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Coulomb stress evolution along Xianshuihe–Xiaojiang Fault System since 1713 and its interaction with Wenchuan earthquake, May 12, 2008

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ABSTRACT

The curved left-lateral strike-slip Xianshuihe–Xiaojiang Fault System (XXFS) in southwestern China extends at least 1400 km in the eastern margin of the Tibetan Plateau. Fieldworks confirm that the XXFS is one of the longest and most seismically active faults in China. The strain released by the slip motion on the XXFS is related to the convergence between the Indian and Eurasian plates. The entire fault system has experienced at least 35 earthquakes of $M > 6$ in the recent 300 years and almost all segments of the system have been the locus of major historical earthquakes. Since the XXFS region is heavily populated (over 50 million people), understanding the migration of the large earthquakes in space and time is of crucial importance for the seismic hazard assessment in this region. We analyze a sequence of 25 earthquakes ($M \geqslant 6.5$) that occurred along the XXFS since 1713, and investigate their influence on the 2008 Mw7.9 Wenchuan earthquake occurred on the adjacent Longmenshan fault. In our analysis, the relevant parameters for the earth crust are constrained by seismic studies. The locations and geometries of the earthquake faults as well as the rupture distributions are taken from field observations and seismological studies. Results from the Coulomb failure stress modeling indicate significant interactions among the earthquakes. After the 1713 earthquake, 19 out of 24 earthquakes occurred in the positive stress zone of the preceding earthquakes. The other 5 earthquakes located in the area without significant stress changes induced by the preceding events. In particular, we can identify 4 visible earthquake gaps with increasing seismic hazard along the XXFS, consistent with the findings from the paleo-seismological studies. The seismic activity and tectonic motion on the XXFS reduced the Coulomb stress accumulation at the hypocenter of 2008 Mw7.9 Wenchuan earthquake, implying that the Wenchuan earthquake might not be triggered directly by the seismic activities on the XXFS. On the other hand, the Coulomb failure stress induced by the Wenchuan earthquake has increased in a region of 125-km-long segment of the XXFS, northwest of Kangding City.

1. Introduction

The Xianshuihe–Xiaojiang Fault System (XXFS), located in southwest China, is a curved left-lateral strike-slip structure extending at least 1400 km (Allen et al., 1991) in the eastern margin area of the Tibetan Plateau (Fig. 1). Field work confirms that the XXFS, whose slip motion releases strain that is related to the convergence between the India and Eurasia plates (e.g. Molnar and Tapponnier, 1975), is one of the largest and most seismically active faults in China.

The XXFS is a complex system of active faults, including the Xianshuihe fault, the Anninghe fault, the Zemuhe fault, and the Xiaojiang fault (Allen et al., 1991; Wang and Burchfiel, 2000). The entire fault system has experienced at least 35 earthquakes of $M > 6$ in recent 300 years and almost all segments of the system have been the locus of major earthquakes within the historic record (Fig. 1) (Allen et al., 1991). The time-space progression on XXFS evidenced by the historic earthquakes suggests certain interaction among earthquakes (Wen et al., 2008). Since the XXFS region is heavily populated (over 50 million people) (Fig. 1), understanding the spatial and temporal dependent distribution of strong earthquakes and their interaction with each other is important for assessing seismic hazard in this region.

In general, interaction between earthquakes is suggested to realize in a manner of earthquake triggering by the change of Coulomb Failure Stress (ΔCFS) (Stein, 2003): positive ΔCFS brings the fault closer to failure and thus earthquake occurrence, while

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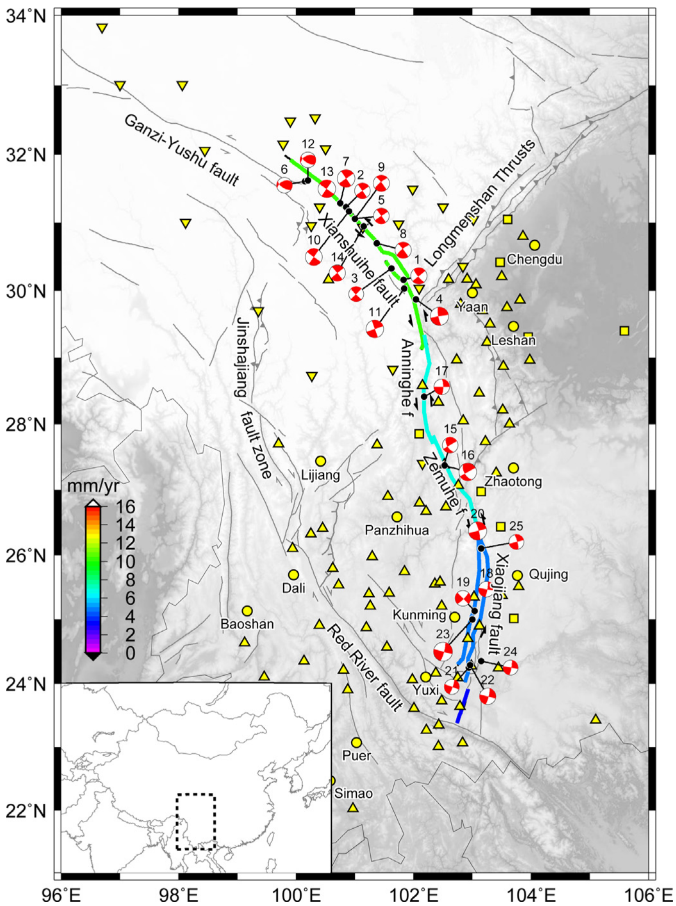

Fig. 1. Location map of the Xianshuihe–Xiaojiang Fault System (XXFS) and the space distribution of 25 M ⩾ 6.5 earthquakes along the XXFS during the period 1713 to 1966. The focal mechanisms with serial number are listed in Table 1. Colorful lines show the slip rate of the XXFS. The symbols represent the locations and populations of cities (downward solid triangle: population <0.1 million; upward solid triangle: 0.1–0.5 million; solid square: 0.5–1 million; solid circle: >1 million). Inset shows the location of the study region in the whole China. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

negative ΔCFS retards subsequent events (Stein, 1999; Freed, 2005). Based on the earthquake stress triggering theory, numerous studies have successfully explained the features of aftershock distribution (King et al., 1994; Reasenberg and Simpson, 1992; Parsons et al., 1999; Toda et al., 1998; Wyss and Wiemer, 2000; Ma et al., 2005), time-dependent earthquakes migration (Stein et al., 1994; Hodgkinson et al., 1996; Nalbant et al., 1998), and the triggering phenomena of moderate to large earthquakes (Harris et al., 1995; Deng and Sykes, 1996; Jaume and Sykes, 1996; Martínez-Díaz et al., 2006). Based on the physical mechanisms of stress transfer, the processes of earthquake interaction are divided into static, quasi-static (time-dependent) and dynamic triggering (Freed, 2005). As mentioned above, seismic activity in stress shadow where stress accumulation is released would be depressed. Actually, stress shadow only exists in the process of static and quasi-static stress transfer. Therefore, the stress shadow effect is very important for separating static from dynamic fault interaction (Felzer and Brodsky, 2005, 2006; Richards-Dinger et al., 2010). Thus, the theory of earthquake stress triggering provides us an important tool to assess time-dependent earthquake hazard (McCloskey et al., 2005; Nalbant et al., 2005).

The active seismicity and well-documented long-term earthquakes record (at scale of several hundred years) of the XXFS (Allen et al., 1991; Wen et al., 2008) make the XXFS an ideal place to analyze earthquake triggering mechanism and the earthquake migration process. Previous works (e.g., Papadimitriou et al., 2004; Paradisopoulou et al., 2007) have proven the possibility of stress interaction on the XXFS. Assuming purely elastic behavior for the crust and upper mantle and taking into account the co-seismic slip of earthquakes together with the inter-seismic loading due to tectonic stress build-up, Papadimitriou et al. (2004) and Paradisopoulou et al. (2007) analyzed the stress evolution and found that all the strong earthquakes along the Xianshuihe–Xiaojiang fault occurred on the stress-enhanced fault segments. However, both of these studies do not take into account the process of post-seismic relaxation of a viscous lower crust and upper mantle following major earthquakes, which may influence on the long-term stress transfer process.

Co-seismic stress models assume purely elastic behavior for the crust and upper mantle. In reality, however, the lower crust and upper mantle behave as an inelastic body. Due to the post-seismic relaxation, the co-seismically induced stress change in the lower crust and upper mantle can be transferred upwards to the seismogenic upper crust (Lorenzo-Martín et al., 2006; Freed et al., 2007; Ali et al., 2008). Numerous studies have proposed that the stress transfer due to post-seismic relaxation may have a significant impact on the evolution of the regional stress (Deng et al., 1999; Freed and Lin, 2001; Pollitz et al., 2003; Lorenzo-Martín et al., 2006; Smith and Sandwell, 2006; Freed et al., 2007; Ali et al., 2008). Hence, post-seismic relaxation should be considered in analysis of stress transfer and earthquake interaction.

In this work, we improve the studies of Papadimitriou et al. (2004) and Paradisopoulou et al. (2007) by incorporating the stress transfer due to post-seismic relaxation. A sequence of 25 magnitude M > 6.5 earthquakes (Table 1 and Fig. 1) that occurred on the XXFS over the past 300 years are used for the analysis. The purpose of this work is to study the evolution of the Coulomb stress changes along the XXFS due to co-seismic slip, post-seismic relaxation and inter-seismic tectonic loading to illuminate how the earthquake occurrence is related to these stress changes. In contrast to Papadimitriou et al. (2004) and Paradisopoulou et al. (2007), in which the sub-faults were studied independently, we study the entire XXFS as a whole fault system in this work. A more complete earthquakes catalog is employed and new knowledge from studies (Wen et al., 2008) in recent years is included to constrain the medium properties and stratification, as well as the stress build-up on the XXFS. On 12 May 2008, the Mw7.9 Wenchuan earthquake occurred on Longmenshan fault, which is adjacent to the XXFS (Fig. 1). This earthquake and its aftershock sequence have been well studied using the seismic and geodetic data. In this study, we also calculate the stress accumulation at the hypocenter of the Wenchuan earthquake induced by the historic earthquakes on the XXFS, to investigate the impact of historic earthquakes on XXFS upon the Wenchuan earthquake, and in turn, the influence of Wenchuan earthquake upon the future seismic hazard on the XXFS.

2. Neotectonics and historical seismicity

2.1. Historical earthquakes

Although the earliest record of historical earthquakes in official documents is found as early as in the fourteenth century, the earliest seismo-tectonic investigation on the XXFS was conducted in 1934 for studying the surface rupture and damage of the 1893 and 1923 events (Wen et al., 2008). Based on the historical records, field surveys (Allen et al., 1991) and paleo-seismological studies (Wen et al., 2007), a catalog of strong historical earthquakes on the XXFS has been available. Since early events are poorly located, evidences from the field surveys and damage reports are employed