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Late Cenozoic east–west crustal shortening in southern Longmen Shan, eastern Tibet: Implications for regional stress field changes

Zhigang Li [a], Dong Jia [a,*], Wei Chen [b], Hongwei Yin [a], Li Shen [a], Chuang Sun [a], Yong Zhang [a], Yiquan Li [a], Shiqin Li [b], Xiaojun Zhou [b], Haibin Li [a], Gaoming Jian [c], Meng Zhang [a], Jian Cui [a]

[a] Department of Earth Sciences and Institute of Energy Sciences, Nanjing University, Nanjing 210093, China
[b] Resources and Environment Institute, Southwest Petroleum University, Chengdu 610500, China
[c] The Southwest Branch of SINOPEC, Chengdu 610016, China

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ABSTRACT

The co-seismic slip sense of the 2008 Wenchuan earthquake (Mw 7.9) has resulted in the present east–west (E–W) crustal shortening and oblique thrusting across Longmen Shan, which are inconsistent with southeast-directed thrusting that occurred during the late Triassic. Although the two major periods of compressional deformations in Longmen Shan have long been recognized, the fault slip rate of the late Cenozoic deformation and the initial E–W crustal shortening remain poorly investigated. This study confirms the fault slip rate in the Dayi Thrust Fault System (DYFS) based on data from the petroleum industry and shallow seismic reflection profiles, and well data. Folded late Pliocene to present strata are analyzed and yield with an average slip rate of 0.2 mm/yr on the DYFS. An average fault slip rate of 0.25 mm/yr is then obtained from the late Pliocene to present for the range front thrust of Longmen Shan. The E–W crustal shortening is investigated by using 3-D seismic reflection data, interpreting satellite image, and conducting a field investigation in the DYFS to determine stress field changes during the late Cenozoic. Two-period tectonic deformations during the late Cenozoic are found in the DYFS, which correspond to the NE- and NS-trending structures, respectively. The activities of the DYFS may reflect a change in the field direction of the regional stress—from NW–SE during the Oligocene to early Pliocene to E–W during the late Pliocene to Holocene, which is consistent with the present stress measurements. The 120 km NS-trending structures in the southern Longmen Shan range front as well as the Wenchuan earthquake co-seismic ruptures are assumed to reflect the active, E–W crustal shortening in Longmen Shan.
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1. Introduction

The devastating Mw 7.9 Wenchuan earthquake in Longmen Shan on May 12, 2008 resulted in enormous economic losses and casualties by destroying the homes of more than 1.5 million people (Stone, 2008). The earthquake also resulted in crustal shortening along the eastern margin of the Tibetan Plateau (Hubbard and Shaw, 2009; Liu-Zeng et al., 2009; Wang et al., 2011; Zhao et al., 2012). Field investigations show that the co-seismic surface slip of the Wenchuan earthquake along the NE-trending Longmen Shan is mainly divided into the oblique right-lateral reverse faulting on the NW-dipping Yinxiu–Beichuan Fault (~260 km long), the nearly pure thrusting on the NW-dipping Pengguan Fault (~70 km long), the oblique reverse right-lateral faulting on the NW-dipping Qingchuan Fault (~60 km long), and the oblique reverse left-lateral faulting on the SW-dipping Xiaoyudong Fault (~8 km long) (Jia et al., 2010; Li et al., 2010; Lin et al., 2012; Liu-Zeng et al., 2009, 2012; Wang et al., 2011; Xu et al., 2009; Zhang et al., 2010) (Fig. 1). This slip sense highlights present east–west (E–W) crustal shortening and oblique thrusting across Longmen Shan, which has not been entirely validated in previous studies (Liu-Zeng et al., 2009; Luna and Hetland, 2013). This crustal shortening implies a change in the direction of the stress field. According to Burchfiel et al. (1995), Longmen Shan has been formed by southeast-directed thrusting during the late Triassic, which has been accommodated by NE-trending structures. Although the compressional deformations during the late Triassic and the Cenozoic as well as the related folds and blind thrusts in Longmen Shan have long been recognized and mapped, the initial E–W crustal shortening remains unclear (Burchfiel et al., 1995; Chen and Wilson, 1996; Jia et al., 2006). Moreover, the Quaternary slip rate of the Dayi Thrust Fault System (DYFS) and the range front thrust of Longmen Shan are poorly investigated compared with that of other faults in Longmen Shan and the Sichuan Basin, such as Yinxiu–Beichuan, Pengguang, and Qiongxi (Arne et al., 1997; Densmore et al., 2007; Godard et al., 2009; Kirby et al., 2002; Wang et al., 2013b).

* Corresponding author at: Institute of Energy Sciences, Department of Earth Sciences, Nanjing University, Hankou Road No. 22, Gulou District, Nanjing, Jiangsu 210093, China. Tel./fax: +86 25 83685197.
E-mail address: djia@nju.edu.cn (D. Jia).

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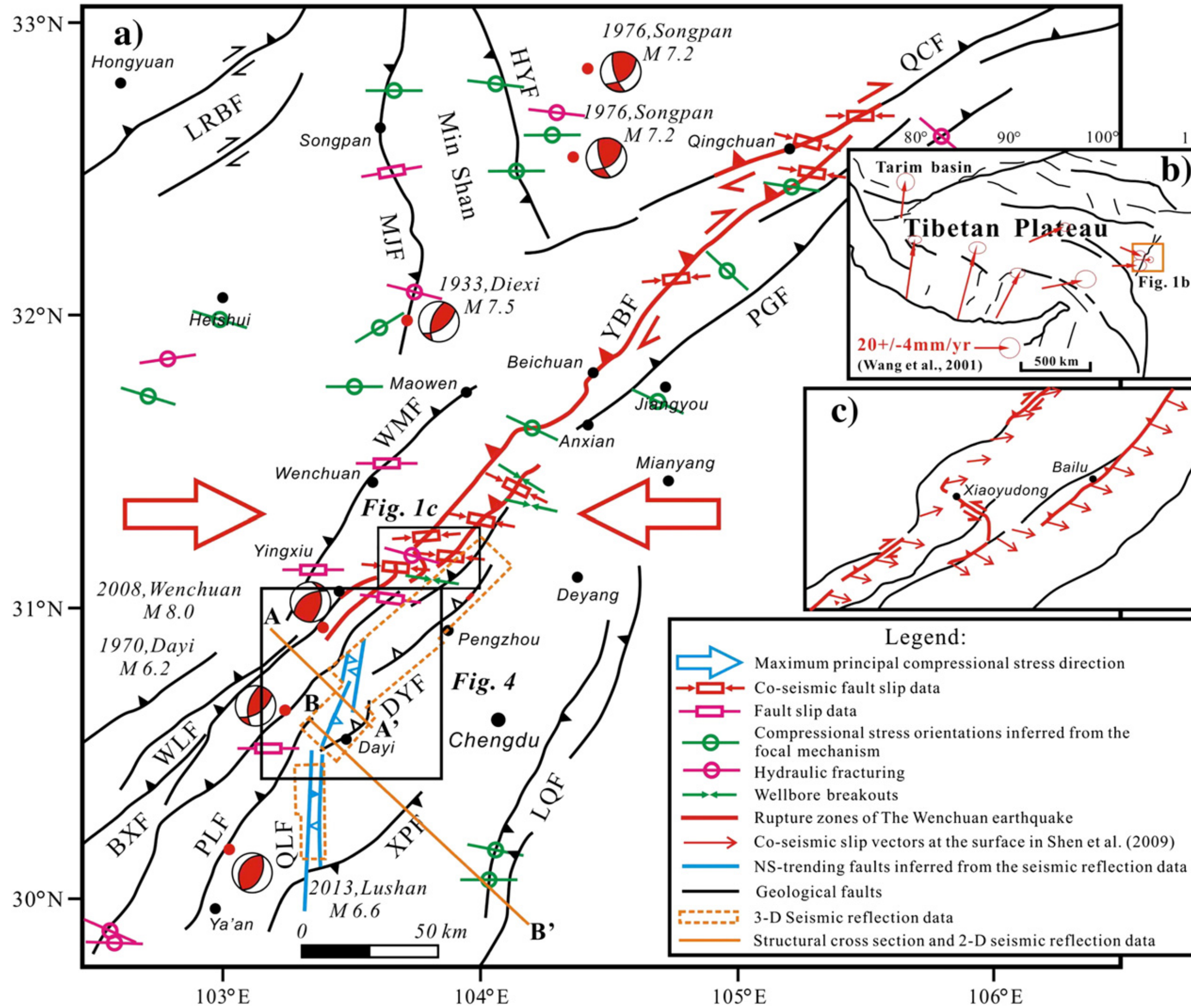

Fig. 1. (a) Tectonic setting of Longmen Shan and the western Sichuan Basin that shows the epicenter and focal mechanism of the 2008 Wenchuan earthquake, co-seismic surface ruptures, and unruptured major faults. The main-shock hypocenter and focal mechanism obtained from the China Digital Seismograph Network (CDSN) are distinguished (Xu et al., 2008). The co-seismic ruptures of the 2008 Wenchuan earthquake (Lin et al., 2009; Liu-Zeng et al., 2009; Wang et al., 2011; Xu et al., 2009) are shown in red whereas the other main faults are shown in blue and black. The maximum horizontal principal compressional stress (σ_{1max}) orientations for Longmen Shan and adjacent areas are modified from Du et al. (2009) and Wang et al. (2011). The focal mechanisms of the 1970 Dayi and 1976 Songpan earthquakes (Jones et al., 1984) as well as the position of 3D seismic data are shown. The locations of AA′ (Fig. 2) and the DYFS (Fig. 4) are indicated. (b) The inset map shows the location of the Tibetan Plateau and current Global Positioning System displacement rates from Wang et al. (2001). (c) The inset figure shows the location of surface ruptures and co-seismic slip vectors at the surface of the Xiaoyudong Fault, which was modified from Shen et al. (2009) and Liu-Zeng et al. (2012). YBF, Yingxiu–Beichuan Fault; PGF, Pengguan Fault; WMF, Wenchuan–Maowen Fault; QCF, Qingchuan Fault; MJF, Minjiang Fault; HYF, Huya Fault; LRBF, Longriba Fault; WLF, Wulong Fault; BXF, Baoxing Fault; DYF, Dayi Fault; QLF, Qionglai Fault; PLF, Pingluo Fault; LQF, Longquan Fault; XPF, Xiongpo Fault.

Although numerous studies have investigated the situation of Longmen Shan (summarized by Zhang, 2012) after the 2008 Wenchuan earthquake, the seismic potential of the active faults located in southern Longmen Shan remains unclear. Moreover, the crustal shortening of southern Longmen Shan, as well as its subsurface fault pattern during the late Cenozoic, remains largely unexplored. Nalbant and McCloskey (2011) computed the co-seismic stress changes that resulted from the Wenchuan earthquake and found an increase in the static Coulomb stress of southern Longmen Shan, which is consistent with the findings of Parsons et al. (2008), Wan and Shen (2010), and Chen et al. (2011). Wang et al. (2013a,b) investigated the co-seismic fold scarps, paleoseismic events, and 3D subsurface structure of the 50 km NS-trending Qiongxi Thrust Fault System in the range front of southern Longmen Shan. However, only a few studies have examined the 3D structural modeling and activities of the DYFS near the epicenter of the Wenchuan earthquake. Therefore, seismic potential in southern Longmen Shan, which is directly beneath the densely populated Sichuan Basin, must be quantitatively reevaluated as soon as possible (Yin, 2010).

By conducting field observations and interpreting remote sensing image, Densmore et al. (2007) documented the Quaternary activities of the DYFS in the southern Longmen Shan range front and suggested that the area may threaten the densely populated Sichuan Basin (Liu-Zeng et al., 2009). The Ms 6.2 Dayi earthquake (30.6° N, 103.2° E) occurred at 15 km in 1970 (Chen et al., 1994; Deng et al., 1994; Liu-Zeng et al., 2009; Tang and Han, 1993; Wang et al., 2010) (Fig. 1). The present study describes the subsurface structural geometry and kinematics of the blind faults in the DYFS to understand the crustal structure during the late Cenozoic and its implications for the Quaternary fault slip rate as well as for the stress field changes in Longmen Shan and the Sichuan Basin.

2. Geological setting

The Tibetan Plateau was formed by the collision between the Indian and Eurasian Plates at approximately 50 Ma (Molnar and Tapponnier, 1975; Tapponnier et al., 2001). The 500 km long and 30 km to 50 km wide southeastward-verging Longmen Shan, which is located between

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