing the topographic features and distribution of 2008 co-seismic surface ruptures, and index map (b) showing the locations of photographs presented in this atlas

4. Deformation Characteristics of Co-seismic Surface Rupture

Surface rupture zone associated with the Wenchuan earthquake is defined by distinct thrust faults, fault scarps, shortening structures (e.g., folds and mole track structures), and numerous extensional fractures. Co-seismic fault scarps are generally characterized by complex surface morphology, and thrusting and folding structures. The fault planes on which the main slip occurred were observed at several locations, striking N10°~50°E and dipping to the northwest at an average of ~30°. Fault planes observed within basement rocks generally dip at a high angle (>50°) and have a linear surface trace. Fold structures are characterized by flexure-slip folds and mole tracks, generally developed within alluvial deposits, river channels, and sealed road surfaces, and mainly restricted to within a <100-m-wide corridor (generally<50 m) about co-seismic thrusting fault scarps within the co-seismic surface rupture zone.

(Figures 11~48)

4.1 Co-seismic fault scarp

Figure 11 Co-seismic fault scarp cutting across a sealed road (vertical offset, 2.5 m). View to the north. Location: ~1km southeast of the Beichuan town

Figure 12 6.5-meter-high fault scarp formed on the lower terrace. (a) This site records the largest vertical offset along the entire co-seismic surface rupture zone. View to the south. (b) Vertical offset of a river channel, where a small waterfall subsequently formed. View to the northwest. Location: Shenxigou village

Figure 13 Five-meter-high co-seismic fault scarp formed within an alluvial fan. View to the north. Location: Yanyan village

Figure 14 Co-seismic fault scarp cutting across the bent road. (a) The road built across an alluvial fan was offset vertically by 4.8 m. View to the southeast. (b) Front face of the co-seismic fault scarp shown in (a). View to the northwest. Location: Yanyan village

Figure 15 Co-seismic fault scarp formed on the river channel and road. (a) Road across a terrace riser was offset vertically by 2.5 m. View to the northwest. (b) The lower terrace riser was offset vertically by 2~2.5 m. View to the northeast. Location: Jiulong town

Figure 16 Destroyed houses sited upon a co-seismic fault scarp (vertical offset, 3 m). View to the northwest. Location: Quanshui village

Figure 17 Fault scarp developed across a road (vertical offset, 2.5 m). View to the northwest. Location: Wulangmiao village

Figure 18 Co-seismic fault scarps developed upon a terrace riser (vertical offset, 4.6 m). (a) View to the northwest, (b) View to the southwest. Location: Bajiaomiao village, Hongkou town

Figure 19 Co-seismic fault scarps developed within basement rocks. (a) Fault scarp exposed in a river channel (vertical offset, 4~5 m). View to the souhwest. (b) Fault plane developed within basement rocks, along which seismic slip occurred. View to the southeast. Location: Bajiaomiao village, Hongkou town

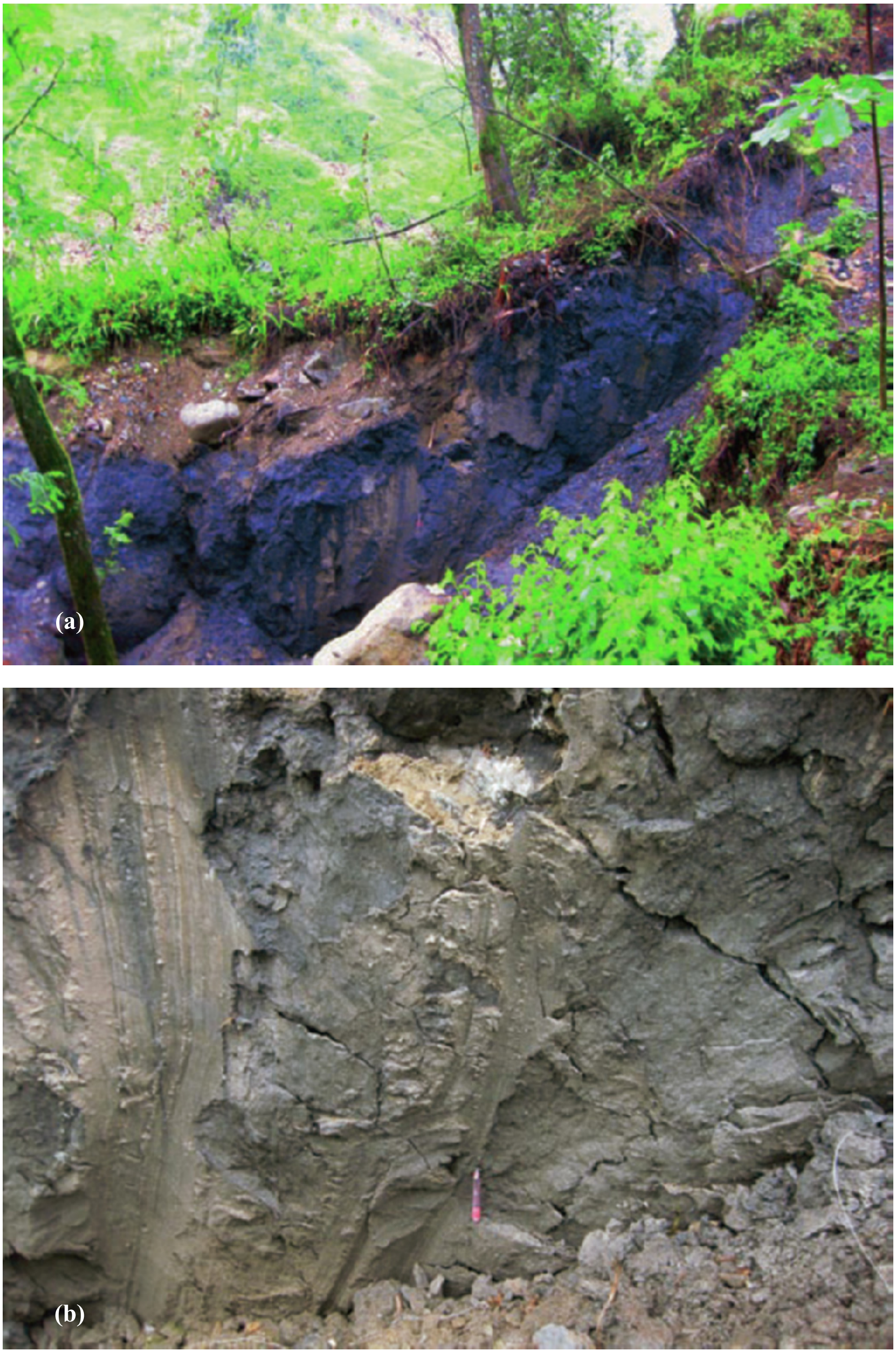

Figure 20 Slickensides upon a co-seismic fault plane developed within basement rock. (a) Fault scarp and fault plane. (b) Vertical striations indicate thrusting upon the fault plane. (a),(b) View to the northwest. Location: Bajiaomiao village, Hongkou town

Figure 21 Close-up view of the striations on the co-seismic fault plane. View to the northwest. Location:Bajiaomiao village,Hongkou town

Figure 22 Thrust fault scarp formed upon the lower terrace riser. (a) The terrace was offset vertically by 2 m (central-upper part of the photograph). Dip angle of the fault plane is ~30°. View to the southwest. (b) The road upon the river flat was offset vertically by 1 m with a right-lateral slip component of 1 m. View to the northwest. Location: Hanwang town

Figure 23 Displaced river channel and bank. (a) The bank was offset vertically by 2 m. View to the northeast. (b) Close-up view of the offset of river channel shown in (a). View to the northwest. Location: Hanwang town

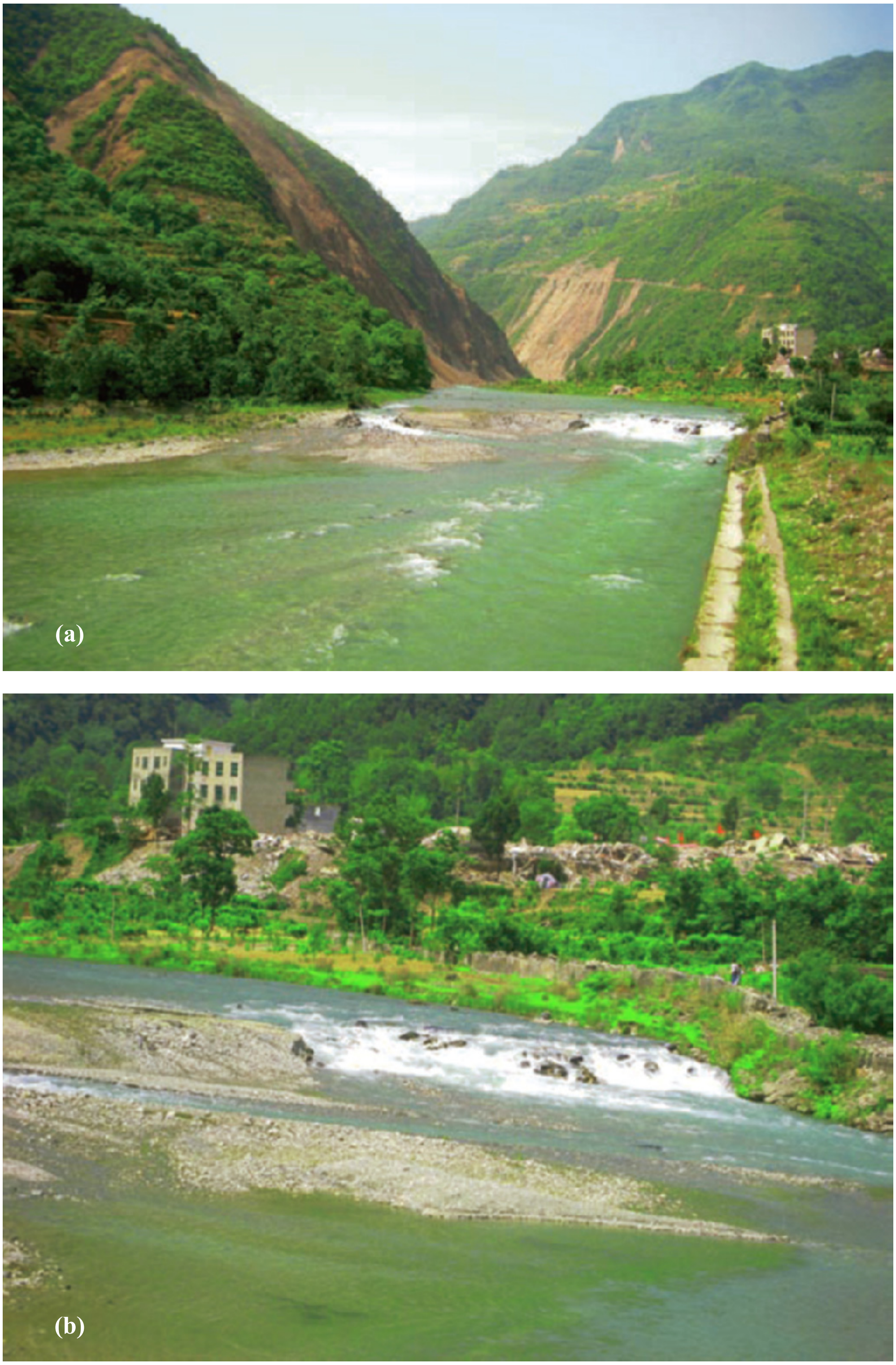

Figure 24 Displaced river channel and lower terrace riser (vertical offset, 1~1.5 m). (a) View to the northwest. (b) Close-up view of (a). View to the northeast. Location: Pingtong town

Figure 25 Displaced river channel (vertical offset, 0.5~1 m). (a) View to the southwest. (b) View to the north. Location: (a) South of the Pingtong town, (b) Yingxiu town

Figure 26 NW-trending fault scarp. (a) The fault scarp records 2.2~m vertical offset and 4.2 m sinistral offset (the distance between the two men standing in the left side of the photograph). View to the southwest. (b),(c) Southeast extension of the fault scarp shown in (a). The road was offset sinistrally by 1.0 m. (b) View to the northeast, (c) View to the southwest. Location: Xiaoyudong town

Figure 27 Trees along a co-seismic fault scarp are tilted and dying as a result of earthquake-related damage (photograph taken on 19 July 2008). View to the northwest. Location: Xiaoyudong town

Figure 28 Two-meter-high fault scarp formed upon the lower terrace riser. The road was offset dextrally by 1m. View to the northwest. Location: ~1km south of the Pingtong town

Figure 29 Displaced road (vertical offset, 0.3 m).Located at the northeastmost end of the co-seismic surface rupture zone. View to the northeast. Location: 1 km south of the Qingchuan town

Figure 30 The road was offset dextrally by 0.3 m. View to the southeast. Location: Guanzhuang town

Figure 31 Fault scarp formed on the road. (a) Displaced road at the southwestern end of the co-seismic surface rupture (vertical offset, 0.5 m). (b) Displaced road (vertical offset, 3.2 m). (a),(b) View to the northwest. Location: (a) 3 km south of the Yingxiu town, (b) Yingxiu town

Figure 32 In situ measurement of the amount of strike-slip offset along a co-seismic surface rupture. (a) Measurement of the dextral strike-slip offset along a man-made stone wall. (b) The stone wall was offset dextrally by ~1 m. (a),(b) View to the southeast. Location: ~1 km south of the Pingtong town

Figure 33 Extensional crack occurred on the mountain slope. View to the northeast. Location: ~10 km northwest of the Dujiangyan City

Figure 34 Co-seismic fault scarp formed on a mountain slope (vertical offset, ~3.0 m). View to the southwest. Location: Quanshui village

Figure 35 Five-meter-wide co-seismic surface rupture zone developed across a sealed road. View to the northeast. Location: 4 km south of the Yingxiu town

4.2 Co-seismic flexure-slip fold structure

Figure 36 Co-seismic flexure-slip fold structure formed on the lower terrace riser.It was offset vertically by 5.15 m. The path was offset dextrally by 1 m. The terrace riser was covered by many small-short woods in which mushrooms were farmed. View to the west. Location: ~1 km south of the Pingtong town

Figure 37 Co-seismic flexure-slip fold structure formed within a wheat field. (a) Front face of the fold structure. View to the northwest. (b) Southwest extension of the flexure-slip fold scarp shown in (a) Prior to the Wenchuan earthquake, the left- and right-hand sides of the structure formed a continuous horizontal surface. View to the northeast. Location: ~1 km south of the Pingtong town

Figure 38 Flexure-slip fold structure developed across a sealed road. It was horizontal prior to the earthquake and was offset vertically by 2 m. The buildings to the right of the road collapsed during the earthquake. (a),(b) View to the northwest. Location: (a) Hanwang town, (b) Beichuan town

Figure 39 Flexure-slip fold structure formed within the schoolyard of Bailu Middle School. (a) The schoolyard was offset vertically by ~2 m.View to the northeast. (b) Mole track structure developed in front of the flexure-slip fold structure. View to the northwest. Location: Bailu town

Figure 40 Flexure-slip fold structure developed within a wheat field. The buildings (right side of the photograph) on the fold scarp were tilted and damaged. View to the northwest. Location: Pingtong town

Figure 41 Flexure-slip fold structure developed within a river channel and lower terrace risers. The northwest side of the structure (upper right) was uplifted by 1~2 m, where the buildings (lower right) were collapsed. View to the south. Location: Pingtong town

Figure 42 Folded road surface. The buildings were damaged. View to the northeast. Location: Qingchuan town

Figure 43 Angular-type mole track structures developed within a section of sealed road. (a) View to the northwest. (b) Close-up view of the mole track structure shown in (a). View to the northeast. Location: Gaoyuan village

Figure 44 Mole track structure developed upon a section of sealed ground surface. View to the southwest. Location: Hanwang town

Figure 45 Broken and shortened section of sealed road. View to the southwest. Location: Leigu town

Figure 46 Mole track structure developed upon a section of sealed ground surface. (a),(b) View to the north. Location: (a) Guanzhuang town, (b) Guanzhuang substation

Figure 47 Suspension bridge bent and damaged by strong ground motions. View to the southwest. Location: Beichuan town

Figure 48 Deformation of the railway line led to overturning of the train. (a) View to the east, (b) View to the west. Location: Hanwang town

5. Relationship between Surface Rupture and Pre-existing Active Faults

Field observations indicate that the co-seismic surface rupture of the Wenchuan earthquake occurred along pre-existing active faults of the Longmen Shan Thrust Belt along a distance of ~285 km. Co-seismic surface ruptures occurred on pre-existing active fault scarps that record the accumulated co-seismic vertical offsets associated with multiple seismic events. The aftershocks of magnitude > 4 that occurred during the month following the Wenchuan earthquake were concentrated along a ~300 km section of the co-seismic surface rupture zone. Analyses of InSar images reveal that surface deformation is restricted to a 285-km-long zone, coincident with the co-seismic surface rupture zone identified in the field. The results of field investigations, in combination with seismic and geodesic data, indicate that the distribution of co-seismic surface ruptures was mainly constrained by the orientation of pre-existing thrust faults of the Longmen Shan Thrust Belt.

(Figures 49~56)

Figure 49 Co-seismic fault scarp developed within a river channel and terrace risers along a pre-existing active fault scarp. Vertical offset associated with the 2008 Wenchuan earthquake was about 2~3 m. The total height of the fault scarp on the terrace risers is up to 5~10 m. View to the southwest. Location: Xiaoyudong town

Figure 50 Co-seismic fault scarp (fresh slope in the central-upper part of the photograph) duplicated upon a pre-existing active fault scarp. The total scarp height is >5 m, and the co-seismic vertical offset associated with the 2008 Wenchuan earthquake at this site was 2~3 m. View to the northwest. Location: Pingshang village

Figure 51 Pre-existing fault scarp in the town of Beichuan. (a) Ten-meter-high pre-existing active fault scarp developed along the boundary between a mountain range and basin. View to the northwest. (b) Close-up view of photograph (a). A 2~3-meter-high co-seismic fault scarp was developed in the lower part (indicated by the shovel) of the pre-existing fault scarp. (a),(b) View to the northwest. Location: Beichuan town

Figure 52 Co-seismic fault scarp duplicated on a pre-existing active fault scarp.The pre-existing scarp indicated by the man-made stone wall (centre-right part of the photograph). The total height of the fault scarp is 5.4 m, including a co-seismic vertical offset of 2.8 m. View to the southwest. Location: Leigu town

Figure 53 Co-seismic fault scarp developed within a corn field (SW extension of the fault scarp shown in Figure 52). View to the southwest. Location: Leigu town

Figure 54 Co-seismic fault scarp duplicated upon a pre-existing active fault scarp. The pre-existing scarp was indicated by the man-made stone wall (oriented horizontally within the central part of the photograph; a man is standing in front of the wall). View to the northwest. Location: Leigu town

Figure 55 Collapse of the pre-existing active fault scarp.It was indicated by the collapse of a man-made stone wall (beneath the large tree on the left-hand side of the photograph). A co-seismic surface rupture developed in the lower part of the scarp. The total height of the fault scarp is ~6 m, which includes 2~3 m of vertical co-seismic offset. View to the northwest. Location: Pingshang village

Figure 56 Co-seismic fault scarp duplicated upon a pre-existing active fault scarp and damaged constructions.(a) A co-seismic surface rupture developed in the lower part of the scarp upon the sealed road. The total height of the fault scarp is ~7 m, which includes 3.2 m of vertical co-seismic offset. View to the northwest.(b) Full view of the trench across the fault scarp shown in photograph (a). All constructions located in the both sides of the co-seismic fault scarp were destroyed. View to the southeast. Location: Yingxiu town

6. Relationship between Surface Rupture and Damage to Infrastructure

Many densely populated cities located upon and close to surface ruptures associated with the Wenchuan earthquake were strongly damaged or even decimated during the event. Field investigations reveal that two of the severely damaged towns (Beichuan town and Yingxiu town) located on a co-seismic surface rupture zone developed along the Yingxiu-Beichuan Fault. Most of the buildings sited on or across co-seismic surface ruptures was seriously damaged or destroyed, whereas other buildings located just several meters from seismic ruptures were only slightly damaged. A closely related group of phenomena that caused great damage to structures following the earthquake comprises landslides, rock falls, and mud-rock flows, all of which were associated with pre-existing active faults on which co-seismic ruptures developed.

(Figures 57~66)

Figure 57 Destroyed houses located across a co-seismic fault scarp. View to the north. Location: Bajiaomiao village, Hongkou town

Figure 58 Destroyed constructions located across a co-seismic fault scarp. View to the northwest. Location: Pingtong town

Figure 59 Damaged and destroyed constructions along a co-seismic fault scarp that passes through the bridge in the central part of the photograph. The right-hand side of the scarp was uplifted by ~1~2 m. View to the south. Location: Beichuan town

Figure 60 Destroyed buildings located along a co-seismic fault scarp. The left-hand side of the scarp was uplifted by ~1~2 m. View to the northwest. Location: Beichuan town

Figure 61 Damaged and destroyed roads and buildings along a co-seismic fault scarp. View to the northwest. Location: Beichuan town

Figure 62 The first floor of a student dormitory at Beichuan Vocational School was crushed. A co-seismic surface rupture passes beneath the central part of the building. The area to the left of the scarp was uplifted by ~0.5 m. View to the northwest. Location: Northern Beichuan town

Figure 63 Co-seismic flexure-slip fold scarp formed within the schoolyard between two buildings at Bailu Middle School. (a) The schoolyard was offset vertically by ~2 m. Note that the two buildings are largely undamaged. View to the northeast. (b) The schoolyard that includes the two undamaged buildings will be preserved as an earthquake museum. The buildings are referred to as “The strongest buildings against the force of the earthquake”. View to the northwest. Location: Bailu Middle School

Figure 64 Damaged Yingxiu town.(a) Co-seismic surface rupture developed along a pre-existing active fault scarp that marks the boundary between a mountain range and adjacent basin. The flat part of the ridge (right-central part of the photograph) is the Yingxiu substation. (b) Close-up view of the left part of the photograph (a). The collapsed buildings of the Yingxiu Middle School.(c) Close-up view of the right part of the photograph (a). The co-seismic surface rupture occurred along the pre-existing fault scarp (central-upper part of the photograph). (a),(b),(c) View to the northwest. Location: Yingxiu town

Figure 65 Damaged Yingxiu substation and co-seismic surface rupture. (a) Co-seismic surface rupture developed along a pre-existing fault scarp (marked by the man-made stone wall). View to the northwest. (b) The Yingxiu substation was destroyed and many telegraph poles were broken during the 2008 Wenchuan earthquake. View to the south. Location: Yingxiu town

Figure 66 Damage arising from the 2008 Wenchuan earthquake at the northeastern end of the co-seismic surface rupture zone. (a) Collapsed constructions within the town of Shazhou. (b) The first floor of building was crushed. (a),(b) View to the northwest. Location: Shazhou town, Qingchuan County

7. Co-seismic Landsliding and Liquefaction

Landsliding and liquefaction induced by the 2008 Wenchuan earthquake caused extensive damage and casualties over a wide area along pre-existing active faults within the Longmen Shan Thrust Belt. The results of fieldwork and analyses of Landsat images demonstrate that earthquake-induced landslides were mainly restricted to a corridor of < 18 km in width about the co-seismic surface rupture zone, along pre-existing active faults. Numerous sand boils formed over wide areas along and near co-seismic surface ruptures in association with earthquake-induced liquefaction, generally within river channels and upon river flats, where vents are generally aligned along the surface rupture zone. Some of the sand boils are similar in geometry to volcanic calderas.

(Figures 67~81)

Figure 67 Large earthquake-induced landslides dammed a valley and traffic fortress to the intermountain areas. View to the southwest. Location: Laohuzui, Anxian County

Figure 68 Earthquake-induced landslides and destroyed constructions in the town of Beichuan. View to the northwest. Location: Beichuan town

Figure 69 Buildings damaged by earthquake-induced landslides. View to the east. Location: Beichuan town

Figure 70 Buildings struck by large rocks associated with an earthquake-induced landslide. (a),(b) View to the south. Location: Beichuan town

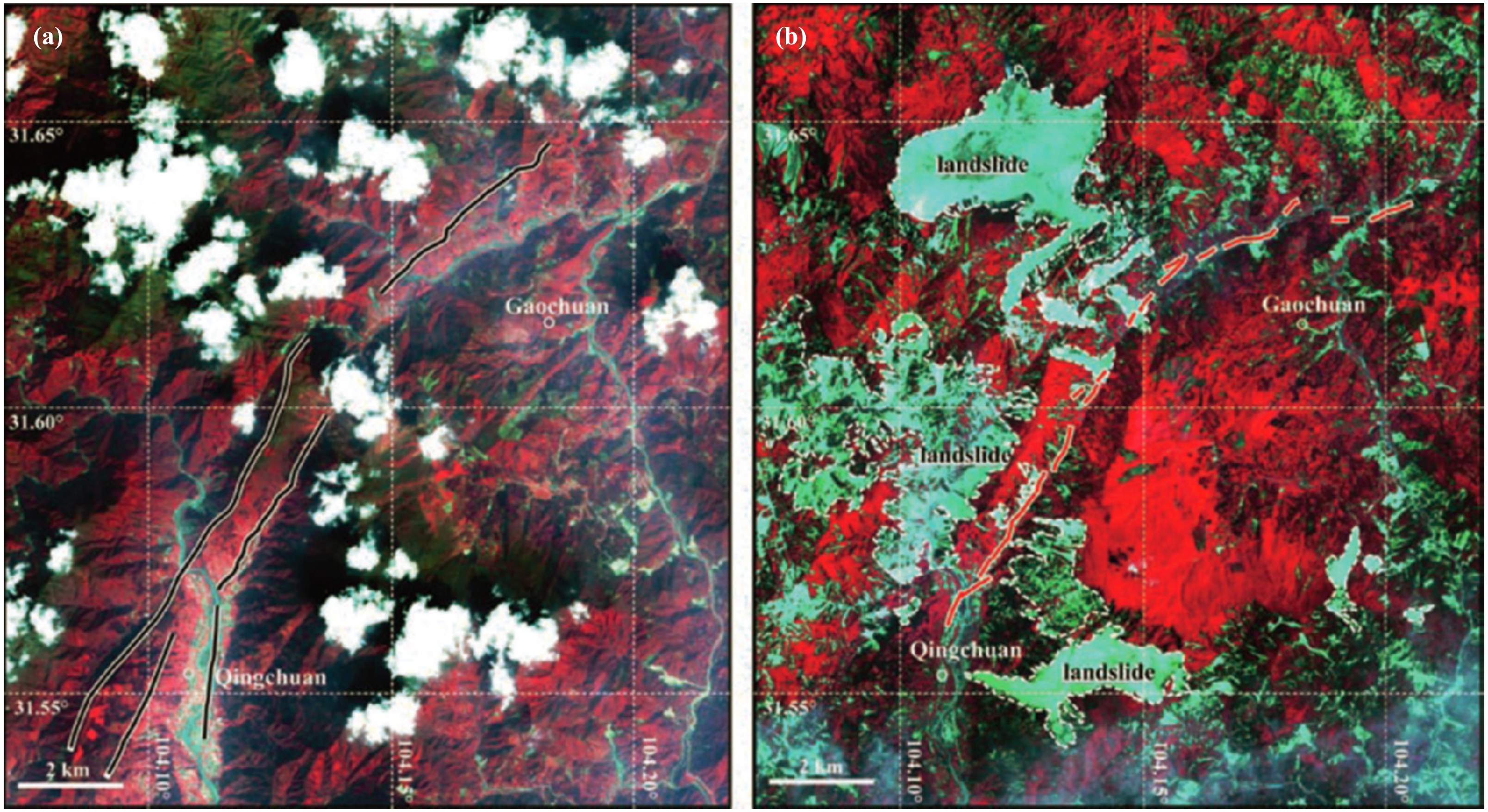

Figure 71 ALOS image of the Gaochuan region. (a) ALOS AVNIR 2 image acquired on 31 March 2007, before the 2008 Wenchuan earthquake. White–black lines indicate pre-existing active faults. (b) ALOS image acquired on 4 June 2008, showing Wenchuan earthquake-induced landslides (blue areas) and co-seismic surface ruptures (red lines) that developed along the pre-existing active faults

Figure 72 Dam developed from material supplied by an earthquake-induced landslide. View to the southwest. Location: 2~3 km northwest of the Gaochuan village

Figure 73 Temporary lake that formed behind an earthquake-induced landslide. The landslide buried an entire village of more than 200 people. View to the southwest. Location: Guixi village

Figure 74 Small-scale landsliding witnessed during field investigations. View to the northwest. Location: Pingtong town

Figure 75 Truck struck by a large rock displaced during an earthquake-induced landslide (photograph taken on 21 July 2008). View to the southeast. Location: Yingxiu town

Figure 76 A monument rock to the 5.12 Wenchuan earthquake. The large rock shown in Figure 75 is now preserved as a monument to the Wenchuan earthquake (photograph taken on 17 October 2008). View to the northwest. Location: Yingxiu town

Figure 77 Sand boils formed by liquefaction developed upon a river flat, with a shape resembling that of a volcanic caldera. View to the northwest Location: ~1 km south of the Pingtong town

Figure 78 Liquefaction and extensional cracks developed upon a river flat. (a) view to the south,(b) View to the southeast. Location: Beichuan town

Figure 79 Sand boils developed in association with liquefaction that occurred within an extensional crack. Location: Beichuan town

Figure 80 Sand boils developed in association with liquefaction that occurred along an co-seismic surface crack. Location : ~1 km south of the Pingtong town

Figure 81 Sand flow arising from liquefaction developed upon a river flat. View to the north. Location: Southern Nanba town

8. Earthquake Disaster

The lack of earthquake-proofing in building construction has been cited as one of the main reasons for the widespread destruction in urban areas. Field investigations reveal that not only were buildings constructed on or across co-seismic surface ruptures seriously damaged or destroyed, but that wooden or reinforced-concrete structures with or without earthquake-proofing were seriously damaged or destroyed throughout a wide area surrounding the co-seismic surface rupture zone.

(Figures 82~107)

Figure 82 Views of the town of Beichuan following the Wenchuan earthquake (photograph taken on 19 May 2008, 1 week after the earthquake). View to the northwest. Location: Beichuan town

Figure 83 Secondary damage of the town of Beichuan caused by the flood after earthquake (photograph taken on 12 October 2008, after the flood of September 24). View to the northwest. Location: Beichuan town

Figure 84 Damage to buildings and a Chinese gate. (a) Building damaged (but not collapsed) by large blocks that formed part of an earthquake-induced landslide (photograph taken on 19 May 2008). (b) Collapsed Chinese gate and adjacent buildings damaged by floodwaters following the Wenchuan earthquake (photograph taken on 24 July 2008). (a),(b) View to the northwest. Location: The town of Beichuan

Figure 85 Damaged new downtown of Beichuan. (a) View of the devastated new town of Beichuan (photograph taken on 19 May 2008, 1 week after the Wenchuan earthquake). (b) Close-up view of collapsed buildings. (a),(b) View to the south. Location: Beichuan town

Figure 86 Secondary damage to the town of Beichuan arising from flooding following the Wenchuan earthquake (photographs taken on 24 July 2008). (a) The town of Beichuan is largely buried by driftwood deposited by the floodwaters . View to the northwest. (b) Buildings destroyed by the flood. View to the west. Location: Beichuan town

Figure 87 The town of Beichuan was largely buried by driftwood and sand-clay driftwood flow caused by the flood. (a),(b) photographs taken on 24 July 2008. View to the northwest. Location: Beichuan town

Figure 88 Buildings destroyed by the flood (photograph taken on 24 July 2008). The traces of floodwaters remained on the walls of damaged buildings. (a),(b) View to the northwest. Location: Beichuan town

Figure 89 Destroyed Beichuan Middle School. (a) School gate. View to the west. (b) The collapsed school buildings. View to the northwest. Location: Beichuan town

Figure 90 Constructions submerged within a temporary lake formed behind an earthquake-induced landslide. (a) photograph taken on 20 July 2008, (b) photograph taken on 21 July 2008. (a)View to the northwest, (b) View to the southwest. Location: (a) Zhoujiawan village, north of Donglinshi, (b) ~10 km southwest the Xuankou town

Figure 91 Collapsed road. View to the southeast. Location: 1 km south of the Yingxiu town

Figure 92 Collapsed bridge. (a),(b) View to the northwest. Location: (a) Chenjiaba village, (b) Nanba town

Figure 93 Crushed second floor of a building under construction. View to the southeast. Location: Yingxiu town

Figure 94 Crushed first floor of the Beichuan Hotel. View to the south. Location: Beichuan town

Figure 95 Buildings damaged by an earthquake-induced landslide. View to the southeast. Location: Beichuan town

Figure 96 The first floors of many buildings in the town of Beichuan were crushed during the Wenchuan earthquake. View to the south. Location: Beichuan town

Figure 97 Collapsed reinforced-concrete buildings. View to the northwest. Location: Dujiangyan City

Figure 98 Destruction of the Yingxiu substation. (a) Many telegraph poles were broken. View to the northwest. (b) Reinforced-concrete telegraph poles were broken. View to the southeast. Location: Yingxiu town

Figure 99 Collapsed buildings at Yingxiu Middle School. View to the northwest. Location: Yingxiu town

Figure 100 Collapsed buildings at the Yingxiu town. (a),(b) View to the northeast. Location: Yingxiu town

Figure 101 Collapsed house (Qinyanlou), located on the edge of Dujiangyan Dam. View to the west. Location: Dunjiangyan Dam

Figure 102 Collapsed wooden houses. (a) View to the southeast. (b) View to the northwest. Location: (a) Laohuzui, Anxian County, (b) 2 km north of Dujiangyan City

Figure 103 Damage to the Sino–French Bridge at Bailu Middle School. (a) View to the northeast, (b) View to the northwest. Location: Bailu town

Figure 104 All of the buildings along this street in the town of Beichuan were damaged or collapsed. View to the south.
Location: Beichuan town

Figure 105 Damage to a river bank and bridge. View to the northeast. Location: Beichuan town

Figure 106 Collapsed buildings in the town of Beichuan. View to the southwest. Location: Beichuan town

Figure 107 The tower on a building was broken during the earthquake and slid along the roof surface. View to the northeast. Location: Jiangyou City

9. Relief Operations

Immediately following the Wenchuan earthquake, rescue-relief troops dispatched by the Chinese Government and numerous domestic and international volunteers arrived at devastated areas, seeking to quickly locate and rescue survivors under dangerous conditions before turning their attention to preventing outbreaks of disease and rebuilding lives in the days and weeks that followed.

(Figures 108~121)

Figure 108 Volunteer nurses leaving for the devastated area. Location: Chengdu International Airport

Figure 109 Searching for survivors within the debris of collapsed buildings. Location: (a) Pingtong town, (b) Mianzhu City

Figure 110 Relief operations were mounted under dangerous conditions. Location: Hanwang town

Figure 111 Rescuing the injured from an area hit by a landslide. Location: Hanwang town

Figure 112 Administering first aid to the injured at a river flat. Location: Hanwang town

Figure 113 Administering first aid to the injured. Location: Hanwang town

Figure 114 An injured rescue team member. Location: Hanwang town

Figure 115 Rescue corps helping the earthquake victims to run away from a devastated area. Location: Hanwang town

Figure 116 Rescue corps cutting away the debris of collapsed buildings to reach survivors (a), (b). Location: Shazhou town

Figure 117 Plague-protected rescue. (a) Plague-protected rescue corps working in devastated areas. (b) Disinfecting collapsed buildings. Location: Beichuan town

Figure 118 Earthquake victim running away from a devastated area. Location: Hanwang town

Figure 119 Earthquake victims mourning their losses. Location: Hanwang town

Figure 120 Babies awaiting to be reunited with missing mothers. Location: Hanwang town

Figure 121 Hope for the future: volunteers (university students) teaching pupils in a tent after the Wenchuan earthquake.
Location: Guanzhuang town

References

[1] China Earthquake Networks Center (2008) Rupture Process of the 2008 M_s 8.0 Wenchuan Earthquake (2008汶川8.0级大地震地表破裂过程). http://www.cenc.ac.cn. Accessed 15 May 2008

[2] China Earthquake Information Networks Center (2008) Speuial lssue of the 2008 M_s 8.0 Wenchuan Earthquake (2008汶川8.0级大地震专辑). http://www.csi.ac.cn. Accessed 12 May 2008

[3] Geographical Survey Institute (2008) Analytic Results of PALSAR Data for Sichuan Earthquake. http://www.gsi.go.jp. Accessed 15 May 2008

[4] Harvard University (2008) Global CMT Catalog, 200805120628A Eastern Sichuan, China. http://www.globalcmt.org. Accessed 12 May 2008

[5] Lin A, Jia D, Ren Z, et al (2008) Reports on the coseismic surface rupture and related disasters associated with the M_w 7.9 Wenchuan earthquake, China (2008年M_W 7.9中国汶川地震の地表地震断層と被害状況の速報). Journal of Geography, 117(3), 593-598

[6] Lin A, Ren Z, Jia D, et al (2009a) Co-seismic thrusting rupture and slip distribution produced by the 2008 M_w 7.9 Wenchuan earthquake, China. Tectonophysics, 47(3-4), 203-215

[7] Nishimura N, Yagi Y (2008) Preliminary results of coseismic-slip for the 2008 M_w 7.9 Wenchuan Earthquake, Southwest China, 2008 (2008年5月12日中国四川省で発した巨大地震) http://www.geol.tsukuba.ac.jp. Accessed 12 May 2008

[8] Ren Z, Lin A (2009) Co-seismic landslides produced by the 2008 M_w 7.9 Wenchuan earthquake, China, as revealed by ALOS imagery data. International Journal of Remote

Sensing, in press
[9] Zhang P, Shen, Z, Wang M, et al (2004) Continuous deformation of the Tibetan Plateau from global positioning system data. Geology, 32(9), 809-812
[10] United States Geological Survey (2008) Magnitude 7.9 Eastern Sichuan, China. http://earthquake.usgs.gov. Accessed 12 May 2008

Index of Figures