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Analysis of fluid induced aftershocks following the 2008 Wenchuan Ms 8.0 earthquake

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ABSTRACT

After the strong Ms 8.0 Wenchuan earthquake, aftershock sequences occurred in a specific spatio-temporal distribution. This paper investigates the role of fluids in the aftershocks of the Wenchuan Ms 8.0 earthquake. We apply pore pressure diffusion mechanics to analyze the aftershock spatio-temporal distributions from eight study areas along the fault zone, which belong to different rupture patterns. The eight study areas from the south to the north are SA, SC, SJ, SM, NA, NB, ND and NG. The aftershocks within rupture patterns exhibited a migration of hypocenters that appears to be represented by the pore pressure diffusion equation. Furthermore, the aftershocks can be divided into three stages during 2008.05.12–2008.11.28, and each stage corresponds to a process of pore pressure diffusion. The hydraulic diffusivities have a range of 1.8 to 4.2 m^2/s, and the mean hydraulic diffusivities of the eight study areas from the south to the north are 3.5 m^2/s, 3.3 m^2/s, 3.2 m^2/s, 2.9 m^2/s, 2.8 m^2/s, 2.3 m^2/s, 2.1 m^2/s and 2.7 m^2/s, revealing a decreasing trend. The mean hydraulic diffusivities of the three stages demonstrate an increasing trend: 2.5 m^2/s, 2.8 m^2/s and 3.3 m^2/s. Strong aftershocks from the Wenchuan earthquake occurred mainly in the northern part of the fault zone. The differences in the hydraulic diffusivities from the north to the south may be related to the strength of the aftershocks. A comprehensive analysis of this topic may help us gain a deeper understanding of the role of fluid in the spatio-temporal evolution of earthquakes and produce better earthquake hazard assessments.

1. Introduction

Large earthquakes are often accompanied by long-term aftershocks, and the process of aftershock activity is attracting attention from the scientific community. The evolution of the aftershocks is probably related to the deep fluid in the crust (Noir et al., 1997). Because aftershocks of large earthquakes often occurred in ~5–20 km underground (Sibson, 1983); the region at this depth easily forms supercritical fluid with high temperatures and high pressures (Rice, 1992). On the one hand, the occurrence of aftershocks may be due to the upwelling of deep fluid which can reduce the effective stress and then trigger earthquake (Wang and Manga, 2009). In April 2009, the Mw 6.3 earthquake occurred in L'Aquila, Italy, and produced more than 10,000 aftershocks. Terakawa et al. (2010) used FMT (focal mechanism tomography) to investigate these aftershocks and showed that the aftershocks were mainly distributed in high pore pressure areas. On the other hand, the spatio-temporal distribution of aftershocks may be related to the transport of fluid (Nur and Booker, 1972), such as the aftershocks of the 1992 Landers earthquake (Bosl and Nur, 2002), the aftershocks of northern Chile's 1995 Antofagasta earthquake (Shapiro et al., 2003), the aftershocks of Italy's 1997 Umbria–Marche earthquake (Miller et al., 2004), and the aftershocks of the 2004 Sumatra earthquake (Waldhauser et al., 2012). All of these studies suggest that aftershock activity and fluid occurrence are closely related.

On May 12, 2008, the Wenchuan Ms 8.0 earthquake occurred in the Longmen Shan fault zone. Many authors have discussed the role of fluid in the Wenchuan earthquake, whether the concentrate on Zipingpu reservoir (Kerr and Stone, 2009) or the deep fluid in the crust (Wang et al., 2009). By numerical stimulation, the calculated stress changes caused by the Zipingpu reservoir storage showed that it facilitated the occurrence of the Wenchuan earthquake (Ge et al., 2009; Lei et al., 2008). However, Wenchuan earthquake does not comply with the characteristics of reservoir induced seismicity (Chen, 2009). Furthermore, P-wave tomography evidence showed that there are low velocity anomalies below the main shock hypocenter area and deep fluid may influence the occurrence of Wenchuan earthquake (Lei et al., 2009). All these researches suggest that fluid may have played an important role in the process of the Wenchuan earthquake and the aftershock activity. However, these studies rarely combine the fluid diffusion processes with the spatio-temporal distribution of the aftershocks and describe the pore pressure characteristics in fault zones. In order to clarify this relationship and extract information about deep fluid activities, it is essential

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to apply pore pressure diffusion mechanism which is often used to analyze the triggering mechanism of some induced earthquakes (Shapiro et al., 1997), volcanic earthquakes (Yukutake et al., 2011), reservoir induced earthquakes (Liu et al., 2011) and aftershocks (Shapiro et al., 2003).

In the present study, we clarify the remarkable features revealed by the spatio-temporal distribution of the hypocenters belonging to different rupture patterns based on the hypocenters of Wenchuan aftershocks with high precision. We obtain hydraulic diffusivities based on the theory of pore pressure diffusion, analyze their spatial and temporal variety and discuss its meaning to predict the permeability in the fault zone and assess earthquake hazard. The results show that the fluid flows within a fault zone controlled the occurrence of aftershocks for the Wenchuan earthquake.

2. Tectonic setting

As the easternmost thrust belt of the Songpan–Ganzi orogen (Xu et al., 1992), the Longmen Shan fault zone includes three thrust faults from west to east: the Wenchuan–Maoxian, Yingxiu–Beichuan and Anxian–Guanxian faults (Fig. 1) (Li et al., 2006; Wang and Meng, 2008). Pre-earthquake GPS measurements suggest that the deformation rate across the entire Longmen Shan fault zone is less than 2 mm/year (Zhang et al., 2008), indicating that the Longmen Shan fault zone has been locked (Xu et al., 2008b). Considering that no earthquake larger than Ms 7.0 has occurred on the Longmen Shan fault zone (Zhang et al., 2008), it means that there was a relative long quite period before the Wenchuan Ms 8.0 earthquake, accumulating energy and increasing the possibility of large earthquake occurrence (Li et al., 2013).

Field surveys show that the Wenchuan earthquake produced at least two surface ruptures on the Longmen Shan fault zone: Yingxiu–Beichuan rupture zone and Guanxian–Anxian rupture zone, which are about 275 km and 80 km respectively (Li et al., 2008). It shows the two peaks along the Yingxiu–Beichuan rupture zone by detailed displacement analysis (Li et al., 2008). The maximum vertical offset is 6–6.7 m in the southern segment whereas in the northern segment, the maximum vertical offset is 11–12 m (Li et al., 2009). Furthermore, the southern segment mainly experienced thrust rupture, whereas the northern part is almost purely dextral strike-slip rupture (Li et al., 2009) which generally correspond with two rupture processes indicated by seismic wave inversion (Wang et al., 2008).

3. Spatio-temporal distributions of Wenchuan aftershocks

The northwest side and the southwest side of the Longmen Shan fault zone belong to the Bayan Har block and the South China block, respectively, and the velocity structures of their regional crustal and upper mantle are fairly different (Xu et al., 2008a). To reduce the substantial impact of the horizontal velocity structure variations, we applied a different velocity model across the Longmen Shan fault zone and constructed a hierarchical velocity model in the vertical direction.

The aftershocks that occurred following the Wenchuan Ms 8.0 earthquake were recorded by the Sichuan seismic network (May–December 2008). We selected 10,413 of these aftershocks. After relocation of the aftershocks via HYPODD (Waldhauser and Ellsworth, 2000) we obtain 8604 M ≥ 2.0 aftershocks. To improve the accuracy of the relocation process, we use data collected from the stations of the Sichuan seismic network and the seismic networks of neighboring provinces, the temporary mobile seismic stations that were set up after the earthquake, and the regional business and telemetry stations. The average uncertainty of the relative hypocenter in the E–W, N–S and U–D directions are approximately 0.76 km, 0.76 km and 1.09 km, respectively. For the data

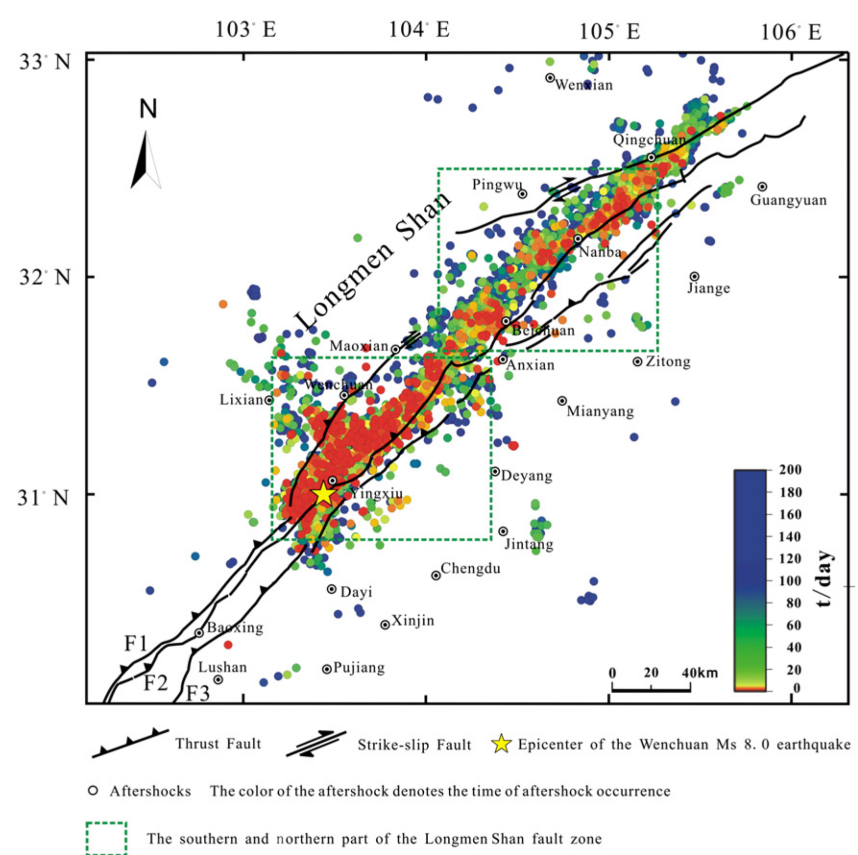

Fig. 1. Spatio-temporal distributions of aftershocks. F1: Wenchuan–Maoxian fault; F2: Yingxiu–Beichuan fault; F3: Guanxian–Anxian fault (fault data from Zhang et al., 2008).