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Preface

A special issue on the great 12 May 2008 Wenchuan earthquake (M_w7.9): Observations and unanswered questions

1. Introduction

The 12 May 2008 Wenchuan earthquake (M_w 7.9) ruptured the active Longmen Shan thrust belt bounding the eastern margin of the Tibetan plateau against the Sichuan basin (Fig. 1) (Burchfiel et al., 2008). Initial observations of this devastating earthquake were reported in several short papers focusing on coseismic slip and earthquake-fault geometry (e.g., Wang et al., 2008; Xu et al., 2009; Lin et al., 2009; Liu-Zeng et al., 2009; Hubbard and Shaw, 2009; Shen et al., 2009; Feng et al., 2010). Subsequent work has addressed the questions of whether reservoir had triggered the earthquake (Ge et al., 2009) and if a weak middle and lower crust in eastern Tibet had controlled the location of the earthquake fault zone (Xu et al., 2010a; Zhang et al., 2010a). The early studies have established some of the basic facts about the Wenchuan earthquake. First, the main shock ruptured two northwest-dipping faults in the eastern part of the Longmen Shan thrust belt: the sub-parallel Beichuan–Yingxiu fault (~230 km) in the northwest and the Pengguan fault (~110 km) in the southeast (Fig. 2). Second, coseismic slip was accommodated dominantly by thrust motion on the Pengguan fault and by mixed right-slip and thrust motion on the Beichuan–Yingxiu fault. Specifically, coseismic slip on the Beichuan–Yingxiu fault changes systematically northeastward, from dominant thrust motion on shallow-dipping rupture planes to nearly pure right-slip motion along fault strike. Third, the Longmen Shan thrust belt lies along a crustal-scale boundary between the younger and possibly weaker Triassic Songpan–Ganze terrane in the northwest from the much older and thus stronger South China block in the southeast.

The current issue collects a total of 22 papers that expand greatly on the early reports of the Wenchuan earthquake. The volume covers the following six subjects: (1) coseismic slip, (2) evolution of static Coulomb stresses induced by the Wenchuan earthquake and recent seismicity in eastern Tibet, (3) recurrence times of late Quaternary seismicity, (4) tectonic setting and structural framework of the Longmen Shan thrust belt that hosts the Wenchuan earthquake fault, (5) lithospheric structure of the eastern Tibetan plateau, and (6) interplay between exhumation and tectonics across the Longmen Shan thrust belt at various time scales. Below I summarize the main points of the papers presented in this issue and outline some of the outstanding issues with regard to the Wenchuan earthquake and the tectonic evolution of the eastern Tibetan plateau.

2. Coseismic slip

Seven papers in this issue deal with coseismic slip of the Wenchuan earthquake investigated via surface observations, inversion of geodetic data and modeling of teleseismic data. The paper by Wang et al. (2010a — this issue) reports the results of their field surveys of the earthquake fault zones via excavation of several trenches. This approach allows them to better determine the earthquake-induced surface-fault geometry and chronologic relationships between structures and morphologic units offset by earthquake faults. Better determination of fault geometry in turn permitted the authors to more accurately convert the vertical scarp heights to coseismic horizontal shortening across the fault. Similar work was also pursued by Lin et al. (2010a — this issue) but with a wider coverage. Their work was built upon the early work of Lin et al. (2009) that was focused only on the vertical and horizontal coseismic slip without detailed observations on fault geometry. Similar to the work of Wang et al. (2010a — this issue), Lin et al. (2010a — this issue) also provide a systematic estimate of the coseismic shortening across the earthquake rupture zones. In addition, these authors have shown an array of impressive geomorphologic expressions of coseismic deformation along the Beichuan–Yingxiu fault. A field study employing detailed morphologic surveys was carried out by Li et al. (2010a — this issue) on the 70-km long northernmost segment of the Beichuan–Yingxiu fault. This segment of the rupture zone exhibits scarps that are 1–6 m high with folding and tension cracks along the scarp crest. The maximum measured vertical and right-slip components are 9 and 3 m and the fault dip angles vary from 54 to 84°.

Coseismic deformation associated with the Wenchuan earthquake was also inverted using ALOS and PALSAR images by Hashimoto et al. (2010 — this issue). Their analysis provides a more complete coverage of the coseismic deformation field across a wider range of the rupture zone and its adjacent regions. This work complements well the field observations on coseismic slip. The coseismic slip and rupture–surface geometry of the Wenchuan earthquake were also modeled using teleseismic data by Nakamura et al. (2010 — this issue) and Wang et al. (2010b — this issue). Nakamura et al. consider the source fault (i.e., the Beichuan-Yingxiu fault) to consist of two segments: a low-angle thrust segment in the southwest and a high-angle strike-slip fault segment in the northeast and that rupture had transferred from the thrust to strike-slip fault during the main shock. They pointed out that a high-angle rather low-angle strike-slip fault in the northeastern rupture zone would create the best fit of the teleseismic data. This result places additional constraints on the geometry of the Beichuan–Yingxiu fault at depth. Wang et al. (2010b — this issue) reviewed the currently available source models for the rupture process of the Wenchuan earthquake from teleseismic data. They emphasized that an accurate fault-slip model and a more realistic dislocation theory are essential in modeling coseismic deformation. These authors further suggest that joint inversion of GPS and seismic waveform data in conjunction with the use of a spherical dislocation theory yield the

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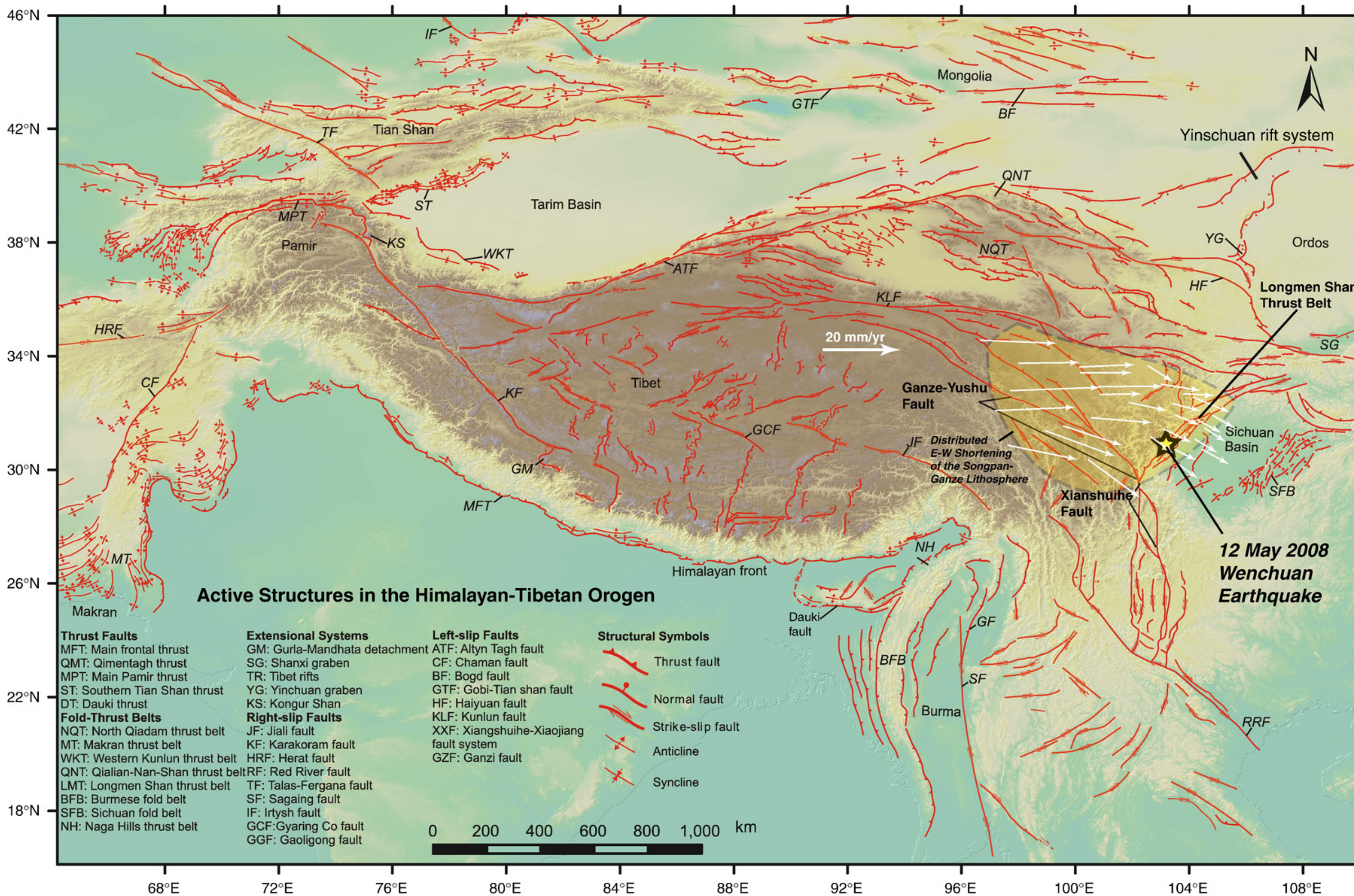

Fig. 1. Active tectonic map of the Indo-Asian collision zone modified from Taylor and Yin (2009) and location of the Wenchuan earthquake. White arrows are GPS velocity measurements relative to fixed Eurasia from Gan et al. (2007). The shaded area is interpreted to experience active distributed east-west shortening in a pure-shear manner over the whole Songpan–Ganze lithosphere. This is in contrast to simple-shear deformation (i.e., continental subduction) across the southern margin of the Tibetan plateau in the Himalayas.

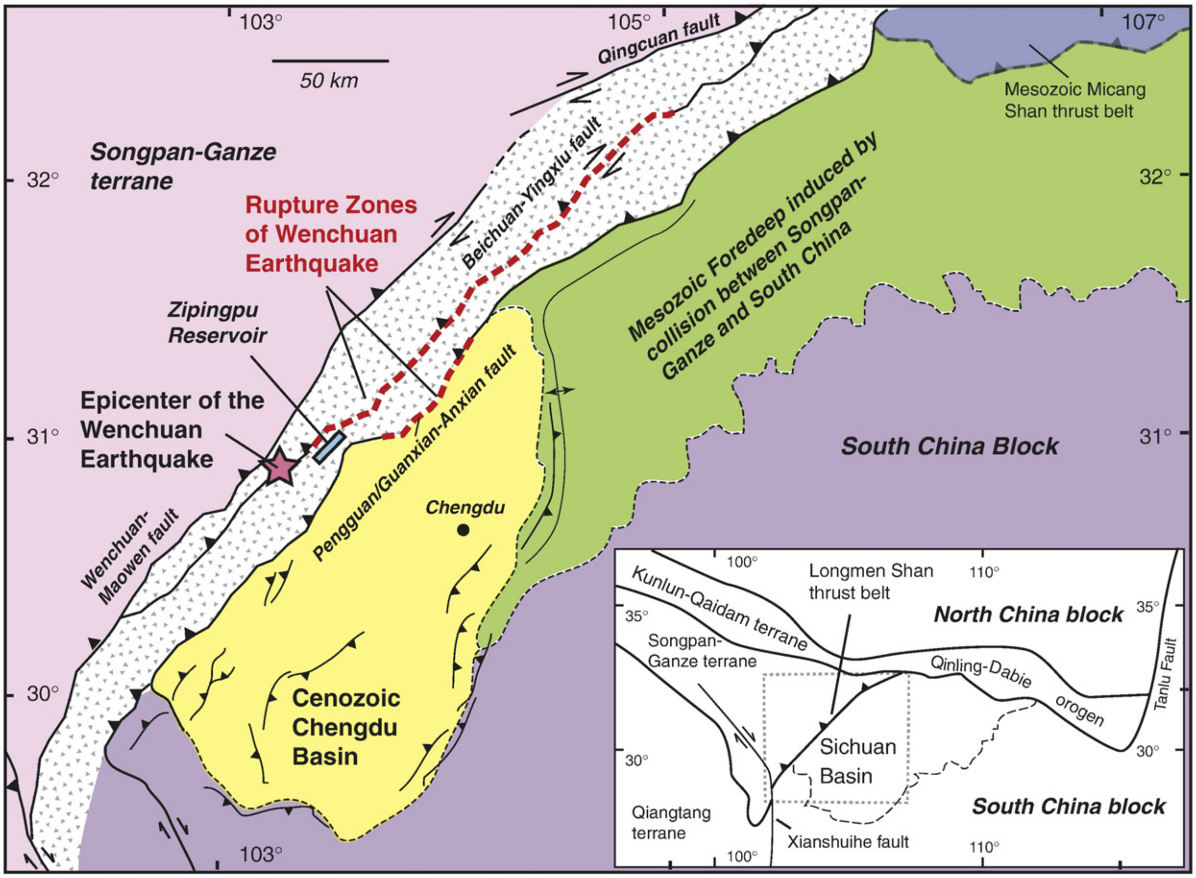

Fig. 2. A simplified tectonic map of the Longmen Shan thrust belt modified from Jia et al. (2006).

best fit and thus most plausible source model for the Wenchuan earthquake.

Coseismic deformation related to the Wenchuan earthquake was investigated by determination of spatial distribution of aftershocks by An et al. (2010 — this issue). They show that aftershocks were not confined along a simple northwest-dipping thrust zone but instead concentrated in the hanging wall of the Beichuan–Yingxiu thrust, a conclusion consistent with early report by Xu et al. (2009). In detail, An and his coworkers show that the aftershocks define two zones dipping to the southwest and northwest, respectively. This observation led them to suggest that the Wenchuan earthquake may have been initiated at the intersection of the two fault segments with different orientations. An et al. (2010 — this issue) also note a correlation between clustering of aftershocks and the location of the Zipingpu Reservoir near the epicenter of the Wenchuan earthquake (Fig. 2). This observation lends support for the controversial proposal that loading of the reservoir and fluid infiltration may have hastened the Great Wenchuan earthquake (Ge et al., 2009). Finally, An et al. (2010 — this issue) report that all the aftershocks are located no deeper than 20 km, which places a bound for the depth of the seismogenic zone in eastern Tibet.

3. Evolution of Coulomb stress on major active faults in Eastern Tibet

Three papers discuss the evolution of Coulomb failure stresses in the eastern Tibetan plateau as induced by historical earthquakes including the recent Wenchuan earthquake. The paper by Wan and Shen (2010 — this issue) explores the consequence of the Wenchuan earthquake on changes in static Coulomb stresses on major faults in eastern Tibet. Utilizing the estimated coseismic-slip distribution on the main Wenchuan earthquake fault as the driving source (Shen et al., 2009), Wn and Shen show that the Coulomb failure stress has increased by 1.6×10^4–1.8×10^4 Pa at the southwestern and northeastern ends of the Longmen Shan thrust belt, by 1.4×10^4 Pa along the southernmost Xianshuihe fault, and by 1.3×10^4 Pa along the southeastern Kunlun fault. Their work predicts that the Wenchuan earthquake may have advanced the recurring time on the Xianshuihe fault. Note that the Xianshuihe fault is linked to the Yushu–Ganze fault in eastern Tibet (e.g., Spurlin et al., 2005; Taylor and Yin, 2009) (Fig. 1), which had generated the 14 April 2010 Yushu earthquake (M_w 6.9) in southeastern Qinghai Province of western China. Another study on the evolution of Coulomb failure stress is presented by Xu et al. (2010b — this issue). These authors show that spatial correlation between positive Coulomb-stress changes and aftershocks is 58.20% on optimally oriented planes according to the Coulomb fracture criterion vs. 46% on uniformly oriented planes for the Wenchuan earthquake.

Whether static Coulomb stress induced by an earthquake can trigger seismicity on nearby faults depends critically on pre-earthquake stress states on these faults. This knowledge can only be gained via long-term tracking of earthquake occurrences throughout a large region where geometric linkages among the active faults are clearly defined. This issue was addressed in the paper by Luo and Liu (2010 — this issue) who show that the cumulative Coulomb-stress changes are significantly different when previous large earthquakes in the region are included. Opposite to the conclusions of Wan and Shen (2010 — this issue) who suggest that the Wenchuan earthquake has caused a positive increase in Coulomb failure stress on the Xianshuihe fault, Luo and Liu (2010 — this issue) argue instead that the southeastern Xianshuihe fault has stayed in a stress shadow due to stress release by previous six $M \geq 6.9$ events since 1893. Finally, Luo and Liu find that interseismic locking on the Xianshuihe fault can increase the loading rate on faults in the Longmen Shan thrust belt by up to ~50 Pa/yr.

4. Late Quaternary seismicity and recurrence intervals

An important question raised by the devastating Wenchuan earthquake is how often large earthquakes of such a size had occurred on the Beichuan–Yingxiu and the Pengguan faults in the eastern Longmen Shan thrust belt. This issue in turn is related to how fast the faults in the Longmen Shan thrust belt have moved in the Late Quaternary. Surprisingly, there has been very little work on such a critical problem. Early work by Densmore et al. (2007) showed that the Beichuan–Yingxiu and Pengguan faults are dominantly right-slip structures offsetting Pleistocene fluvial fill terraces with slip rates of <1 mm/yr on individual faults. Such a slow rate of fault motion is consistent with the GPS-measured 1–3 mm/yr shortening rate across the Longmen Shan thrust belt, which implies a long recurrence interval of 2000–10,000 years for $M=8$ earthquakes (e.g., Burchfiel et al., 2008). The lack of age constraints on many offset markers documented in the work of Densmore et al. (2007) left uncertainties on the rates and recurring times of the major active faults in the region. This problem is addressed in the paper by Ran et al. in this issue. By excavating the surface rupture zones of the Beichuan–Yingxiu and Pengguan faults, Ran et al. (2010 — this issue) discovered *at least* one major earthquake event, which they infer to be equivalent in size to the Wenchuan earthquake on the Beichuan–Yingxiu fault between 2.3 and 3.3 kyr. Ran et al. also found three events including the Wenchuan earthquake itself since 7.7 kyr. Although at the face value their findings appear to be consistent with slow convergence rates across the easternmost margin of the Tibetan plateau at ~3 mm/yr (e.g., Zhang et al., 2004), one has to keep in mind that erosion could have removed records of past earthquakes if the trench sites are not well selected. Thus, 2300–3300 years may be regarded as a minimum recurring time for a major earthquake. In fact, a recent work by Lin et al. (2010b) shows that the recurrence interval on the Beichuan–Yingxiu fault is only 1000–1200 years, in contrast to the earlier estimated recurrence interval of 2000–10,000 year by Burchfiel et al. (2008). Another cautionary note is their inferred sizes of the past earthquakes, which is mainly based on similarities in the magnitude of coseismic slip between the past events and the Wenchuan earthquake at the trench site. As the lateral extent of the newly discovered paleo-earthquake events remains poorly known, we must be careful about their inferred magnitudes of seismic events in the Longmen Shan area in the Holocene.

A major issue of using paleoseismology (e.g., trenching active fault zones) to infer recurrence intervals on individual active fault is that the recurring time on a single fault may not be uniform with time. In other words, large earthquakes could be clustered in a short period due to complex interactions of interconnected fault systems in eastern Tibet (Fig. 1). The paper by Wang et al. (2010c — this issue) provides some answers to this question. These authors used GPS data to invert for the slip rates on each fault responsible for the Wenchuan earthquake, and then calculated and compared the rate of moment accumulation with that released by earthquakes on these faults. Their analysis leads to the conclusion that a repeat of great earthquakes on the ruptured segment of the Longmen Shan thrust belt is unlikely in the next few hundred years, but the unruptured southwestern segment of the Longmen Shan thrust belt is capable of producing a M_w 7.7 earthquake in the next 50 years.

5. Structural geology of the Longmen Shan thrust belt

The occurrence of the Wenchuan earthquake along the Beichuan–Yingxiu fault in the pre-Cenozoic bedrock raises the question of whether and how this structure is linked with the Cenozoic thrusts and folds across the westernmost margin of the Sichuan Basin. Except the paper by Jia et al. (2006) and recent paper by Hubbard and Shaw (2009), this question was largely unanswered due to the lack of subsurface controls on the fault geometry (e.g., Burchfiel et al., 1995). The paper by Jia et al. (2010 — this issue) expands their early study on the structural geology of the Longmen Shan area (Jia et al., 2006). Using seismic-reflection profiles and drill-hole data Jia and his colleagues suggest two style of deformation during the Wenchuan earthquake: (1) the southern segment consists two thrusts (the Beichuan–Yingxiu and Pengguan faults) that sole into a main detachment at a depth 15–17 km; and (2) the northern segment occurs on a shallow thrust acting as a roof fault above an imbricate system. The paper by Robert et al. (2010a — this issue) places the Longmen Shan thrust belt in a broader tectonic context. Using the newly acquired seismic data by the same group (Robert et al., 2010b — this issue), these authors suggest that the basic style of deformation in the Longmen Shan region is thick-skinned thrusting, involving the entire crust of the previous Songpan–Ganze terrane. They also envision that the strong and thin Sichuan-basin crust has indented into the soft and much thicker Tibetan crust of the Triassic Songpan–Ganze terrane. The thick-skinned tectonic style proposed by Robert et al. differs drastically from the classic view that Sichuan basin crust has been subducted below the eastern Tibet (e.g., Jiang and Jin, 2005; Jia et al., 2006; Hubbard and Shaw, 2009; Jia et al., 2010 — this issue). However, it is consistent with the long-noted low values of effective elastic thickness across the region (<10 km) (Kirby et al., 2000; Braitenberg et al., 2003).

6. Lithospheric structure

Six papers in this issue provide new constraints on the crustal and lithospheric structures of the Tibetan plateau with emphasis on its eastern margin. The paper by Xu and Song (2010 — this issue) uses an iterative scheme to jointly invert the crustal velocity and the Moho depth across eastern Tibet. Their results show rapid Moho-depth variation and a slow Pn at the easternmost Tibetan plateau. These authors also show that high Poisson's ratio (implying low mechanical strength) exists in the middle and lower crust below eastern Tibet, which they take as evidence for the occurrence of channel flow in the eastern Tibetan plateau.

Surface geology indicates that the Longmen Shan thrust belt marks a low-angle and west-dipping boundary between the Songpan–Ganze terrane and the South China craton (e.g., Burchfiel et al., 1995). However, how the contact extends downwards was not clear. This problem has been significantly clarified by three papers presented in this issue. Li et al. (2010b — this issue) obtained a high-resolution tomography model using the ambient-noise technique. Their model reveals a nearly vertical boundary beneath the Longmen Shan thrust belt, which separates a prominent low-velocity zone in the mid-to-lower crust to the west from the high-velocity Sichuan-basin crust to the east. This result is similar to that of Xu and Song (2010 — this issue), suggesting the robustness of low seismic velocity for the eastern Tibetan middle and lower crust. The low Pn velocity obtained by Xu and Song (2010 — this issue) below eastern Tibet also implies that its mantle lithosphere has a lower velocity than that below the Sichuan basin. The above observation led Li et al. (2010b — this issue) to suggest that the middle and lower crust of eastern Tibet has flowed eastward; the flow has been blocked by the strong Sichuan basin crust.

Pei et al. (2010 — this issue) present a three-dimensional *P*- and *S*-wave model of the eastern Tibetan crust using a double-difference tomography code that simultaneously solves for Vp, Vs, Vp/Vs and event locations. Their results show that the Longmen Shan thrust belt is a major boundary in Vp, Vs and Vp/Vs ratio down to a depth of ~15 km: high Vp and Vs and lower Vp/Vs ratio west of the Longmen Shan thrust belt whereas low Vp and Vs and higher Vp/Vs ratio east of the thrust belt. Additionally, the above authors also show that the two large slip patches of the Wenchuan earthquake correspond to two high-velocity bodies in the Longmen Shan thrust belt, implying a structural control on the coseismic slip distribution along the rupture plane.

The view that the eastern Tibetan lower crust has flowed in a channel is disputed by Robert et al. (2010b — this issue). These authors show that Moho directly below the Beichuan–Yingxiu fault is offset about 20 km. This observation led the authors to suggest that the entire crust of eastern Tibet was thickened in a pure-shear fashion and thus there was no decoupling between the upper and lower crust as required by the channel flow model.

Zhang et al. (2010b — this issue) investigated the relationship between the Longmen Shan thrust belt and gravity anomalies in the region. Their work shows that the Longmen Shan thrust belt lies along the eastern margin of a large gravity gradient zone across eastern Tibet. Their modeling results suggest that the crustal and uppermost mantle density of eastern Tibet is lower than that below the Sichuan basin; the two regions are separated approximately by a sub-vertical boundary below the Longmen Shan thrust belt.

Although He et al.'s (2010 — this issue) work focuses on the extent of the subducted Indian slab beneath southern Tibet, more than 1000 km away from the site of the Wenchuan earthquake, it is a good reminder of drastically different deformation processes between the southern and eastern margins of the Himalayan–Tibetan orogen. These authors determined a detailed three-dimensional P-wave velocity structure of the crust and upper mantle down to the 400-km depth. They show that the Indian lithospheric mantle has been subducted beneath central Tibet with its northern tip passing the downward projection of the Bangong–Nujiang suture at latitude 34°N below the Qiangtang terrane. As mentioned above, the large offset of the Moho below the Longmen Shan thrust belt as reported by Robert et al. (2010b — this issue) is inconsistent with subduction of the Sichuan basin lithosphere beneath eastern Tibet (cf., Jiang and Jin, 2005).

7. Interplay between exhumation and tectonics in Eastern Tibet

Understanding how the eastern margin of the Tibetan plateau was constructed requires the knowledge of not only its deformation processes but also the exhumation history. Research on this subject has so far presented an apparent disparity in that the short-term erosion rates at 0.2–0.3 mm/year over a time span of 2000–3000 years appear to be a factor of 2–3 slower than the long-term erosion rates of 0.6–0.7 mm/yr over the past 10 Ma (Kirby et al., 2002). This discrepancy is addressed in the paper by Ouimet (2010 — this issue) who presents a detailed study of landslide occurrence associated with the Wenchuan earthquake. The author uses satellite and aerial-photographic images to track the pulse of landsliding related to the earthquake. He shows that an intense zone of landsliding had occurred along the Beichuan–Yingxiu and Pengguan faults. The pulse of high erosion induced by a major earthquake and the long recurrence intervals of >3000 yr on the earthquake-generating faults suggest that the estimated short-term erosion rates missed the input from earthquake-induced landslides and thus underestimated the long-term average erosion rates.

In the paper by Godard et al. (2010 — this issue), the authors address the question of what controls the long-term topographic evolution of the eastern Tibetan plateau. They present a new dataset that documents the intensity and distribution of denudation processes associated with Quaternary fluvial incision. Their results show erosion rates at ~0.5 mm/year in the eastern margin of the Longmen Shan, 0.5–1 mm/year across the Longmen Shan, and a gradual decrease in erosion rates from 1.0 mm/yr to below 0.1 mm/yr in the interior of the Tibetan Plateau directly west of the Longmen Shan. The authors also suggest that the construction of the impressive topographic front of the Longmen Shan range was caused a combined effect of slow thrusting and relatively slow westward propagation of the head waters of major rivers.

8. Unanswered questions

The occurrence of the Wenchuan earthquake has provided new impetus for detailed studies of the eastern Tibetan plateau and reexamination of previously held consensus. The rapid advances in our geologic and geophysical knowledge of the eastern Tibetan plateau have also raised some outstanding questions that require more attention in future research. I briefly discuss these questions below.

(1) *What is the recurrence interval of major earthquakes across the Longmen Shan thrust belt?* The views presented by Burchfiel et al. (2008) and that by Lin et al. (2010b) are drastically different, with the former emphasizing long recurrence intervals of 2000–10,000 years and the latter short intervals of only about 1000 years. The central issue of the debate is whether the GPS-based decadal convergence rates can be extrapolated over thousands of years or even millions of years in the past. One should note that the GPS convergence rate between the interior Tibetan plateau at the intersection of the Yushu–Ganze fault and the Xianshuihe fault and the western margin of the Sichuan basin is about 12–15 mm/yr (Gan et al., 2007) (Fig. 1). As shown by Feldl and Bilham (2006), elastic strain could be stored some 500 km away from the frontal trace of a major thrust such as the one along the Himalayan front; its release can drive the occurrence of major earthquakes that would not be obvious from the near field observations of GPS rates across the active fault trace. Thus, it is likely that the strain-accumulation over a much broader region of the eastern Tibetan plateau, not just the Longmen Shan thrust belt alone along the easternmost plateau margin, had contributed to the occurrence of major historical earthquakes at a faster pace as proposed by Lin et al. (2010b).

(2) *What controls the development of the steep and high-relief eastern margin of the Tibetan Plateau?* Although slow thrusting and slow erosion rates across the eastern margin of the Tibetan plateau may be used to explain the observed steep topography of the eastern Tibetan plateau, the above arguments are all based on decadal GPS rates or Late Quaternary studies. As it is currently unclear if the eastern Tibetan plateau was built by a steady-state or time-varying process, it is essential to determine the total amount of Cenozoic shortening and the convergence rate of the Longmen Shan thrust belt at a various time scales. Unfortunately, this information is currently unavailable, making assessment of the mechanism of eastern Tibet uplift highly uncertain.

(3) *What are the detailed coseismic-slip distributions along the Wenchuan earthquake rupture zones?* Evaluating the effect of the Wenchuan earthquake on changes in Coulomb stresses across eastern Tibet depends critically on the knowledge of coseismic-slip distributions over the earthquake rupture zones (Wan and Shen, 2010-this issue). Currently, there are three independent field studies that cover the whole length of the Beichuan–Yingxiu fault. The most readily observed offset features is the vertical scarps created by earthquake faulting, whereas the estimates of strike-slip motion and inference of horizontal slip require better observational conditions such as the availability of offset markers near the fault and exposure of the fault surface (Liu-Zeng et al., 2009; Xu et al., 2009; Lin et al., 2009; Li et al., 2010a — this issue). Although the existing studies show a broadly similar trend in the estimated vertical offsets, they differ significantly in several places along the Beichuan–Yingxiu fault (see comparison shown in Fig. 3).

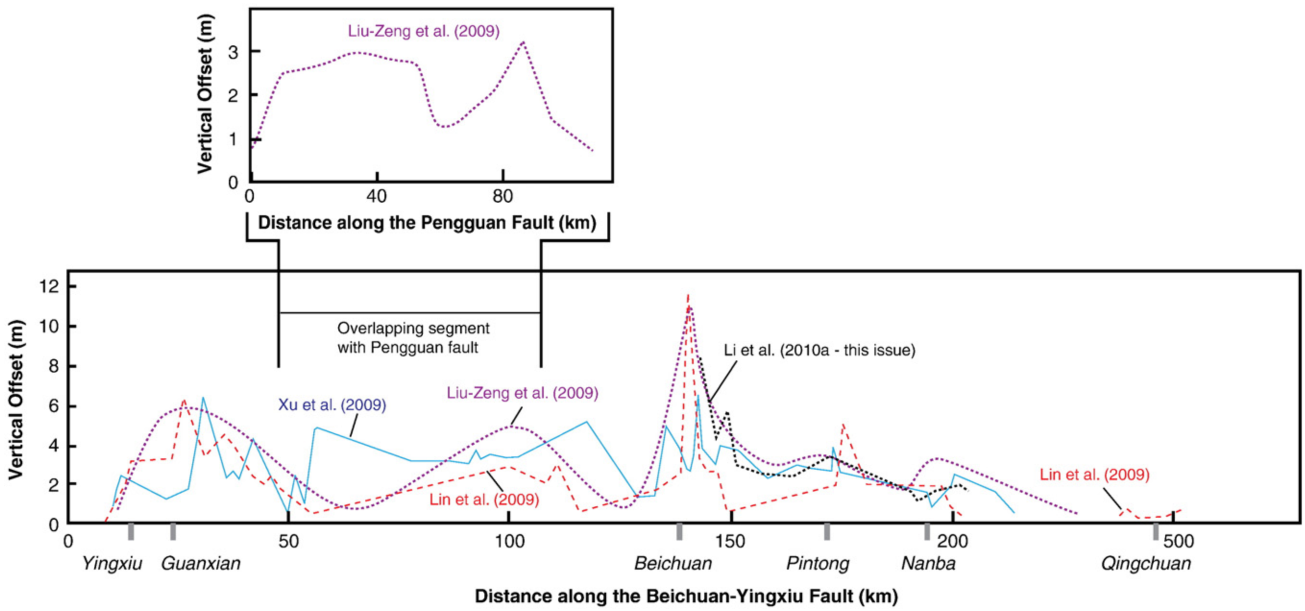

Fig. 3. Comparison of vertical offset distributions along the Beichuan–Yingxiu fault from Liu-Zeng et al. (2009), Lin et al. (2009), Xu et al. (2009), and Li et al. (2010a — this issue). See text for discussion.

These could have been induced by different survey methods, different assumptions of assumed reference planes, different sites of observations, and variable field experiences of the observers. In any case, as many roads have been reopened in the region, geologists may now have better access to resurvey the coseismic offsets with improved spatial coverage.

(4) *Was earthquake-triggered stress transmitted elastically?* Elastic dislocation models dealing with changes in Coulomb failure stresses induced by coseismic slip assume that coseismic deformation and its induced stress were transmitted elastically (Wan and Shen, 2010 — this issue; Xu et al., 2010b — this issue; Luo and Liu, 2010 — this issue). An additional complication may be the effect of viscoelastic deformation of the crust that could delay the stress transmission from one fault to another (e.g., Freed and Lin, 2001). One should also keep in mind that our current geologic knowledge in eastern Tibet tends to overlook the presence of potentially active faults that lie entirely in pre-Cenozoic rocks (the Beichuan–Yingxiu fault is a good example). Recognition of zones or regions of distributed deformation is another challenge. Their existence is hinted by the large convergence rate of ~12 mm/yr between the Sichuan basin and the interior of the Tibetan plateau some 150–200 km west of the Longmen Shan (Gan et al., 2007) (Fig. 1). The presence of distributed zones of deformation, if verified in the field, will have important impacts on our currently used block models for assessing changes in Coulomb failure stresses induced by major earthquakes.

(5) *What is the origin of a low seismic-velocity zone in the middle and lower crust of eastern Tibet?* Geologic history and thus the composition of the eastern Tibetan plateau are fundamentally different from those of the Sichuan basin (Fig. 2). The former is mainly composed of highly folded Triassic flysch deposits while the latter is part of the ancient South China craton (Yin and Nie, 1993; Burchfiel et al., 1995). Because of this complexity, termination of the low seismic-velocity zone in the middle and lower crust beneath eastern Tibet should not be regarded as a sole result of Cenozoic deformation (i.e., crustal thickening leading to partial melting in the middle and lower crust). The observed low velocity zone could have been inherited from the Triassic collision between South China and the Songpan–Ganze terrane. Differentiating the two end-member cases has important dynamic implications for the Cenozoic formation of the Tibetan plateau and the issue should be addressed by future geophysical experiments.

(6) *Is the apparent Moho offset below the Longmen Shan thrust belt induced by Triassic or Cenozoic deformation?* Robert et al. (2010a and 2010b — this issue) show that the Moho below the Longmen Shan thrust belt appears to be offset vertically for about 20 km with the east side up. As all the geophysical studies reported in this issue and by other workers (Pei et al., 2010 — this issue; Li et al., 2010b — this issue; Zhang et al., 2010a,b — this issue; Xu et al., 2010a) show that the Longmen Shan thrust belt marks a sub-vertical crustal-scale boundary between the Songpan–Ganze terrane to the west and the Sichuan basin of South China to the east. The offset of the Moho could have been induced by the Triassic collision between the two. Ascertaining whether the offset occurred in the Triassic or Cenozoic has important implications for the mechanical strength and thus the thermal state of the lithosphere beneath eastern Tibet. A Triassic offset requires that the mantle below the Longmen Shan has been cold and strong enough to sustain the steep Moho topography over some 230 Ma. In contrast, a Cenozoic offset implies that the Moho had been flattened prior to the Indo-Asian collision and was offset later in the Cenozoic (Robert et al., 2010a,b — this issue). A possible test of the two end-member cases is the use of detailed reflection seismology across the Longmen Shan region, which may determine whether the structures that offset the Moho can be traced to the known Cenozoic faults mapped at surface and imaged in the upper crust.

(7) *Does the presence of a low seismic velocity zone in the middle and lower crust of eastern Tibet indicate channel flow?* Citing low seismic velocity in the middle and lower crust of eastern Tibet as indicating the operation of channel flow is the most common inferences in the literature. Although low seismic velocity most likely implies low mechanical strength, the inferred rheological properties of the crust cannot independently determine how the crust may have deformed. An additional deciding factor is

the boundary condition (and initial condition to be complete). That is, a velocity field of a fluid is not only determined by its viscosity but also how the boundary conditions are enforced. No one would infer water in a swimming pool must flow in a manner of channel flow simply because the pool water is liquid. A complete constraint on the mode of crustal and lithospheric deformation requires the knowledge of three-dimensional deformation fields and their histories, all of which cannot be determined by the currently available seismic velocity models for the eastern Tibetan plateau. A challenge is to relate seismic anisotropies in the middle and lower crust to velocity fields, so that competing tectonic models with distinctive predictions on the developmental history of rock fabrics can be differentiated.

(8) *What is the mode of tectonic deformation across the eastern margin of the Tibetan plateau and why there is no prominent foreland basin development?* This is perhaps the most important question with regard to future preparation of seismic hazards across the eastern margin of the Tibetan plateau. Different tectonic models as discussed below have very different stress-loading mechanisms and thus lead to different scenarios for earthquake occurrences. From our current knowledge, there are at least six end-member models that are capable of explaining first-order yet highly fragmentary geologic and geophysical observations across the eastern Tibetan plateau (Fig. 4): (a) westward underthrusting of the South China block (i.e., Sichuan basin) accommodated by distributed shortening in the Tibetan upper crust (Fig. 4A) (Hubbard and Shaw, 2009; Jia et al., 2006, 2010 — this issue), (b) westward underthrusting of the South China block accommodated by distributed shortening of the whole Tibetan crust (Fig. 4B) (Jiang and Jin, 2005; Robert et al., 2010a — this issue), (c) pure-shear shortening of the whole Tibetan lithosphere (Fig. 4C), (d) simple-shear deformation of the whole Tibetan lithosphere (Fig. 4D), (e) indentation of strong South China crust into the weak Songpan–Ganze crust (Robert et al., 2010a) (Fig. 4E), and (f) inflation of middle and lower crust via channel flow (Clark and Royden, 2000; Burchfiel et al., 2008) (Fig. 4F).
The above six models do not consider possible interactions between the mantle lithosphere and underlying asthenosphere. However, the eastern Tibetan mantle lithospheric may have been partially removed by convective flow of the underlying asthenosphere, as its thickness is about 30 km thinner than that of the adjacent Sichuan basin (Zhang et al., 2010a). The convective-removal model may provide a heating mechanism for the

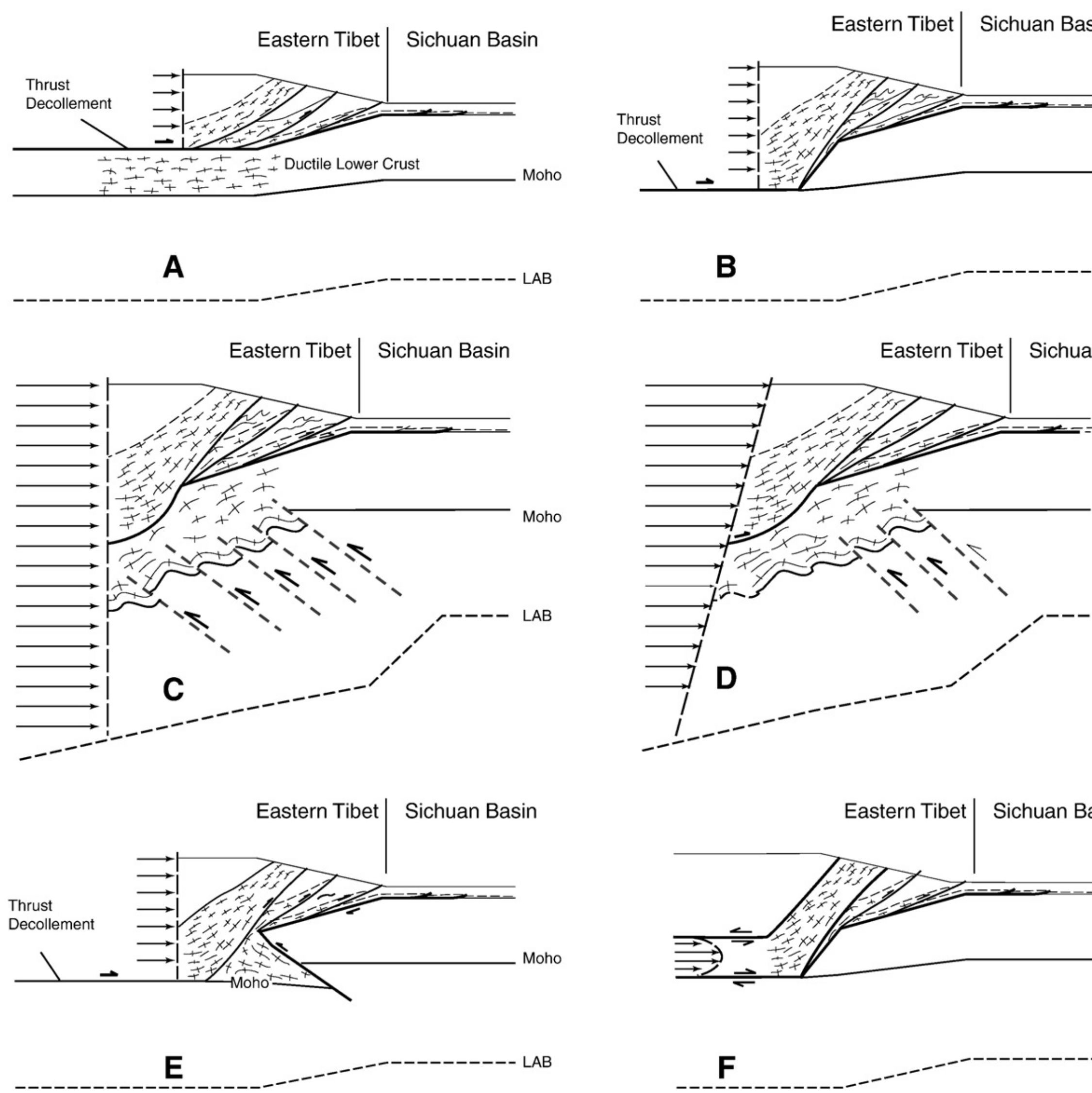

Fig. 4. Possible tectonic models for the development of the eastern Tibetan plateau. Models in (A) and (B) require strong lower crust and mantle lithosphere below eastern Tibet while models (C) to (F) implies that crustal shortening has been in situ and the mantle lithosphere beneath eastern Tibet is weak and highly deformable.

presence of a low-velocity channel in the middle and lower crust of the eastern Tibetan plateau as observed by Xu and Song (2010 — this issue) and Li et al. (2010b — this issue). It may also explain the extremely low values of effective elastic thickness for the eastern Tibetan lithosphere (mostly <10 km; see Braitenberg et al., 2003). Taking together, a weak Tibetan lithosphere may have led to its decoupling from the strong Sichuan basin. That is, the thrust load across the Longmen Shan thrust belt would be accommodated mostly via Airy isostasy, exerting little force over the Sichuan basin. This may explain the absence of a Cenozoic foreland east of the Longmen Shan as noted long ago by Burchfiel et al. (1995).

9. Discussion and summary

The papers collected in this special volume shed important light on issues related to the occurrence of the 12 May 2008 Wenchuan earthquake. These include (1) coseismic-slip distributions along the fault rupture zones and their effect on changes in Coulomb stresses across the neighboring faults, (2) determination of earthquake recurrence intervals, (3) lithospheric structures, and (4) tectonic development of the eastern Tibetan plateau. New results from these papers also raise several important questions such as (a) what is the fundamental mode of deformation that has created the eastern margin of the Tibetan plateau and (b) how stress and strain have been built up and then transmitted with time from fault to fault in this actively deforming region. Despite the above uncertainties, studies from recent years and particular the papers presented in this issue have led to an alternative view of how the eastern Tibetan plateau may have developed. The fundamental basis of this new perspective is the realization that the eastern Tibetan lithosphere may be much weaker than that of the Sichuan basin. As a result, its thickening was mainly accommodated by *in situ* lithospheric shortening of the previous Songpan–Ganze terrane; the newly thickened crust in the Cenozoic has been compensated dominantly via Airy isostacy with negligible support from the Sichuan-basin lithosphere. This means that either subduction of the South China lithosphere below the eastern margin of Tibet is negligible or that its subducted mantle lithosphere has been largely removed by deep mantle convection. This view is supported by the seismological observations (Robert et al., 2010b — this issue; Xu and Song, 2010—this issue; Li et al., 2010a — this issue; Pei et al., 2010 — this issue; Zhang et al., 2010a), modeling of gravity data (Zhang et al., 2010b — this issue), and inferences on the flexural rigidity of the lithosphere (Braitenberg et al., 2003) across the Longmen Shan area. Taking together, the absence of foreland-basin development against the eastern margin of the Tibetan plateau can simply be explained by the exceptionally low mechanical strength of the eastern Tibetan plateau inherited from Mesozoic tectonics of the region. Thus, the mechanism for the formation of the eastern Tibetan margin is fundamentally different from that for the development of the Himalayan orogen along the southern edge of the Tibetan plateau. The former is dominated by lithospheric-scale pure-shear (vertical thickening) contraction associated with a weak and thus highly deformable underlying mantle lithosphere, while the latter by discrete simple-shear deformation expressed by lithospheric subduction in association with a strong and thus little deformed underlying mantle lithosphere below the thickened Tibetan crust.

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References

An, M., Feng, Z., Long, C., 2010. Deep ruptures around the hypocenter of the 12 May 2008 Wenchuan earthquake deduced from aftershock observations. Tectonophysics 491, 96–104 (this issue).

Braitenberg, C., Wang, Y., Fang, J., Hsu, H.T., 2003. Spatial variation of flexure parameters over the Tibet-Quinghai plateau. Earth Planet. Sci. Lett. 205, 211–224.

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

Burchfiel, B.C., Royden, L.H., van der Hilst, R.D., Hager, B.H., Chen, Z., King, R.W., Li, C., Lü, J., Yao, H., Kirby, E., 2008. A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, People's Republic of China. GSA Today 18 (7). doi:10.1130/GSATG18A.

Clark, M.K., Royden, L.H., 2000. Topographic ooze: building the eastern margin of Tibet by lower crustal flow. Geology 28, 703–706.

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 TC4005. doi:10.1029/2006TC001987.

Feldl, N., Bilham, R., 2006. Great Himalayan earthquakes and the Tibetan plateau. Nature 444, 165–170.

Feng, G.C., Hetland, E.C., Ding, X.L., Li, Z.W., Zhang, L., 2010. Coseismic fault slip of the 2008 Mw 7.9 Wenchuan earthquake estimated from InSAR and GPS measurements. Geophys. Res. Lett. 37, L01302. doi:10.1029/2009GL041213.

Freed, A., Lin, J., 2001. Delayed triggering of the 1999 Hector Mine earthquake by viscoelastic stress transfer. Nature 411, 180–183.

Gan, W., Zhang, P., Shen, Z.-K., Niu, Z., Wang, M., Wan, Y., Zhou, D., Cheng, J., 2007. Present-day crustal motion within the Tibetan Plateau inferred from GPS measurements. J. Geophys. Res. 112, B08416. doi:10.1029/2005JB004120.

Ge, S., Liu, M., Lu, N., Godt, J.W., Luo, G., 2009. Did the Zipingpu Reservoir trigger the 2008 Wenchuan earthquake? Geophys. Res. Lett. 36, L20315. doi:10.1029/2009GL040349.

Godard, V., Lavé, J., Carcaillet, J., Cattin, R., Bourlès, D., Zhu, J., 2010. Spatial distribution of denudation in Eastern Tibet and regressive erosion of plateau margins. Tectonophysics 491, 253–274 (this issue).

Hashimoto, M., Enomoto, M., Fukushima, Y., 2010. Coseismic Deformation from the 2008 Wenchuan, China, Earthquake Derived from ALOS/PALSAR Images. Tectonophysics 491, 59–71 (this issue).

He, R., Zhao, D., Gao, R., Zheng, H., 2010. Tracing the Indian lithospheric mantle beneath central Tibetan Plateau using teleseismic tomography.

Hubbard, J., Shaw, J.H., 2009. Uplift of the Longmen Shan and Tibetan plateau, and the 2008 Wenchuan (M = 7.9) earthquake. Nature 458, 194–197. doi:10.1038/nature07837.

Jia, D., Wei, G., Chen, Z., Li, B., Zeng, Q., Yang, G., 2006. Longmen Shan fold-thrust belt and its relation to thewestern Sichuan Basin in central China: newinsights fromhydrocarbon exploration. AAPG Bull. 90, 1425–1447. doi:10.1306/03230605076.

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

Jiang, X., Jin, Y., 2005. Mapping the deep lithospheric structure beneath the eastern margin of the Tibetan Plateau from gravity anomalies. Journal of Geophysical Research 110, B07407. doi:10.1029/2004JB003394.

Kirby, E., Whipple, K.X., 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. Geol. Soc. Am. Bull. 112, 375–393.

Kirby, E., Reiners, P.W., Krol, M.A., Whipple, K.X., Hodges, K.V., Farley, K.A., Tang, W.Q., Chen, Z.L., 2002. Late Cenozoic evolution of the eastern margin of the Tibetan Plateau: inferences from 40Ar/Ar39 and (U–Th)/He thermochronology. Tectonics 21. doi:10.1029/2000TC001246.

Li, C.Y., Wei, Z.Y., Ye, J.Q., Han, Y.B., Zheng, W.J., 2010a. Amounts and styles of coseismic deformation along the northern segment of surface rupture, of the 2008 Wenchuan Mw 7.9 earthquake, China. Tectonophysics 491, 35–58 (this issue).

Li, H.Y., Su, W., Wang, C.-Y., Huang, Z.X., Lv., Z.Y., 2010b. Ambient noise Love wave tomography in the eastern margin of the Tibetan plateau. Tectonophysics 491, 194–204 (this issue).

Lin, A., Ren, Z., Jia, D., Wu, X., 2009. Co-seismic thrusting rupture and slip distribution produced by the 2008 M7.9 Wenchuan earthquake, China. Tectonophysics 471, 203–215.

Lin, A., Ren, Z., Jia, D., 2010a. Co-seismic ground-shortening structures produced by the 2008 Mw 7.9 Wenchuan earthquake, China. Tectonophysics 491, 21–34 (this issue).

Lin, A., Ren, Z., Jia, D., Miyairi, Y., 2010b. Evidence for a Tang-Song Dynasty great earthquake along the Longmen Shan Thrust Belt prior to the 2008 Mw 7.9 Wenchuan earthquake, China. J. Seismol. doi:10.1007/s10950-010-9186-7.

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

Luo, G., Liu, M., 2010. Stress evolution and fault interactions before and after the 2008 Great Wenchuan earthquake. Tectonophysics 491, 127–140 (this issue).

Nakamura, T., Tsuboi, S., Kaneda, Y., Yamanaka, Y., 2010. Rupture process of the 2008 Wenchuan, China earthquake inferred from teleseismic waveform inversion and forward modeling of broadband seismic waves. Tectonophysics 491, 72–84 (this issue).

Ouimet, W.B., 2010. Landslides associated with the May 12, 2008 Wenchuan earthquake: Implications for the erosion and tectonic evolution of the Longmen Shan. Tectonophysics 491, 244–252 (this issue).

Pei, S., Su, J., Zhang, H., Sun, Y., Toksöz, M.N., Wang, Z., Gao,, X., Liu-Zeng, J., He, J., 2010. Three-dimensional seismic velocity structure across the 2008 Wenchuan Ms 8.0 earthquake, Sichuan, China. Tectonophysics 491, 211–217 (this issue).

Ran, Y., Chen, L., Chen, J., Wang, H., Chen, G., Yin, J., Shi, X., Li, C., Xu, X., 2010. Paleoseismic evidence and repeat time of large earthquakes at three sites along the Longmenshan fault zone. Tectonophysics 491, 141–153 (this issue).

Robert, A., Pubellier, M., de Sigoye, J., Vergne, J., Lahfid, A., Cattin, R., Findling, N., Zhu, J., 2010a. Structural and thermal characters of the Longmen Shan (Sichuan, China). Tectonophysics 491, 165–173 (this issue).

Robert, A., Zhu, J., Vergne, J., Cattin, R., Chan, L.S., Wittlinger, G., Herquel, G., de Sigore, J., Pubellier, M., Zhu, L.D., 2010b. Crustal structures in the area of the 2008 Sichuan earthquake from seismologic and gravimetric data. Tectonophysics 491, 205–210 (this issue).

Shen, Z.K., Sun, J., Zhang, P., Wan, Y., Wang, M., Bürgmann, R., Zeng, Y., Gan, W., Liao, H., Wang, Q., 2009. Slip maxima at fault junctions and rupturing of barriers during the 2008 Wenchuan earthquake. Nat. Geosci. 2, 718–724. doi:10.1038/NGEO636.

Spurlin, M., Yin, A., Horton, B.K., Zhou, J., Wang, J., 2005. Structural evolution of the Yushu-Nangqian region and its relationship to syncollisional igneous activity east-central Tibet. Geol. Soc. Am. 117, 1293–1317.

Taylor, M.H., Yin, A., 2009. Active structures of the Himalayan–Tibetan orogen and their relationships to earthquake distribution, contemporary strain field, and Cenozoic volcanism. Geosphere 5, 199–214.

Wan, Y., Shen, Z.K., 2010. Static Coulomb stress changes on faults caused by the 2008 Mw 7.9 Wenchuan, China earthquake. Tectonophysics 491, 105–118 (this issue).

Wang, W.M., Zhao, L.F., et al., 2008. Rupture process of the Ms8.0 Wenchuan earthquake of Sichuan. China. Chin. J. Geophys. 51 (5), 1403–1410 (in Chinese).

Wang, H., Ran, Y.K., Chen, L.C., Shi, X., Liu, R.C., Gomez, F., 2010a. Determination of horizontal shortening and amount of reverse-faulting from trenching across the surface rupture of the 2008 M_W 7.9 Wenchuan earthquake, China. Tectonophysics 491, 10–20 (this issue).

Wang, W.M., Sun, W., Jiang, Z., 2010b. Comparison of fault models of the 2008 Wenchuan earthquake (Ms8.0) and spatial distributions of co-seismic deformations. Tectonophysics 491, 85–95 (this issue).

Wang, H., Liu, M., Shen, X., Liu, J., 2010c. Balance of seismic moment in the Songpan-Ganze region, eastern Tibet: Implications for the 2008 Great Wenchuan earthquake. Tectonophysics 491, 154–164 (this issue).

Xu, Z.J., Song, X., 2010. Joint inversion for crustal and Pn velocities and Moho depth in Eastern Margin of the Tibetan Plateau. Tectonophysics 491, 185–193 (this issue).

Xu, X.W., Wen, X.Z., Yu, G.H., Chen, G.H., Klinger, Y., Hubbard, J., Shaw, J., 2009. Coseismic reverse- and oblique-slip surface faulting generated by the 2008 Mw7.9 Wenchuan earthquake, China. Geology 37 (6), 515–518. doi:10.1130/G25462A.1.

Xu, Z., Huang, R., Xu, Y., 2010a. Seismic structure of the Longmen Shan region from S-wave tomography and its relationship with the Wenchuan Ms 8.0 earthquake on 12 May 2008, southwestern China. Geophys. Res. Lett. 37, L02304. doi:10.1029/2009GL041835.

Xu, C.J., Wang, J., Li, Z., Dummond, J., 2010b. Applying the Coulomb failure function with an optimally oriented plane to the 2008 Mw 7.9 Wenchuan earthquake triggering. Tectonophysics 491, 119–126 (this issue).

Yin, A., Nie, S., 1993. An indentation model for the north and south China collision and the development of the Tan-Lu and Honam fault systems, eastern Asia. Tectonics 12, 801–813.

Zhang, P.Z., Shen, Z.K., Wang, M., Gan, W.J., Bürgmann, R., Molnar, P., Wang, Q., Niu, Z.J., Sun, J.B., Wu, J.C., Sun, H.R., You, X.Z., 2004. Continuous deformation of the Tibetan Plateau from global positioning system data. Geology 32, 809–812.

Zhang, Z., Yuan, X., Chen, Y., Tian, X., Kind, R., Li, X., Teng, J., 2010a. Seismic signature of the collision between the east Tibetan escape flow and the Sichuan Basin. Earth Planet. Sci. Lett. 292, 254–264.

Zhang, J., Gua, R., Zeng, L., Li, Q., Guan, Y., He, R., Wang, H., Lu, Z., 2010b. Relationship between characteristics of gravity and magnetic anomalies and the earthquakes in the Longmenshan range and adjacent areas. Tectonophysics 491, 218–229 (this issue).

An Yin
University of California Department of Earth and Space Sciences,
Box 951567, Los Angeles CA 90095-1567 United States
Fax: +1 310 825 2779.
E-mail address: yin@ess.ucla.edu.

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