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Crustal deformation along the Longmen-Shan fault zone and its implications for seismogenesis

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ABSTRACT

The Longmen-Shan fault zone, at the eastern margin of the Tibetan Plateau, is one of the most extensively studied areas in the world, yet the deformation model and earthquake-generating mechanism remain subjects of vigorous debate. This paper presents a new three-dimensional (3-D) velocity model determined using a large volume of seismic data and two-dimensional (2-D) magnetotelluric (MT) profiles from previous studies, to investigate the mechanisms of crustal deformation and earthquake generation along the reverse-thrust and strike-slip fault zone. It has been observed that low-velocity, and low-resistivity anomalies related to the Sichuan foreland basin, is in sharp contrast to high-velocity and high-resistivity anomalies in the Songpan-Ganze block in the upper crust. The tomographic model presented here reveals two crustal bodies with low-velocity and high-conductivity anomalies underneath the Longmen-Shan fault zone, separated into three contrasting segments by the two crustal bodies. The two low-velocity and low-resistivity bodies have been interpreted as being associated with extrusion of either fluids or products of partial melting from the lower crust and/or the upper mantle. This suggests strong variations in the rheological strength of the rock along the fault zone. This finding implies that coupling between these presumably fluid-bearing bodies and earthquake generation could be extremely complex and that there is dramatic variation from the southwestern area to the northeastern segment along the fault belt. It is suggested here that this complex and variable deformation system along the fault zone played a principal role in controlling seismic generation and rupturing during the 2008 Wenchuan earthquake (Ms 8.0) and that it will do so again during possible future earthquakes in the region.

1. Introduction

The Longmen-Shan range front, characterized by convergent mountain building with a greater topographic gradient than anywhere else on the Tibetan Plateau (Burchfiel et al., 2008; Clark and Royden, 2000), lies in a conjunctional area between the northwestern Songpan–Ganze terrane and the Sichuan foreland basin (Fig. 1). The Songpan–Ganze fold system has obliquely collided with the Sichuan foreland basin, resulting in three large reverse-thrust and strike-slip faults along the Longmen Mountain region of 250–300 km in extent, including the Guanxian–Jiangyou fault (fore fault: f1), the Yingxiu–Beichuan fault (central, principal fault: f2), and the Wenchuan–Maowen fault (rear fault: f3), oriented from southwest to northeast across the fault zone (Fig. 1).

Many studies of the geology, geodetics, and geophysics of the area have been conducted in the last three decades (Bai et al., 2010; Burchfiel, 2004; Lei and Zhao, 2009; Meade, 2007; Royden et al., 1997; Wang et al., 2009b, 2010, 2011; Zhang et al., 2009). These revealed strong seismic velocity variations, slip-rate gradients, crustal stress changes, and Longmen Orogenic evolution along Longmen Mountain and its surrounding regions. On the basis of these studies, two hypotheses have been proposed for how the Longmen Mountain crust was deformed. One hypothesis holds that the Longmen Orogeny was formed by crustal faulting and shortening as well as time-dependent, localized shear between coherent lithospheric blocks (Meade, 2007; Tapponnier et al., 2000). According to the other hypothesis, the Longmen Orogeny has been uplifted and is maintained by dynamic pressure from lower crustal flow (Burchfiel, 2004; Huang et al., 2009; Hubbard and Shaw, 2009; Royden et al., 1997; Wang et al., 2010). Although previous geologic and geodetic studies have indicated limited crustal shortening (<3 mm/year) across the Longmen-Shan collision front (Meade, 2007; Shen et al., 2005), a devastating earthquake of Ms 8.0 in magnitude, centered in the Longmen-Shan fault zone, occurred at Wenchuan on May 12, 2008, resulting in more than 85,000 fatalities and causing widespread environmental damage in southwestern China. This seismotectonic feature prompted a number of researchers to attach great importance to correlation of the crustal deformation model and the earthquake-generating mechanism and to the complex rupture process that occurred during the Wenchuan earthquake. The aim of this study is to provide important geophysical evidence on these issues from analyses of seismic data and magnetotelluric (MT) soundings.

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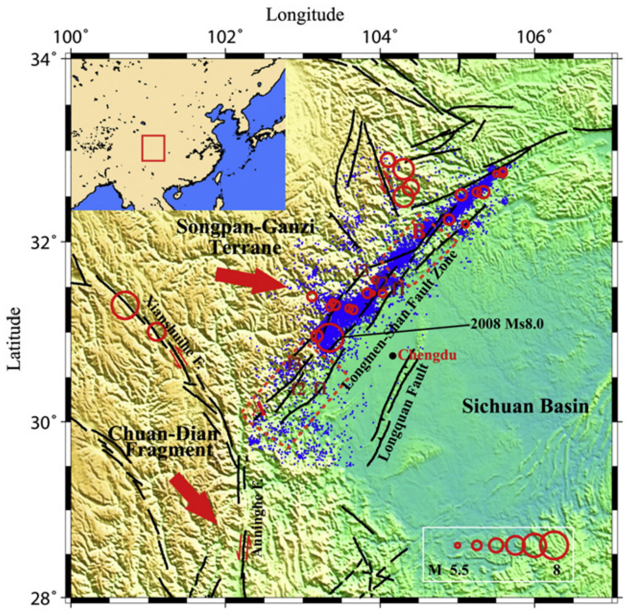

Fig. 1. Tectonic framework map of the Longmen-Shan tectonic zone and its surrounding regions. Red circles show locations of large historic earthquakes (M >5.5) during 1913–2008. Blue dots indicate aftershocks of the 2008 Wenchuan earthquake. Black solid lines show active faults in the Longmen-Shan Fault zone. The two red arrows indicate the rotation directions of the Songpan–Ganze fold system and the Chuan-Dian fragment, respectively. The magnitude of the large crustal earthquakes is shown in the bottom right corner of the map. A red box in the insert map shows the study region. f1, f2, and f3 (dark red) indicate the Guanxian–Jiangyou fault (fore fault), the Yingxiu-Beichuan fault (central principal fault) and the Wenchuan-Maowen fault (rear fault), respectively, from east to west.

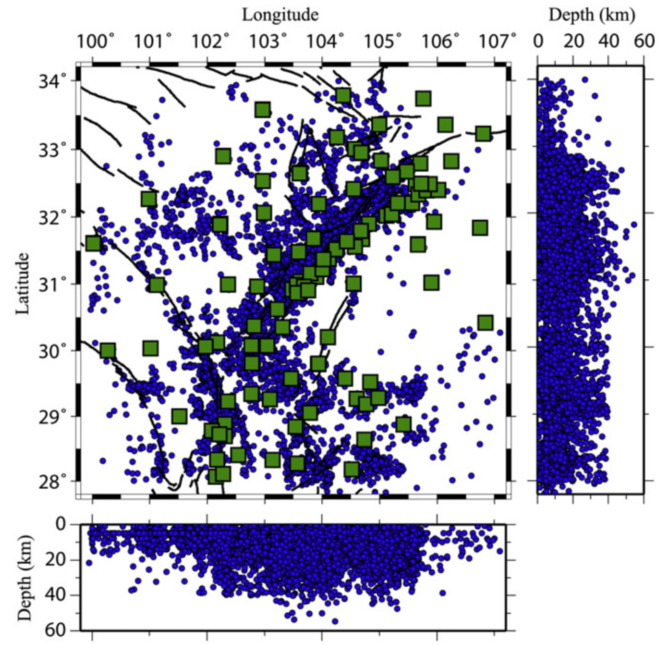

Fig. 2. Locations of the earthquakes and seismic stations (green squares) that recorded arrival times for local earthquakes used to image the seismic structures. Blue dots show the 3-D hypocentral locations of 16,142 local earthquakes of magnitude greater than 1.0 from January 2000 to July 2008. These stations include 89 permanent stations and 34 temporary seismic stations after the Ms 8.0 Wenchuan earthquake along the Longmen fault zone (see the text for details). Black solid lines denote the active faults.

2. Data and methods

To image seismic velocity structures in the crust, a large number of high-quality P- and S-wave arrival times from local earthquakes, which included two earthquake groups, were used. The first group includes 7854 background seismicity occurrences from January 2000 to December 2007. The second group includes 8288 aftershocks of the Wenchuan earthquake for May 12–17, 2008. Two groups of earthquakes were carefully selected according to several criteria. For data from the first group, the criteria were: (1) an earthquake focal depth ≤60 km and a magnitude greater than Mb 1.0 in the study region; (2) epicenter distances of 0–1.8° for Pg and Sg phases and of 3–6° for Pn and Sn arrivals, with Pn and Sn being the first P and S arrivals within the epicenter range, respectively; and (3) local events recorded by more than eight seismic stations. Pg and Sg phases were selected from the aftershocks for the arrival times from the second group. Absolute travel-time residuals with variations of −2.5 s and +2.5 s for P and Pn phases and −3.0 s and +3.0 s for S and Sn phases, respectively, were selected from the two groups. In total, data for 136,795 P and Pn phases and 121,292 S and Sn phases from 16,142 local earthquakes were collected to invert the 3-D Vp and Vs structures.

A total of 123 seismic stations were used in this study (green squares in Fig. 2). These included 89 permanent stations deployed by the Earthquake Bureaus of Sichuan and Yunnan provinces and the Institute of Geophysics of the China Earthquake Administration (IGCEA) and 34 temporary seismic stations installed by the Sichuan Earthquake Bureau immediately after the Wenchuan earthquake.

A 1-D initial velocity model was derived from recent receiver function and local tomography studies (Wang et al., 2009b; Xu et al., 2007). An optimal 1-D velocity model was then calculated, using inhomogeneous velocities in each of the layers of laterally varying thickness. Once the optimal 1-D Vp and Vs models were determined, earthquakes with more than 10 P-wave and nine S-wave arrivals were selected for calculations using the initial P-wave and S-wave models, respectively. A grid model was used with a horizontal grid spacing of 50 km and a vertical grid spacing of 6–20 km considering the effects of station spacing density, seismic data, and ray-path spatial distributions on the final resolution. To search for the best value of the damping parameter in the tomographic inversion, multiple inversions were conducted with different values of the damping parameter, using arrival times from local events. The 1-D velocity model determined and the grid model were then simultaneously considered. The best value of the damping parameter was found to be 16.0, taking into account a balance between the reduction of travel-time residuals and the smoothness of the 3-D velocity model obtained.

To improve the hypocentral accuracy for the earthquakes, their hypocenters were relocated using the double-difference (DD) location method (Waldhauser and Ellsworth, 2000; Wang and Zhao, 2006a). For the DD locations, 1,043,116 relative residuals from 143,676 event pairs were selected from the P absolute travel times, and 912,784 relative residuals from 138,783 event pairs were selected from the S absolute travel times. Analysis of the relocated earthquake hypocenters indicated that more than 94.7% of the background seismic shocks (a total of 7438) and 96.5% of the aftershocks (a total of 7998) were relocated according to the DD method. The earthquakes for which DD relocation was not indicated relocated using the conventional location procedure (Zhao et al., 1996). Fig. 3 shows examples of plan views and cross sections of the relocated aftershocks along the Longmen Mountain region. The tomographic method (Zhao et al., 1992, 1996) was then used to carry out 3-D seismic inversion with the improved relocated hypocenters.

3. Resolution analyses

To evaluate the resolution of the inverted 3-D velocity model, checkerboard resolution tests (CRTs) were used in the study region to