SCIENCE CHINA
Earth Sciences

• RESEARCH PAPER •

September 2011 Vol.54 No.9: 1386–1393
doi: 10.1007/s11430-011-4177-2

Crustal P-wave velocity structure of the Longmenshan region and its tectonic implications for the 2008 Wenchuan earthquake

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Received April 1, 2010; accepted September 10, 2010

The P-wave velocity structure of the crust in the Longmenshan region has been imaged by seismic travel time tomography using local and regional first P-wave arrivals recorded from 2000 to 2008. The tomographic model provides a way to analyze the deep tectonics of the Longmenshan fault belt and the tectonic implications for the 2008 M_s8.0 Wenchuan earthquake. The P-wave velocity images indicate that the initial rupture site and focal depth of the Wenchuan earthquake, together with the direction of rupture propagation, closely relate to the crustal structure of the Longmenshan region. The Pengguan massif to the west of the Longmenshan fault belt is characterized by high velocity anomalies, suggesting that the crust has a strong strain strength that can accumulate large stresses over a long period. The M_s8.0 Wenchuan earthquake is located at the southwestern end of the Pengguan massif and the western edge of the Sichuan Basin. The collision between the Pengguan massif and the Sichuan Basin becomes the primary reason for the occurrence of the M_s8.0 Wenchuan earthquake. To the north of Wenchuan, the occurrence and propagation of rupture benefit from low velocity anomalies along the Longmenshan fault belt; whereas to the south of Wenchuan, the brittle rupture can occur with more difficulty in relatively weak crust with low velocities. This may be one of the reasons for the absence of aftershocks to the south of Wenchuan, and the rupture induced by the M_s8.0 Wenchuan earthquake propagating from the north to the south along the Longmenshan fault belt. The deep geodynamics of the M_s8.0 Wenchuan earthquake may occur due to the discrepancy of crustal structures on the two sides of the Longmenshan fault belt. Ductile deformation and crustal flow can easily occur in the weak middle-lower crust beneath the Songpan-Garze orogenic belt. The eastward movement of the Tibetan Plateau is obstructed by the rigid lithosphere of the Sichuan Basin, and then the thickening of the middle-lower crust and vertical deformation occur in the crust of the Longmenshan fault belt. In addition, the down-warping of the Moho and the basement thrusting onto the range front induced crustal deformation and strain accumulation, which provided the potential energy to trigger the occurrence of the M_s8.0 Wenchuan earthquake.

Longmenshan orogenic belt, Wenchuan earthquake, P-wave velocity, crustal structure, travel time tomography

Citation: Li Z W, Xu Y, Huang R Q, et al. Crustal P-wave velocity structure of the Longmenshan region and its tectonic implications for the 2008 Wenchuan earthquake. Sci China Earth Sci, 2011, 54: 1386–1393, doi: 10.1007/s11430-011-4177-2

The Longmenshan fault belt is located at the margin of the eastern Tibetan Plateau, which forms the tectonic boundary between the Songpan-Garze orogenic belt and the Sichuan Basin. On 12 May 2008, an M_s8.0 earthquake, hereafter referred to as the Wenchuan earthquake, occurred in the Longmenshan fault belt. The Longmenshan fault belt is developed in the ancient metamorphic complex with high strain strength, and consists of three NE striking faults: the Wenchuan-Maoxian, Yingxiu-Beichuan, and Guanxian-Jiangyou faults (Figure 1). The Yingxiu-Beichuan Fault is the main fault for the rupture process of the Wenchuan

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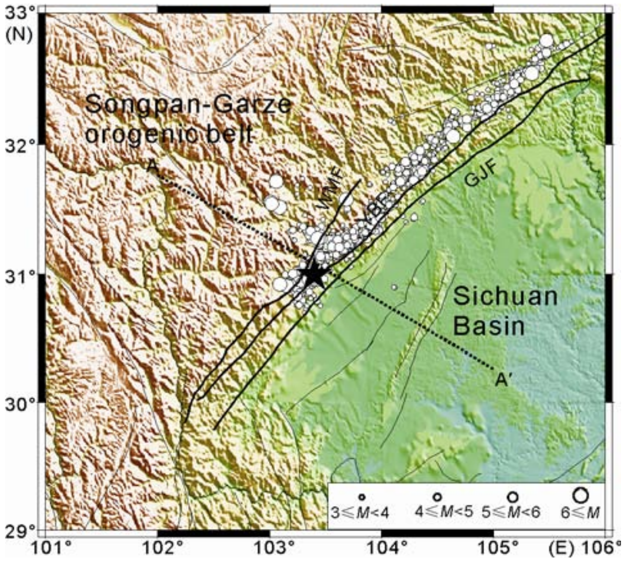

Figure 1 Location of the Longmenshan fault belt and epicenters of the Wenchuan earthquake and its aftershocks. The Wenchuan earthquake is plotted as a black pentagram, and the relocated aftershocks of the Wenchuan earthquake are plotted as open circles. The size represents the magnitude. The relocated aftershock data is from ref. [1]. WMF, Wenchuan-Maoxian Fault; YBF, Yingxiu-Beichuan Fault; GJF, Guanxian-Jiangyou Fault.

earthquake. These faults extend to a depth of ~20 km and converge to a horizontal shear zone in the middle crust, forming the main tectonic structures which control the Longmenshan range thrusting onto the frontal range [2–4]. The topographic discrepancy in the east and west of the Longmenshan fault belt reaches several kilometers. Moreover, the crustal thickness also increases from ~42 km in the Sichuan Basin to ~60 km in the eastern Tibetan Plateau [5, 6], suggesting strong crustal deformation in the Longmenshan region. The geodynamic cause for the apparent discrepancies of topography and crustal thickness may relate to the fact that the eastward movement of the Tibetan Plateau is obstructed by the rigid lithosphere of the Sichuan Basin [4]. The studies using the very long baseline interferometry and global positioning system confirm that both the slip rate of the Longmenshan fault belt since the Cenozoic Era and the crustal shortening of the eastern Tibetan Plateau are small relative to the Sichuan Basin, suggesting that the crustal deformation mainly occurs in the vertical direction [7–9]. The focal depth of the Wenchuan earthquake reported by the China Earthquake Networks Center is 14 km, and 16–18 km from the relocation by the double difference method [1, 10]. Studies on the rupture process reveal that the rupture plane on the Yingxiu-Beichuan fault extends to a depth of 15 km. Previous studies also indicate that the rupture extends deep to the middle crust [11], which means that the geodynamics in the deep crust should be one factor to induce the occurrence of the Wenchuan earthquake.

Geological survey and rupture process studies of the Wenchuan earthquake indicate that the rupture occurred over a length of ~300 km along the Longmenshan fault belt from Yingxiu to Beichuan. The rupture also occurred along more than 60 km of the Jiangyou-Guanxian Fault [3, 11]. However, the rupture and the aftershock sequences are mainly distributed over the northeastern rather than the southwestern Longmenshan fault belt. The relationships between the occurrence and rupture propagation of the Wenchuan earthquake and the crustal structure in the Longmenshan fault belt are of interest to geoscientists. Addressing these problems is meaningful for investigations of earthquake mechanics and their geodynamic processes.

After the Wenchuan earthquake, seismological studies, such as seismic travel time tomography and teleseismic receiver function inversion, were conducted to investigate the velocity structure and deep tectonic implications for the Wenchuan earthquake in the Longmenshan region [5, 12–16]. To establish the tectonic characteristics in the source region of the Wenchuan earthquake, and the intrinsic relations between the Wenchuan earthquake and the crustal structure in the Longmenshan fault belt, a P-wave travel time tomographic study was conducted using the data in Sichuan and adjacent regions. Based on the tomographic results and the aftershock sequences, the deep tectonics of the Longmenshan fault belt and the mechanics of the Wenchuan earthquake are discussed in this paper.

1 Data and method

1.1 Data

Our study mainly focuses on the Longmenshan fault belt and adjacent regions. In order to involve more arrival time data in the tomographic inversion, we have expanded the region to cover 100°–107°E and 28°–34°N. Only arrival time data recorded from 2000 to 2008 (events before the Wenchuan earthquake) were used. To ensure data quality, the following criteria are adopted: only first P arrivals, such as direct P, Pg, and Pn, are used in the inversion; each event has at least five records; the travel time residuals are limited to 3.5 s or less. Using these criteria, we collected 68814 ray paths from 7252 events. The final data coverage is quite good in the Longmenshan, Songpan-Garze and western Sichuan-Yunnan regions, but is poor inside the Sichuan Basin (Figure 2).

1.2 Initial model

The crustal thickness varies rapidly on the two sides of the Longmenshan fault belt. Therefore, a simple one-dimensional crustal model is not appropriate for this area, because large residuals and bias of the velocity structure inversion could be introduced. The Moho discontinuities (Figure 3) were inverted using the harmonious series method with Bouguer gravity data [17–19]. In the initial model, the Moho discontinuities are represented by a linearly continu-

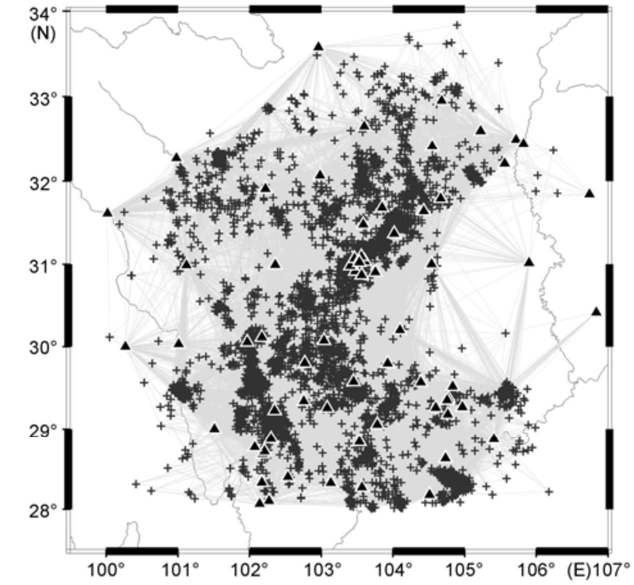

Figure 2 Distributions of earthquakes, seismic stations and seismic ray paths. Black triangles, black crosses and gray lines represent seismic stations, epicenters and seismic ray paths, respectively.

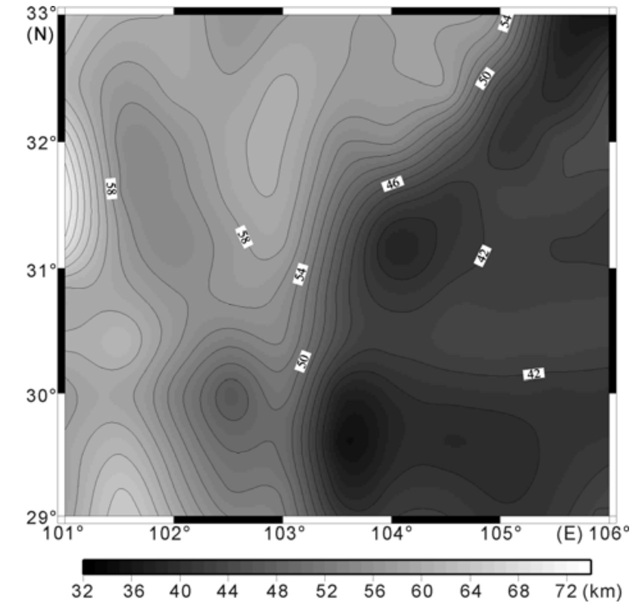

Figure 3 Moho discontinuities from the inversion of Bouguer gravity data.

ous transition layer. Both previous deep seismic sounding and travel time tomography results are referenced to construct the initial model [20, 21]. In addition, the velocity and depth of each layer in the initial model (Table 1) were adjusted according to the travel time residuals. Based on ray path coverage and resolution analysis with different grid spacing, we chose a grid spacing of 0.125°×0.2° in longitudinal and latitudinal directions to solve the set of travel time equations.

Table 1 Average P-wave velocity at grid depth in the initial model

Depth (km)	P-wave velocity (km/s)
0	5.35
5	5.45
10	5.90
15	6.00
20	6.15
30	6.30
40	6.55
53	7.80
71	8.00

1.3 Method

The pseudo-bending method was adopted for three-dimensional seismic ray tracing in a spherical earth [22–24]. A damped-least-squares algorithm was employed for simultaneously solving the P-wave velocity structures and relocating the hypocenter parameters, which minimized the bias of trade-offs between the velocity structures and the hypocenter parameters. A set of Laplacian damping equations were also implemented to regularize the velocity variations in the solution. Generally, two to three iterations were enough for a robust velocity result, and more iterations would only enhance the amplitude of the velocity anomaly while keeping the pattern similar. After two iterations, the root-mean-square of travel time residuals was reduced to 0.87 s from 1.18 s before the inversion.

1.4 Resolution analysis

We performed checkerboard tests to examine the resolution of the tomographic results. Velocity perturbations of ±4% were added to the initial model and synthetic data were generated for the same distribution of events and stations as used in the actual inversion. The recovered model perturbation images with a 0.25°×0.4° grid spacing are shown in Figure 4. Due to the uneven distribution of earthquakes and seismic stations, the resolution varied with the ray path coverage in different areas. The resolution test shows that the checkerboard pattern is well recovered in the regions with good ray path coverage, such as the Longmenshan range and adjacent regions. The inversion result provides quite good resolution to analyze the crustal structure in the Longmenshan region.

2 Results of inversion

The inversion results for P-wave velocity perturbations at depths of 5 to 40 km are shown in Figure 5. The aftershocks of the Wenchuan earthquake relocated using the double-difference method [1] were plotted onto the perturbation images at the corresponding depth (the focal depth uncertainties of relocated aftershocks are less than 2 km [1]).

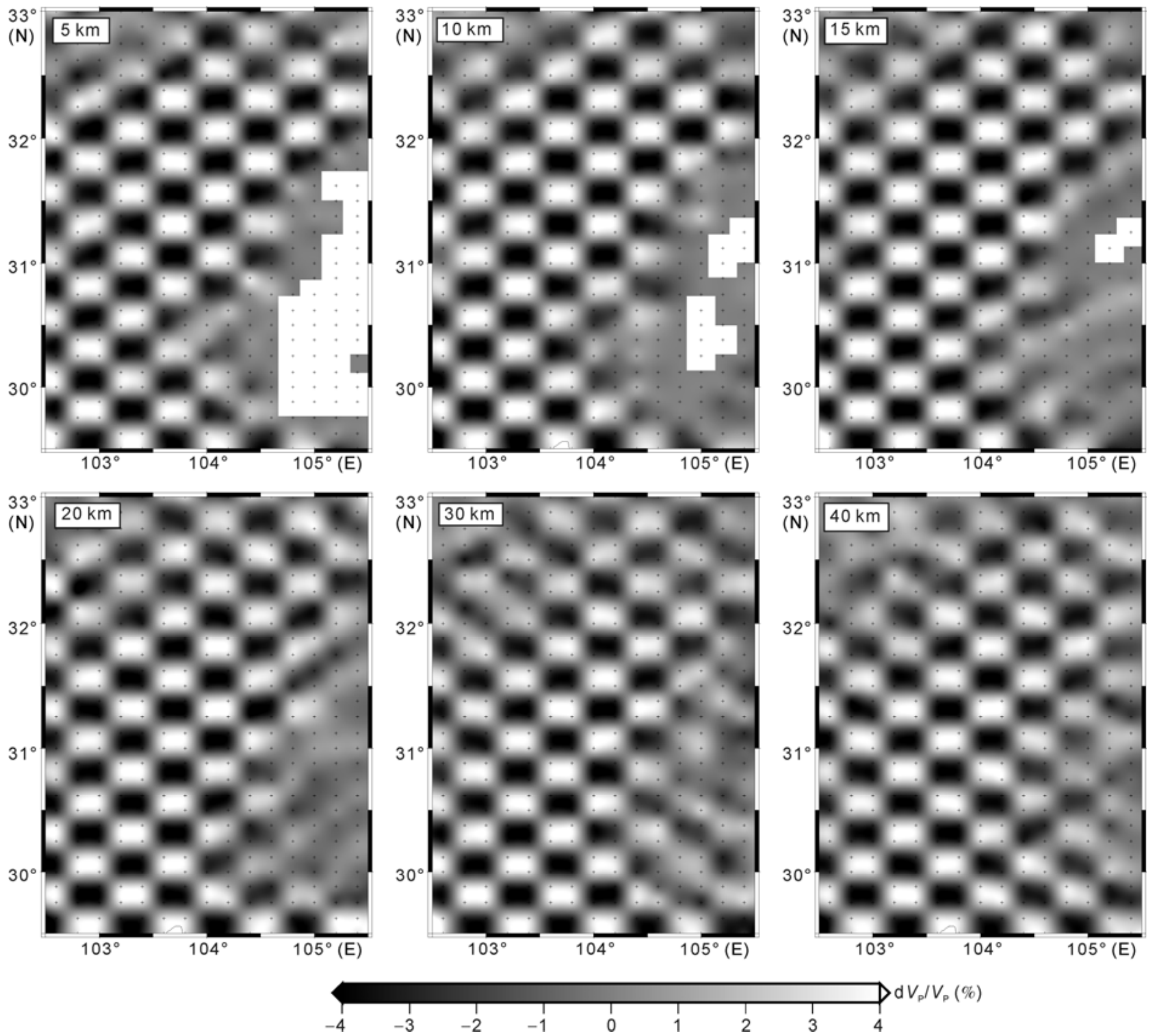

Figure 4 Checkerboard resolution tests for the P-wave velocity images at different depths. Black crosses represent the position of grid in the inversion.

The velocity anomalies at a depth of 5 km indicate the clear discrepancy between the two sides of the Longmenshan fault belt. High velocities are found in the Songpan-Garze orogenic belt and low velocities are found in the piedmont depression of the Longmenshan range and the Sichuan Basin. The boundary between the high and low velocities extends northward from Wenchuan to Jiangyou, which coincides with the location of the Longmenshan fault belt. However, the Longmenshan fault belt to the north of Jiangyou is characterized by low velocity anomalies with few aftershocks at this depth. At a depth of 10 km, high velocity anomalies on the east side of the Longmenshan fault belt converge to the Guanxian-Maowen area. Low velocities appear inside the Sichuan Basin and in the area between Wenchuan and Jiangyou. Aftershocks at this depth are mostly distributed over the southern margin of the high velocity zone in the west of the Longmenshan fault belt.

At a depth of 15 km, high velocity anomalies are present in the Guanxian-Maowen-Mianzhu area on the west side of the Longmenshan fault belt, whereas low velocities are found in the Sichuan Basin. The Wenchuan earthquake was located at the southern margin of the high velocity zone in the Guanxian-Maowen area, and aftershocks were mainly distributed over the Longmenshan fault belt to the northeast. Similar to the velocity image at a depth of 15 km, high velocities are present in Guanxian-Maowen-Mianzhu area, and low velocities are present in Yaan-Chengdu and Deyang-Jiangyou area inside the Sichuan Basin at the depth of 20 km. Most aftershocks are still distributed over the Longmenshan fault belt, and show similar characteristics to those at a depth of 15 km.

At a depth of 30 km, high velocities appear in the area of Guanxian-Mianzhu-Chengdu-Deyang in the western Sichuan Basin, where the Longmenshan fault belt forms the western boundary of the high velocity zone. Low velocity anomalies are observed in the areas of Songpan-Garze,

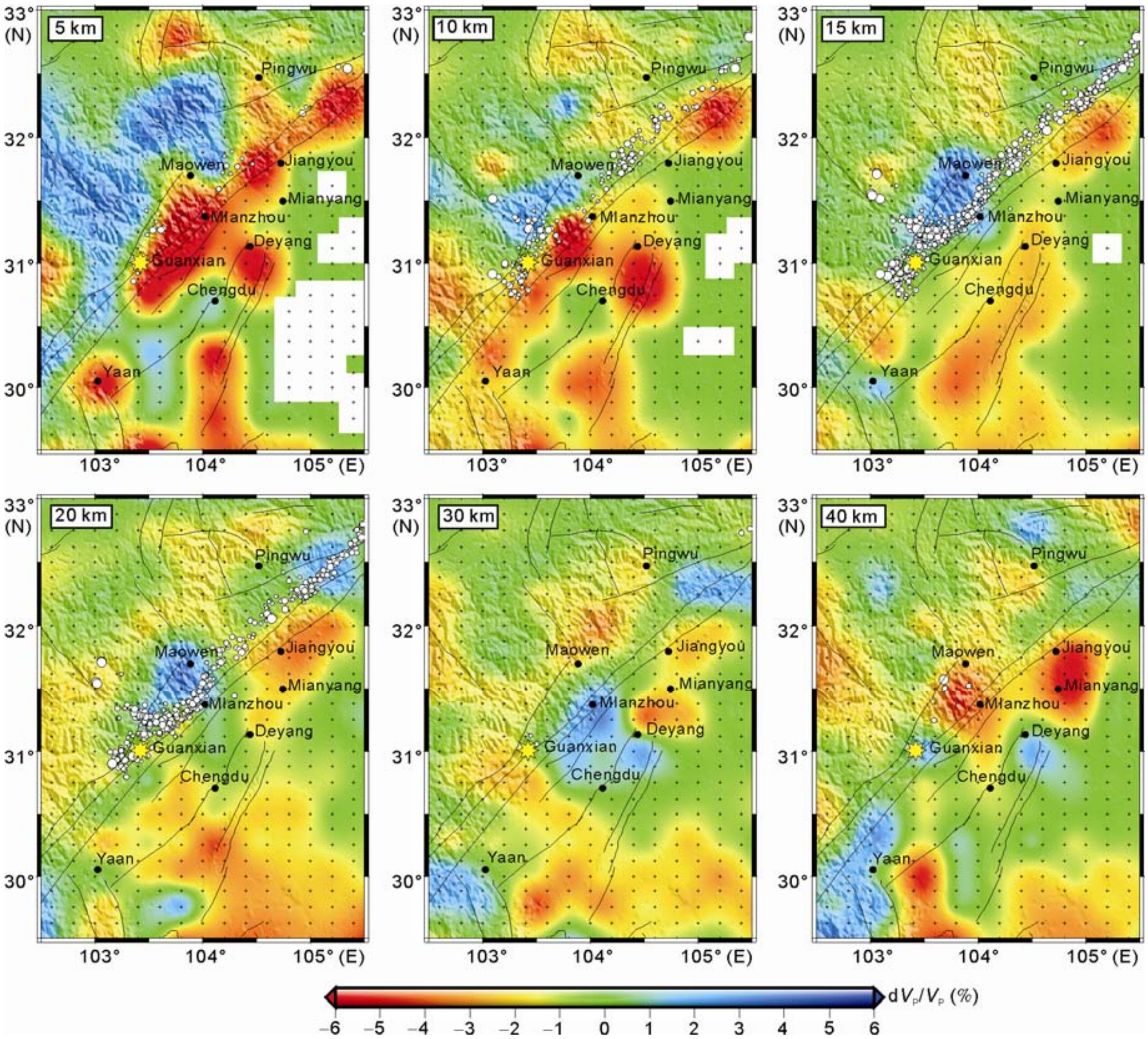

Figure 5 P-wave velocity images at depths as indicated. The epicenter of the Wenchuan earthquake is indicated by a yellow star at the depth of 15 and 20 km. Open circles represent the epicenters of aftershocks within 5 km the indicated depth. Black crosses represent the grids used in the inversion.

Jiangyou-Mianzhu, and to the south of Guanxian. Aftershocks disappear at this depth. At a depth of 40 km, high velocities are present in the Longmenshan range between Guanxian and Yaan and low velocity anomalies are present in the areas between Guanxian and Jiangyou. The Songpan-Garze orogenic belt is also characterized by low velocities.

Figure 6 shows a cross section through the Longmenshan range and the source region of the Wenchuan earthquake. The relocated aftershocks [1] are also projected onto the cross section to assist in the analysis. The shallow crust in the Songpan-Garze orogenic belt is characterized by high velocity anomalies, whereas the middle to lower crust is characterized by low velocity anomalies and large thickness. In the Sichuan Basin, the upper crust is characterized by low velocities with relatively small variations in the horizontal direction. The velocity contours indicate that the sedimentary layer with low velocities thins gradually from the Sichuan Basin to the Longmenshan Range. The Longmenshan fault belt becomes the transition zone between the orogen and the sedimentary basin. Most aftershocks of the Wenchuan earthquake occurred between the depths of 10 and 20 km.

3 Discussions

3.1 Deep tectonics of the Wenchuan earthquake

The tomographic velocity model (Figures 5 and 6) clearly delineates the discrepancy of the crustal structure on the two sides of the Longmenshan fault belt, and also reveals the deep tectonic setting of the Wenchuan earthquake. In the upper crust, high P-wave velocities in the Songpan-Garze orogenic belt relate to the uplift of the widely distributed ancient basement. At depths 10–20 km, the high velocity anomalies on the west side of the Longmenshan fault belt focus on the Guanxian-Maowen areas, which corresponds to the location of the Pengguan massif [3, 4]. The depth distribution of this high velocity anomaly body coincides with the focal depth (16–18 km) of the Wenchuan earthquake [1, 10]. The velocity images suggest that the crust in the source region of the Wenchuan earthquake possesses high strain strength, which facilitates the accumulation of stress over a long period that can then rupture suddenly. In contrast, the high velocity anomalies in the western Sichuan Basin are mainly distributed in the area of Guanxian-Mianzhu-Chengdu-Deyang to the east of the Longmenshan fault belt. Apparently, the occurrence of the Wenchuan earthquake is a manifestation of the interaction between two crustal blocks: the Songpan-Garze orogenic belt and the Sichuan Basin. The deep dynamics may relate to the fact that the eastward extrusion of the Tibetan Plateau is obstructed by the rigid lithosphere of the Sichuan Basin [25].

The initial rupture site and the rupture propagation direction of the Wenchuan earthquake closely relate to the crustal structure beneath the Longmenshan fault belt. At 15–20 km depth, both the Pengguan massif and the Sichuan Basin in the Longmenshan range are characterized by high velocities. The epicenter of the Wenchuan earthquake is located just on the southern edge of the high velocity body, which suggests that the stress induced by the extrusion accumulates for long periods in this region, and then releases suddenly to rupture the fault. The low velocities to the south of Wenchuan suggest that the crust is relatively weak, and that no enough stress can be accumulated to form brittle fracture. It also coincides with the northward fault rupture zone along the Longmenshan fault belt on the edge of the Pengguan massif.

3.2 Crustal thickening and deformation of the Longmenshan fault belt

The crustal shortening and thickening of the eastern Tibetan Plateau is one of the main geodynamic processes in this area. As shown in the cross section in Figure 6, the crustal thickness of the Songpan-Garze orogenic belt is thickened more than 10 km in comparison to the crust of the Sichuan Basin. In addition, the low-velocity middle-lower crust of the Songpan-Garze orogenic belt is also thickened. Our results coincide with the model: crustal thickening of the eastern Tibetan Plateau and its weakened lower crustal flow are obstructed by the strong lithosphere of the Sichuan Basin [25].

Based on the relatively high temperature and low velocity of the crust in the eastern Tibetan Plateau, Clark and Royden [25] proposed that the crustal thickening mainly happens inside the ductile middle-lower crust with lower viscosity. However, Burchfiel et al. [4] doubted that the relatively weak crustal flow can extend eastward to the Longmenshan region, and also argued that the ductile middle-lower crust cannot support the high topography of the Longmenshan region. In recently years, geophysical studies have suggested that a high electrical conductivity layer observed in the middle crust is thickened in the eastern Tibetan Plateau [26]. A magnetotelluric profile cross Beichuan also reveals the high conductivity characteristics beneath the Longmenshan range [27]. Wang et al. [6] and Liu et al. [16] analyzed the S-wave velocity structure of the crust and upper mantle beneath the eastern Tibetan Plateau using teleseismic receiver functions, and confirmed the low S-wave velocity anomalies in the middle-lower crust of the Longmenshan region. The velocity images from seismic travel time tomography also show similar characteristics in this area [12, 13, 15]. These results suggest that the weak and ductile middle-lower crust in the eastern Tibetan Plateau closely relates to the deep geodynamics of the Wenchuan earthquake.

Burchfiel et al. [4] deemed that the thrust faulting activity and folded structures in the Longmenshan region closely relate to the ductile deformation of the deep crust. However, the coupling mechanics between shallow tectonics and the deep crust is not well constrained. Previous geological and geophysical studies [12, 26, 27] and our tomographic results all suggest that the eastward extrusion of the Tibetan Plateau crust is obstructed by the strong lithosphere of the Sichuan Basin. The eastward extrusion also uplifts the basement of the Longmenshan range and results in wide-spread thrust faults and nappes from the west to the east. The ductile deformation of the middle-lower crust beneath the eastern Tibetan Plateau is due to its high flexibility, which thickens the crust and down-warps the Moho. The Wenchuan earthquake was therefore the result of long-period strain accumulation in the Longmenshan fault belt. The initial rupture site and the direction of rupture propagation both closely relate to the crustal structure and strain strength in the Longmenshan region, and especially the collision between the Pengguan massif and the rigid lithosphere of the Sichuan Basin.

4 Conclusions

The occurrence of the Wenchuan earthquake was closely related to the crustal structure and deep dynamic mechanics of the Longmenshan fault belt. The Pengguan massif is characterized by a high velocity anomaly, which suggests strong crust with strain strength accumulating for a long period. The Wenchuan earthquake was located in the southern part of the Longmenshan fault belt, and the primary reason for its occurrence is the collision between the Pengguan massif and the Sichuan Basin. The discrepancy between crustal structure and strain strength in the Longmenshan fault belt dominates the initial rupture site, the focal depth and the direction of rupture propagation. To the north of Wenchuan, the occurrence and propagation of rupture

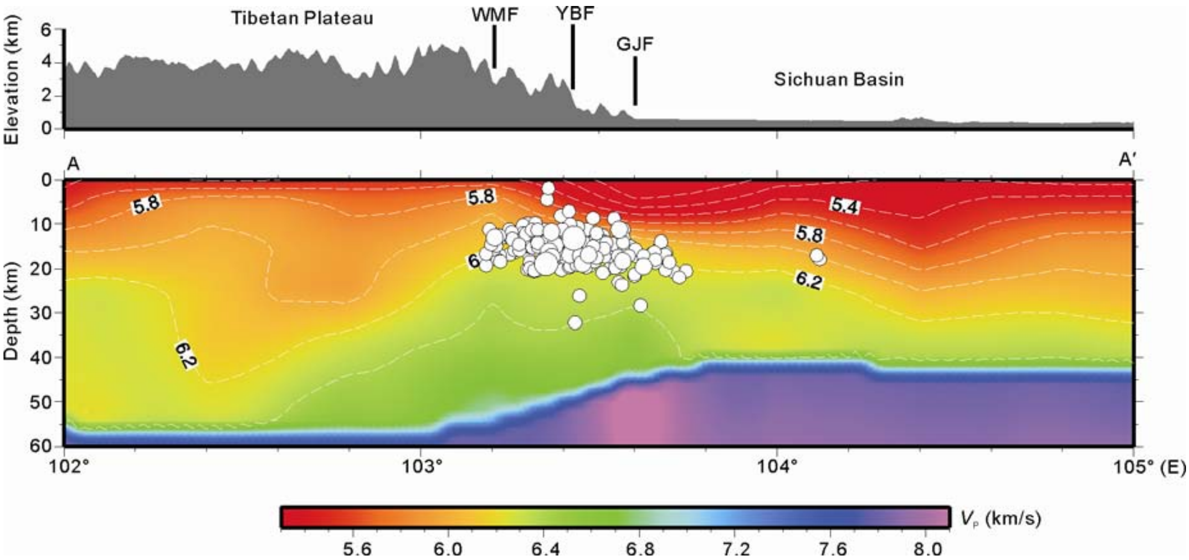

Figure 6 P-wave velocity profile AA' along the source region of the Wenchuan earthquake. The location of profile AA' is shown in Figure 1. Open circles represent the aftershocks within 20 km of the profile. WMF, Wenchuan-Maoxian Fault; YBF, Yingxiu-Beichuan Fault; GJF, Guanxian-Jiangyou Fault.

benefit from the high velocity anomalies along the Longmenshan fault belt. In contrast, a brittle rupture is difficult in the relatively weak crust to the south of Wenchuan. This may be one of the reasons for the absence of aftershocks to the south of Wenchuan, and the observation of rupture propagation for the Wenchuan earthquake running from north to south along the Longmenshan fault belt. The deep geodynamics of the Wenchuan earthquake is dominated by the discrepancy between dominant crustal structures on the two sides of the Longmenshan fault belt. Ductile deformation and crustal flow occur easily in the weak middle-lower crust beneath the Songpan-Garze orogenic belt. The eastward movement of the Tibetan Plateau is obstructed by the rigid lithosphere of the Sichuan Basin, and the thickening of the middle-lower crust and vertical deformation occur in the crust of the Longmenshan fault belt. In addition, the down-warping of the Moho and the basement thrusting onto the range front induce the crustal deformation and strain accumulation, which provide the potential energy to trigger the occurrence of the Wenchuan earthquake.

We are grateful for the direction of Academician Liu G D. We thank the Earthquake Administration of Sichuan for providing the seismic data, and Dr. Chen J H from the Institute of Geology, China Earthquake Administration for providing the relocated aftershocks of the Wenchuan earthquake. We greatly thank the two anonymous reviewers for their constructive comments, which improved the manuscript. This work was supported by State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology (Grant No. DZKJ-0803), Open Fund of Key Laboratory of Geo-detection (China University of Geosciences, Beijing) (Grant No.GDL0905), Ministry of Education, and the China Postdoctoral Science Foundation (Grant No. 20090460511).

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