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New insights into stress changes before and after the Wenchuan Earthquake using hydraulic fracturing measurements

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ABSTRACT

This paper summarizes in situ stress data by hydraulic fracturing method over the past 10 years along the Longmenshan fault belt, and these data can be divided into three segments: northern, middle, and southern. The orientations of the maximum horizontal stress rotate from north-northwest in the northern to northwest in the middle, and to west-northwest in the southern. The stress magnitudes are characterized by higher values in the two ends and lower values in the middle segment. Furthermore, three stress measurement campaigns in two boreholes on the northern segment of the Longmenshan fault belt, before and after the great earthquake, show clear stress decrease of 23%–29% in the shallow crust after the earthquake. Analysis using the mathematical fitting method also indicates a decrease in regional stress state after the earthquake. Meanwhile, the frictional characteristic indexes based on the stress measurements further imply that the frictional strength of the Longmenshan fault belt is characterized by a strong southern segment, a weak middle segment, and a moderately strong northern segment. The analysis based on the stress data implies that the northern and southern segments of the fault belt are extremely important stress concentration and transformation nodes of the regional stress regime.

1. Introduction

Great earthquakes often occur in the locked segment of active fault belts that have accumulated high stresses (Aki, 1984). The manner in which the segment with stress buildup and possible seismogenic information in a fault belt is determined is critical for predicting medium-to-long-term earthquake risks. Wiemer and Wyss (1997, 2000), Wyss and Matsumura (2002), and Wyss et al. (2000) utilized the parameters that define the relation between magnitude and frequency to analyze the spatial distribution of the relative stress level along an active fault and to identify the areas with the highest stress buildup. Diao et al. (2011) analyzed the changes in tectonic stress regimes prior to the 2008 Wenchuan Earthquake and the 1999 Chi-Chi Earthquake using focal mechanism data of Ms 4.0–6.0 earthquakes, and observed that similar local stress regime transformations occurred before both earthquakes, suggesting that this phenomenon may be a precursor to intense earthquakes. The calculation of the increase/decrease in coulomb failure stress (CFS) is another way to analyze stress changes after a strong earthquake and the earthquake's positive or negative effects on neighboring faults (King et al., 1994; Lin and Stein, 2004).

Findings from the World Stress Map (WSM) program show that the in situ stress data from the shallow crust agree well with focal mechanism data from the deep crust. Many studies worldwide (Li and Liu, 1986; Tanaka, 1986; Zoback, 1992; Zoback and Magee, 1991) have demonstrated that the direction of contemporary tectonic stress over a large region is relatively stable. Furthermore, the directions indicate a certain law and are closely related to geological structures and present tectonic movements, which is the basis for utilizing in situ stress data to explore the potential relation between tectonic stresses and earthquakes. By analyzing in situ stress measurements obtained from the shallow crust (depth < 50 m) after the Xintai, Haicheng, Longling, and Tangshan earthquakes, Li and Liu (1986) and Xie et al. (2003) observed that the principal and shear stresses of the epicentral area were considerably lower than those of adjacent areas, and that the maximum shear stresses obtained at locations far from the epicenter were up to two times greater than those in the epicentral area. The orientation of the maximum horizontal principal stress measured at the epicentral area shortly after the Tangshan Earthquake deviated considerably from the orientation of the regional tectonic stress; however, later, the two orientations were consistent (Li and Liu, 1986). Liao et al. (2003) captured the stress changes on the seismogenic fault belt shortly before and after the Kunlun Earthquake (Ms 8.1, 2001.8). Their measurements show that the stress values measured after the earthquake were only one-third of those measured before the earthquake (Liao et al., 2003). Additionally, Guo et al. (2009) obtained valuable hydraulic fracturing in situ stress measurement data

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before and after the Wenchuan Earthquake from the same borehole. The measurements indicate a 23%–29% decrease in horizontal stress magnitudes.

Previous studies on the seismogenesis of the Wenchuan Earthquake conducted from the stress viewpoint include the systematic analysis of focal mechanism data (Cai et al., 2011; Cui et al., 2011; Hu et al., 2008), calculation of CFS (Parsons et al., 2008; Shan et al., 2009; Toda et al., 2008; Xie et al., 2010; Zhu and Wen, 2010), and variation in shear wave splitting (Ding et al., 2008). Few efforts have been made to study the Wenchuan Earthquake using in situ stress measurements. Our research group has conducted tens of hydraulic fracturing stress measurement campaigns along the Longmenshan fault belt for more than 10 years. In this study, all the data were compiled to provide a new approach to enhance our understanding of the stress changes along the Longmenshan fault belt and of the seismogenic mechanisms leading to the Wenchuan Earthquake.

2. Geological background of the Longmenshan fault belt

The Longmenshan fault belt, which has a very complicated structure, is the boundary belt between the Bayan Har Block in the Tibetan Plateau and the South China Block in the eastern China. The fault belt experienced a very long geological evolution. With a 500 km length, the Longmenshan fault belt strikes NE–SW, extending southwestward to the Jinpingshan thrust nappe belt and northeastward to join the Qingling orogenic belt. The fault belt comprises four nearly parallel faults: the Guanxian–Anxian fault in the southeastern part, the Yinxiu–Beichuan fault in the central part, the Wenchuan–Maoxian fault in the northwestern part, and the Qingchuan fault. Among these faults, the Guanxian–Anxian fault is the southeastern most boundary fault of the Longmenshan fault belt; the Yinxiu–Beichuan fault is a major fault, also called the central fault; and the Wenchuan–Maoxian and Qingchuan faults are boundary faults on the northwestern side. The eastern and western sides comprise the Sichuan Basin and the Songpan–Ganzi orogenic belt (Deng et al., 1994).

Seismological observations show that the movement intensity of the Longmenshan fault belt has been relatively weak since the Late Pleistocene epoch (i.e., during the last ten thousand years). The Holocene thrust slip speed of the western faults of the Longmenshan fault belt is 0.5–0.7 mm/a, and the right-lateral slip speed since the Late Pleistocene epoch is 0.8–1.0 mm/a (Ma et al., 2005; Tang and Han, 1993). The vertical slip speed of the central fault is 1 mm/a, and the movement intensity of the eastern faults is similar to that of the central fault (Deng et al., 1994). During the early and middle Pleistocene, the northern faults of the Longmenshan fault belt were active; however, these faults have not moved since the Late Pleistocene epoch, particularly after the middle of the Late Pleistocene epoch (Li et al., 2004). The above findings agree with those obtained by Densmore et al. (2007) and Zhou et al. (2007), who determined that the Yinxiu–Beichuan fault moves at a thrust speed of 0.3–0.6 mm/a with a right lateral slip speed of 1.0 mm/a, and that the Guanxian–Jiangyou fault moves with a thrust rate of 0.2 mm/a. Therefore, the vertical and horizontal slip speeds of the Longmenshan fault belt do not exceed 3 mm/a.

Historical and instrumental earthquake records show that there were five strong earthquakes of more than Ms 6.0 along the Longmenshan fault belt (Zhang et al., 2009a,b, 2010), and no earthquakes greater than Ms 7.0 since the beginning of documented Chinese history. However, historical earthquake records indicating that an earthquake greater than Ms 7.0 that may have occurred in the middle segment of the Longmenshan fault belt during the 1700 years prior to 2008 cannot be omitted (Wen et al., 2009). Evidently, the movement rate of the Longmenshan fault belt over approximately 1000 years, revealed by the intensity of historical earthquakes, was lower than that determined by the seismological observation at a scale of ten thousand years. The GPS observation results at a scale of ten years are consistent with the historical earthquake records (Gan et al., 2007; Shen et al., 2005). These results imply that the Longmenshan fault belt was in a deadlocked state for more than 1000 years before the Wenchuan Earthquake. Additionally, a leveling survey from Aba County to Chengdu indicated that the Chuanxi Plateau was uplifted with respect to the Chengdu Plain during the 10 to 30 years before the Wenchuan Earthquake. The uplift rate peaked at 3.1 mm/a at Barkam, but the uplift rate of the Longmenshan fault belt with respect to the Chengdu Plain was less than 1 mm/a (Zhang et al., 2009a,b, 2010; Department of earthquake monitoring and prediction of CEA, 2009), as shown in Fig. 1.

3. Stress data

3.1. Method of in situ stress measurements

For civil engineering purposes, our research group has conducted tens of stress measurement campaigns along the Longmenshan fault belt for more than 10 years. The in situ stress data were obtained by hydraulic fracturing (Haimson and Cornet, 2003). Hydraulic fracturing determines the orientation of the principal stresses in planes normal to the borehole axis on the basis of the azimuth of induced hydraulic fracturing planes and the pressure of boreholes that are open and close to the hydro-fractures. The curve of the recorded borehole pressure vs. time presents the characteristic pressure parameters P_b, P_r, and P_s borehole. Finally, the horizontal stresses and tensile strength of the rocks are calculated using relevant equations (Lee and Haimson, 1989). After the hydraulic fracturing operation has been conducted over a test interval, a fracture impression is conducted for the same test interval to determine the maximum horizontal stress orientation. Several techniques are available for the interpretation and definition of the typical hydro-fracturing parameters (Amadei and Stephansson, 1997; Zang and Stephansson, 2010). As our data were obtained for civil engineering purposes, the parameter calculations and considerations are based on the suggested method (Haimson and Cornet, 2003), and the main equations are as follows:

$$P_s = S_h \tag{1}$$

$$S_H = 3P_s - P_r - P_0 \tag{2}$$

$$T_{hf} = P_b - P_r, \tag{3}$$

where S_H = maximum horizontal stress, S_h = minimum horizontal stress, P_b = breakdown pressure of fracturing, P_r = fracture reopening pressure, P_s = fracture closure pressure, P_0 = pore water pressure at the test interval, and T_{hf} = tensile strength of rock.

The vertical stress (S_V) can be estimated using the weight of the overburden rock:

$$S_V = \rho g d, \tag{4}$$

where ρ = unit density, g = gravitational acceleration, and d = depth.

Ever since the hydraulic fracturing in situ stress measurement technique was proposed by Haimson and Fairhurst (1970), research using this technique has continued (Amadei and Stephansson, 1997; Ito et al., 1999, 2006; Zang and Stephansson, 2010; Chang et al., 2014). The major drawback of this technique is its inaccurate determination of the maximum horizontal principal stress (Ito et al., 1999) due to inaccurate interpretation of the reopening pressure (P_r). According to a statistical analysis conducted in a previous study (Amadei and Stephansson, 1997), the error range of the minimum horizontal principal stress S_h is approximately 10%. On the basis of Eq. (2), the error range of the maximum horizontal principal stress S_H is up to 30%. To improve the accuracy of hydro-fracturing in situ stress measurement, Ito et al. (2010) developed a BABHY (Baby Borehole Hydraulic fracturing) test system for deep boreholes with depths greater than 2000 m. However, many hollow cylinder rock specimen tests have been conducted to replace Eq. (3) with the results of laboratory tensile strength tests (Amadei and Stephansson,