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Seismic imaging, crustal stress and GPS data analyses: Implications for the generation of the 2008 Wenchuan Earthquake (M7.9), China

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ABSTRACT

Seismic imaging together with global positioning system (GPS) and crustal stress data analyses show that the Mw7.9 2008 Wenchuan earthquake occurred within a distinct area of high crustal stress (~17.5 MPa) and high Poisson's ratio (7–10%) anomalies centered on the Longmen-Shan (Shan means Mountain in Chinese) tectonic fault belt. Low P-wave and S-wave velocities in the southwest (SW) segment contrast with high-velocity anomalies in the central portion (CP) and northeast (NE) segment within the uppermost ~15 km depths along the tectonic fault belt, though a presumably ductile zone with low-velocity anomalies separates the CP and NE segment. The rupture initiated near the southwestern end of the CP at a zone of high Poisson's ratio (σ) which extends down into the lower crust. These low-velocity and high-σ anomalies immediately below the source hypocenter, together with the high crustal stress, indicate the presence of high-pressure fluids from the lower crust, which might have reduced the mechanical strength of the fractured rock matrix and triggered the earthquake. Our study suggests that the structural heterogeneity and high crustal stress played an important role in the nucleation of the Wenchuan earthquake and its rupture process.

1. Introduction

On May 12, 2008 (06:28:01 UTC) the devastating Wenchuan earthquake (Mw7.9) occurred in the center of the Longmen-Shan fault belt, with a complex structure including several large thrust faults with 250–300 km lateral extension (Fig. 1). The shock was characterized by its long time duration, extensive surface fault rupture and shallow hypocenter depth (~16 km); the shock epicenter was about 90 km west of Chengdu, the largest city and the capital of Sichuan province in southwest China. Most of the aftershocks were orientated northeast with 250–300 km length and 50 km width along the tectonic fault zone (Fig. 1). This was the most significant earthquake to have struck China since the 1976 Tangshan Earthquake (M 7.6), which caused great loss of life and economic damage as well as damage to the geoenvironment.

The Longmen-Shan tectonic zone, adjacent to the Sichuan foreland basin at the eastern margin of the Tibetan Plateau (Fig. 1), is characterized by steep topographic gradients, complex reverse-thrust and strike-slip faults and convergent mountain building (e.g., Burchfiel et al., 1995; Chen and Wilson, 1995; Burchfiel et al., 2008; Royden et al., 2008; Wang et al., 2009). The Indian continental plate is being subducted northward at a rate of ~5.5 cm/year into Tibet and the surrounding regions, which has caused strong compressional deformation and crust shortening followed by E–W crust extension and eastward extrusion during the Late Miocene–Quaternary across the Longmen-Shan tectonic thrust belt over an ~50 km horizontal distance (Burchfiel et al., 2008; Parsons et al., 2008; Wang et al., 2009). Several tectonic blocks tens to hundreds of kilometers wide have moved southeastward along the fault zone to accommodate the ongoing northeastward penetration of the Indian plate into the Asian continent (e.g., Molnar and Tapponnier, 1975; Meyer et al., 1998; Pei et al., 2007). In a geologic view, the collision system along the eastern margin of the Tibetan Plateau includes the Songpan–Garze fold system in the west, the Yangtze platform system in the southeast and the Sichuan Foreland basin in the east (Fig. 1). The southeastward extrusion of the Songpan–Garze block, which is obliquely pushing against the Sichuan foreland basin, has resulted in three large reverse-thrust and strike-slip faults, including the Wenchuan–Maowen fault (rear fault), the Yingxiu–Beichuan fault (central principle fault) and the Guanxian–Jiangyou fault (fore fault), oriented from southwest to northeast across the Longmen-Shan fault zone (Fig. 1).

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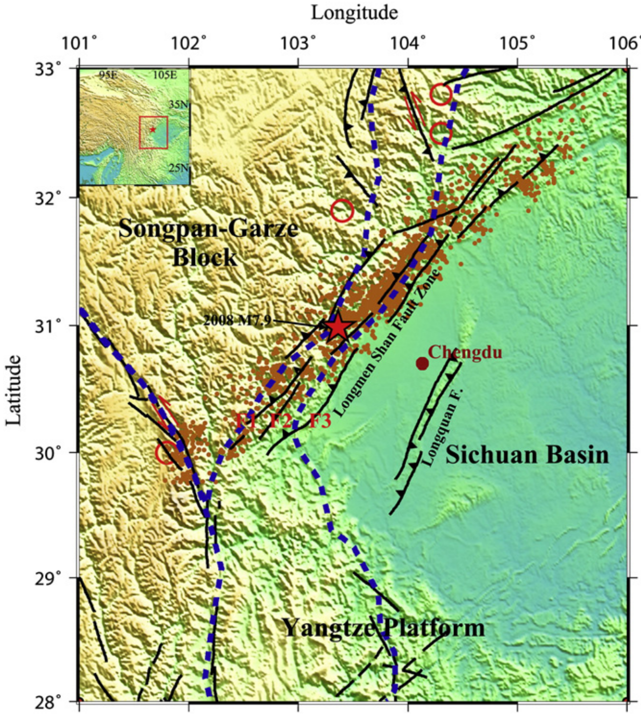

Fig. 1. Schematic illustration of tectonics on topographic map. A red star indicates the epicenter of the Mw7.9 2008 main-shock and dark red dots show those of the aftershocks (Mw>3.0). Open red circles show the large historical crustal earthquakes (Mw>7.0) that occurred during the period of 1970 and 2007. Blue dashed lines indicate the tectonic boundaries between the main blocks. A red box in the insert map shows the study region. F1: Wenchuan–Maowen fault (rear fault). F2: Yingxiu–Beichuan fault (central principle fault).F3: Guanxian–Jiangyou fault (fore fault).

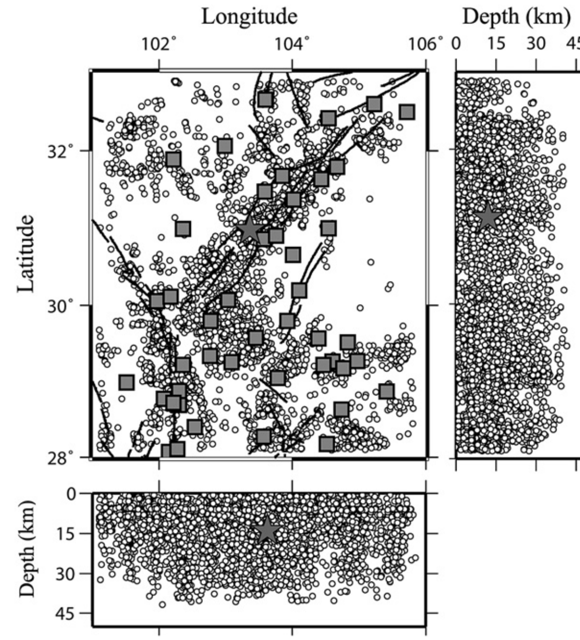

Fig. 2. Three-dimensional hypocentral distribution of 5172 earthquakes (white dots) relocated by the present study. A gray star shows the Mw7.9 Wenchuan hypocenter. Gray squares indicate the 45 stations that recorded the travel times during the period from Jan. 1985 to Dec. 2007. Black solid lines denote the active faults.

We consider that the extensive damage caused by the Wenchuan earthquake might be attributed in part to crustal structural heterogeneities and high crustal stress accumulation, as well as a complex pattern of tectonic thrust and strike-slip faulting, which caused significant ground displacement and acceleration on a regional scale (e.g., Burchfiel et al., 2008; Parsons et al., 2008; Nishimura and Yagi, 2008). We therefore determined the 3-D seismic velocity and Poisson's ratio structures, and analyzed crustal stress and GPS data collected from the tectonic fault zone, to investigate what may have initiated the Wenchuan earthquake and why its rupture propagation was so complex.

2. Data and methods

2.1. Seismic data selection

Fig. 2 shows the three-dimensional (3-D) hypocenter distribution of the 5172 local earthquakes and 45 seismic stations we used. The seismic stations are deployed by the Sichuan Earthquake Bureau (SEB) and the Institute of Geophysics of China Earthquake Administration (IGCEA). We selected the P-, Pn-phases and S-, Sn-phases carefully according to the following criteria. Firstly, epicenter distances are limited to the range of 0–180 km for P and S phases and of 240–400 km for Pn- and Sn-phases, respectively (Fig. 3). The Pn- and Sn-phases are the first arrivals within this distance range. Secondly, only earthquakes that occurred in the study region with magnitude greater than 1.5 and focal depth shallower than 50 km are selected. Thirdly, all the selected events are recorded by more than four seismic stations. Under these criteria a total of 41,675 P- and Pn-phases and 36,783 S- and Sn-phases from 5172 earthquakes were selected. Because there were few earthquakes deeper than 30 km, the combined data set is crucial for imaging the lower crust structure. The travel time residuals with variations from −3.0 s to +3.0 s for P- and Pn-phases and from −4.0 s to +4.0 s for S- and Sn-phases were selected for the inversion of P- and S-wave velocity, respectively (Fig. 3).

2.2. Crustal stress and GPS data

To investigate the spatial distribution of the tectonic stress and its implications for the initiation and rupture process of the Wenchuan earthquake, we have collected 31 crustal stress data from 12 sites along the tectonic fault zone (Table 1). The crustal stress data were estimated before the Wenchuan earthquake by using in-situ stress measurement or borehole over-coring stress release method in fields along the main tectonic fault zones, and collected by the State Key Laboratory of Geohazards Prevention and Geoenvironment Protection, Chengdu University of Technology, China (Huang et al., 2009).

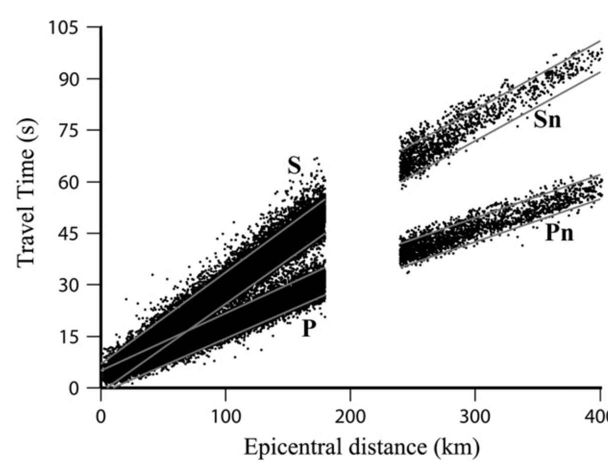

Fig. 3. First P-wave and S-wave travel times versus epicenter distance. The epicenter distances with the ranges of 0–180 km for P and S phases and of 240–400 km for Pn- and Sn-phases were used in this study. The travel time residuals with the variations from −3.0 s to +3.0 s for P- and Pn-phases and from −4.0 s to +4.0 s for S- and Sn-phases (two gray lines) were selected to inverted P- and S-wave velocity, respectively.