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Characteristics and implications of the stress state in the Longmen Shan fault zone, eastern margin of the Tibetan Plateau

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ABSTRACT

Using stress data measured in 16 boreholes along the strike of the Longmen Shan fault zone by hydraulic fracturing from 2008 to 2012 after the Wenchuan earthquake and before the Lushan earthquake, we characterize the contemporary stress state in the Longmen Shan thrust belt along the eastern margin of the Tibetan Plateau to understand the implications of in-situ stress for fault activity. The stress regimes are generally conducive to reverse faulting and partly to strike-slip faulting characterized by $\sigma_H > \sigma_h > \sigma_v$ and $\sigma_H > \sigma_v > \sigma_h$, indicating that the regional stress field is definitely dominated by the maximum horizontal stress. The fracture impression results reveal that the maximum horizontal principal stresses are predominantly NE in the northern segment of the Longmen Shan fault zone and NW in the southern segment, postulating a preliminary understanding of the coupling between the shallow crustal stress field and lower crustal flow. According to Coulomb frictional failure criteria, horizontal principal stresses can be predicted as functions of rock density, ρ, frictional coefficient, μ, depth, H, and water level, H_W, in frictional equilibrium. The influence of H_W on critical stresses is discussed, and the decrease in the stress values corresponds to an increase in the water level. The depth profiles of the stress magnitudes in different segments are illustrated, indicating that the stress values are relatively higher in the southern and northern segments and lower in the middle segment. The stress state in the southern segment, specifically, near the epicenter of the Lushan earthquake, favors the occurrence of earthquakes. Under the stress state in the northern segment, the Longmen Shan fault might be the optimally oriented failure plane, assuming that the plane is critically stressed. This finding may imply that the northern segment of the Longmen Shan fault is likely to be active when the stress builds up sufficiently to destroy the frictional equilibrium.

1. Introduction

Stress measurements play an essential role in geodynamic process analyses, such as those used to determine plate tectonic driving forces and crustal stability. Measurements of the stress field within the crust can provide the most useful information concerning the forces responsible for various tectonic processes, such as earthquakes (McGarr and Gay, 1978). Earthquakes are a major hazard and commonly result in great disasters worldwide. Fault instability and earthquakes have a close relationship with crustal stress. Exploring the crustal stress state and its characteristics is critical to understand the physical processes inside the crust and fault activity (Li, 1973). Previous studies have focused on fault stability, crustal activity, and seismogenics by using measurement stress data. Liao et al. (2003) and Guo et al. (2009) revealed an obvious stress change before and after the 2001 M_S 8.1 West Kunlun Pass and 2008 Wenchuan earthquakes. Lin et al. (2011, 2013) analyzed the stress state before and after the 2011 Tohoku-Oki earthquake, determining that the aftershock faulting stress regime clearly differed from that prior to the earthquake and fault slip could result in a completely reduced stress state. Chang et al. (2010) analyzed the interaction between the regional stress state and faults by examining borehole in-situ stress data and the earthquake focal mechanism in southeastern Korea. Wu et al. (2013) analyzed stress changes before and after large earthquakes using both hydraulic fracturing and piezomagnetic methods in the Tibetan Plateau.

We characterize the present-day stress state in the Longmen Shan fault zone along the eastern margin of the Tibetan Plateau, which is one of the most developed areas of seismic activity and has complex geological structures and active faults caused by the continued northward subduction of the Indian continental plate (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977). The Longmen Shan fault zone and surrounding blocks, as part of the eastern boundary of the Tibetan Plateau and located in the middle section of the famous north-south seismic belt in China, consists of a series of parallel imbricate thrust belts (Fig. 1) that trend 40°N–50°E, with a total length of 500 km and width of 25–40 km. This zone contains the Maoxian-Wenchuan,

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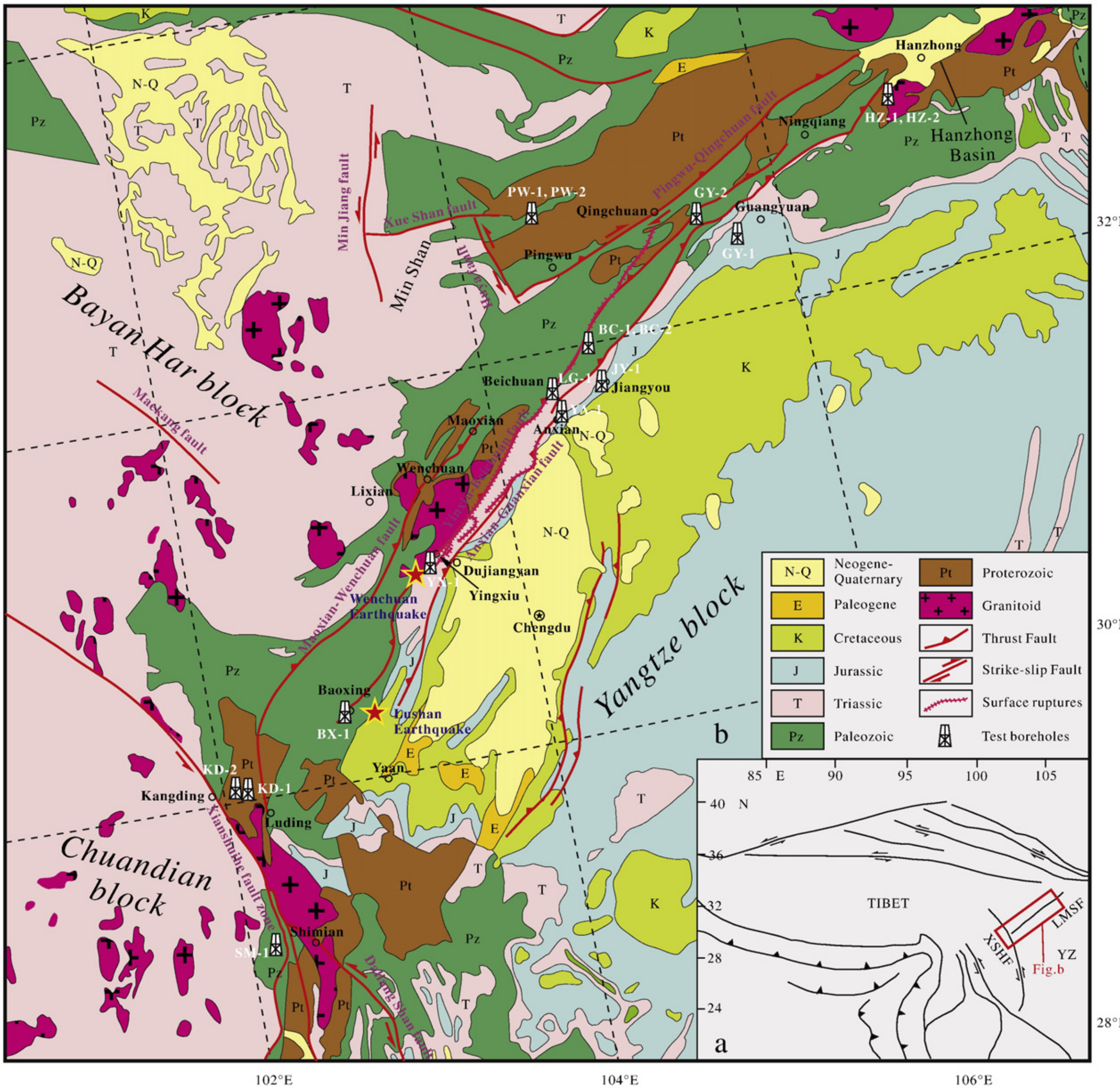

Fig. 1. Geological sketch map of the Longmen Shan region along the eastern margin of the Tibetan Plateau. TIBET, Tibetan Plateau; YZ, Yangtze block; LMSF, Longmen Shan fault zone; XSHF, Xianshuihe fault zone.

Pingwu-Qingchuan, Yingxiu-Beichuan, and Anxian-Guanxian faults (Xu et al., 2008; Dirks et al., 1994; Wu et al., 2009). The Longmen Shan fault zone has experienced the most devastating earthquake of the century, the 2008 M_s 8.0 Wenchuan earthquake, which collapsed buildings and killed thousands in major cities in the western Sichuan Basin in China (Parsons et al., 2008). This earthquake produced a seismic rupture zone of ~240 km along the causative fault, the Yingxiu–Beichuan fault, and a surface rupture zone of ~70 km along the Anxian-Guanxian fault (Lin et al., 2009; Xu et al., 2009). Moreover, thousands of large-scale landslides and debris flows were triggered in the Longmen Shan Mountains. Five years later, the M_s 7.0 Lushan earthquake occurred on April 20, 2013, in the southwestern Longmen Shan fault zone, inducing geological hazards and resulting in the deaths or disappearances of more than 200 people. Because the stress state is responsible for present-day earthquake activity, its characterization is essential. In the present study, the results of hydraulic fracturing in-situ stress measurements conducted in 16 boreholes from 2008 to 2012 after the Wenchuan earthquake and before the Lushan earthquake are used to characterize the present-day stress state in the Longmen Shan fault zone, and the implications of the in-situ stress in terms of the stress magnitude and orientation are discussed for fault activity.

2. In-situ stress measurements

2.1. General conditions of the test boreholes

As shown in Fig. 1, HZ-1 and HZ-2 are located in the transition zone between the northeastern Longmen Shan thrust belt and western margin of the Hanzhong Basin at a distance of ~33 m apart. Hydraulic fracturing stress measurements were performed in Proterozoic granite. GY-1 is located in the footwall of the Longmen Shan fault zone and contains exposed feldspar quartz sandstone and purple siltstone from the Middle Jurassic Shaximiao Formation (J_2s). GY-2 is also located in the footwall of the Longmen Shan central fault, ~2 km from the Yingxiu-Beichuan fault, and contains exposed dolomite, quartz sandstone, and siltstone from the Middle Devonian Guanwushan Formation (D_2g). PW-1 and PW-2 are located in the hanging wall of the Yingxiu-Beichuan fault, ~30 m apart, and contain exposed biotite leptynite and