Joint Inversion of the 3D P Wave Velocity Structure of the Crust and Upper Mantle under the Southeastern Margin of the Tibetan Plateau Using Regional Earthquake and Teleseismic Data

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Abstract: The special seismic tectonic environment and frequent seismicity in the southeastern margin of the Qinghai-Tibet Plateau show that this area is an ideal location to study the present tectonic movement and background of strong earthquakes in mainland China and to predict future strong earthquake risk zones. Studies of the structural environment and physical characteristics of the deep structure in this area are helpful to explore deep dynamic effects and deformation field characteristics, to strengthen our understanding of the roles of anisotropy and tectonic deformation and to study the deep tectonic background of the seismic origin of the block's interior. In this paper, the three-dimensional (3D) P-wave velocity structure of the crust and upper mantle under the southeastern margin of the Qinghai-Tibet Plateau is obtained via observational data from 224 permanent seismic stations in the regional digital seismic network of Yunnan and Sichuan Provinces and from 356 mobile China seismic arrays in the southern section of the north-south seismic belt using a joint inversion method of the regional earthquake and teleseismic data. The results indicate that the spatial distribution of the P-wave velocity anomalies in the shallow upper crust is closely related to the surface geological structure, terrain and lithology. Baoxing and Kangding, with their basic volcanic rocks and volcanic clastic rocks, present obvious high-velocity anomalies. The Chengdu Basin shows low-velocity anomalies associated with the Quaternary sediments. The Xichang Mesozoic Basin and the Butuo Basin are characterised by lowvelocity anomalies related to very thick sedimentary layers. The upper and middle crust beneath the Chuan-Dian and Songpan-Ganzi Blocks has apparent lateral heterogeneities, including low-velocity zones of different sizes. There is a large range of low-velocity layers in the Songpan-Ganzi Block and the sub-block northwest of Sichuan Province, showing that the middle and lower crust is relatively weak. The Sichuan Basin, which is located in the western margin of the Yangtze platform, shows high-velocity characteristics. The results also reveal that there are continuous low-velocity layer distributions in the middle and lower crust of the Daliangshan Block and that the distribution direction of the low-velocity anomaly is nearly SN, which is consistent with the trend of the Daliangshan fault. The existence of the low-velocity layer in the crust also provides a deep source for the deep dynamic deformation and seismic activity of the Daliangshan Block and its boundary faults. The results of the 3D P-wave velocity structure show that an anomalous distribution of high-density, strong-magnetic and high-wave velocity exists inside the crust in the Panxi region. This is likely related to late Paleozoic mantle plume activity that led to a large number of mafic and ultra-mafic intrusions into the crust. In the crustal doming process, the massive intrusion of mantle-derived material enhanced the mechanical strength of the crustal medium. The P-wave velocity structure also revealed that the upper mantle contains a low-velocity layer at a depth of 80-120 km in the Panxi region. The existence of deep faults in the Panxi region, which provide conditions for transporting mantle thermal material into the crust, is the deep tectonic background for

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the area's strong earthquake activity.

Key words: 3D P-wave velocity structure, China seismic array detection, Panxi region, Chuan-Dian Block, Daliangshan Block, southeastern margin of Qinghai–Tibet Plateau

1 Introduction

The southeastern margin of the Tibetan Plateau is located on the southwest border of China, at the intersection between the eastern section of the Indosinian-Tethyan tectonic domain and the Pacific tectonic domain, which is a complicated orogenic zone formed by constant crushing, splitting decompositions, mutual matching and inlaying of multiple terrains or landmasses between Laurasia and Gondwana (Royden et al., 1997). The boundary of the Longmenshan-Jinpingshan-Jade Dragon Snow Mountain tectonic zone and the Red River-Ailaoshan tectonic belt divides the region into two geotectonic elements with completely different natures. To the east of the boundary is the stable Yangtze Block, and only the southeast Yunnan region is part of the South China fold system. To the west of the boundary is a complicated geological block (Fig. 1) spliced with the Sichuan–Yunnan Block and the Songpan–Ganzi geosynclines fold system. The convergence of the Indian Plate and the Eurasian Plate, which started approximately 50 Ma, led to the closure of the Neotethys and the rapid uplift of the Tibetan Plateau, profoundly influenced the geological and physiognomic reforms of the southeastern margin of the Tibetan Plateau (Xu Zhiqin et al., 1992). The eastern Himalayan tectonic knot generates a powerful eastward thrusting force during the northward movement process, forming the west-east thrusting nappe; however, due to the rapid rise of the plateau, the medium of the upper part of the crust creeps to the east and generates a horizontal thrusting force under the action of the gravitational potential. Under the joint action of the two forces, the Longmenshan-Jinpingshan nappe tectonic zone was finally formed and positioned and a significant terrain altitude difference was formed on both sides of the zone (Zhou Jiu and Huang Xiuwu, 1980).

The southeastern margin of the Tibetan Plateau is one of the most violent seismicity regions in the Chinese mainland. Since the 1970s, a series of violent earthquakes have occurred in this region (Wu Zhonghai et al., 2014, 2016; Chen Xiaoli and Liu Chunguo, 2017), e.g. the Ms7.8 Tonghai earthquake in 1970, the Ms7.6 Luhuo earthquake in 1973, the Ms7.1 Zhaotong earthquake in 1974, the Ms7.4 Longling earthquake in 1976, the Ms7.2 Songpan earthquake in 1976, the Ms7.4 Lancang–Gengma earthquake in 1988, the Ms7.3 southwest Menglian earthquake in 1995 and the Ms7.0 Lijiang earthquake in 1996. As a symbolic earthquake indicating a new period of strong earthquakes in the north-south seismic belt, the Ms8.0 great Wenchuan earthquake in 2008 generated a huge and profound influence on the stress environment in the Longmenshan fault zone in Sichuan Province and adjacent regions (Parsons et al., 2008; Toda et al., 2008). As a macroscopic expression of the underground stress level, the seismic activity features of the southwestern margin regions of the Tibetan Plateau changed significantly after the Wenchuan earthquake. There have been frequent strong earthquakes of Ms5.0 or higher in the regions on the southeastern margin of the Tibetan Plateau since the Ms8.0 Wenchuan earthquake in 2008, including the Ms6.1 Renhe-Huili earthquake in Panzhihua on August 30, 2008, the Ms5.7 Yanyuan-Ninglang earthquake in 2012, the Lushan Ms7.0 earthquake on April 20, 2013 (Du Fang et al., 2013; Li Dahu et al., 2015), the Ms Ludian 6.5 earthquake on August 3, 2014 (Xu Xiwei et al., 2014) and the the Kangding Ms6.3 earthquake on November 22, 2014 (Li Dahu et al., 2015). However, due to the complicated geological structural environment and the diversified deep earthquake preparation factors of various earthquake regions, it is difficult to accurately determine the seismogenic structure or to give a reasonable explanation for the frequent moderate-strong earthquakes in this region within a limited special scale relying on just single superficial Seismo-Geological survey studies. Therefore, in-depth studies of the deep structure and seismogenic environment of the southeastern margin of the Tibetan Plateau have a very important scientific significance when explaining the dynamical background of earthquake origins and the seismogenic environment in this region, as well as the deep dynamical mechanism for the internal and boundary breakage activities of the blocks.

With its special seismic tectonic environment and frequent strong earthquakes, the southeastern margin of the Tibetan Plateau is an ideal location for studies of current tectonic movements, the strong earthquake generation background on the Chinese mainland and predicting dangerous zones for strong earthquakes in the future. Since the 1980s, the southeastern margin of the Tibetan Plateau has become a focus for domestic and overseas geoscientists. According to seismo-geologic and active tectonic studies, there is no significant compression



Fig. 1. Map of seismic tectonic environment in the southeastern margin of the Tibetan Plateau. F1: Longmenshan fault, F2: Xianshuihe fault; F3: Anninghe fault; F4: Zemuhe fault; F5: Xiaojiang fault; F6: Daliangshan fault; F7: Yunongxi fault; F8: Xiaojinhe-Lijiang fault; F9: Jinshajiang fault; F10: Honghe fault.

shortening in the Late Cenozoic crust on the southeastern margin of the Tibetan Plateau, which primarily includes strike slip movement along with large-scale faults and tectonic rotation of the blocks (Royden et al., 1997; Clark et al., 2005; Zhang Yueqiao et al., 2016; Zhang Yongshuang et al., 2016; Tong Yabo et al., 2017). Prior to

the Ms8.0 Wenchuan earthquake, the lower crust pipe flow model was the most popular international model to explain the uplift to the east and at the southeastern margin of the Tibetan Plateau, including the Longmenshan region. Obviously, deep geophysical explorations are urgently needed to verify and supplement information obtained

from surface observations and models and multiple geophysical researchers have developed geophysical research methods such as magnetotelluric exploration (Li Li and Guo Yuan, 1987; Zhang Hongrong, 1990; Sun Jie et al., 2003; Zhao Guoze et al., 2008; Wang Xuben et al., 2009; Wan Zhansheng, 2010; Bai Denghai et al., 2010; Zhao et al., 2012; Zhan Yan et al., 2013), deep seismic sounding (Cui Zuozhou et al., 1987; Wang Chunyong et al., 2003), teleseismic receiver functions (Hu Jiafu et al., 2003; Xu et al., 2007; Li et al., 2009) and seismic tomography (Huang et al., 2002; Lei Jianshe et al., 2002; Wu Jianping et al., 2006; Wang et al., 2010; Liu et al., 2014; Yang et al., 2014; Bao et al., 2015; Huang et al., 2015), which play an active role in revealing the crust's structural framework in the orogenic zone in the southeastern margin of the Tibetan Plateau, the structural environment of the upper mantle and deepening our awareness of the evolution of the orogenic zone and its dynamics. According geological studies, geophysical exploration and imaging studies, there are low-velocity and low-resistance abnormities closely related to the middle and lower crust medium channel flows on the southeastern margin of the Tibetan Plateau; however, there are still large disputes and differences with respect to the distribution ranges and the horizontal changes in the lowvelocity layer in the crust. According to some scholars, it is unlikely that large-scale flows exist in the lower crust at the eastern margin of the Tibetan Plateau; instead, such flows are likely limited to local regions due to the constraints of the fault and structural boundaries (Yao et al., 2008; Wang et al., 2010) and only flow towards the south of Yunnan Province along two arced channels crossing the Jinshajiang-Red River fault zone (Bai et al., 2010). According to other scholars, the lower crust flow from the eastern margin of the Tibetan Plateau is obstructed by the Lijiang-Jinhe fault zone, which reaches north of Yunnan Province (Chen et al., 2013). As a hot spot in the field of geosciences, this is a problem worthy of in-depth consideration and study.

By collecting the observational data of a total of 634 stations (arrays), e.g. digital seismic observational networks in regions such as Sichuan and Yunnan Provinces as well as mobile seismic arrays such as the 'China Earthquake Science Array Detection–South Section of the north–south Seismic Belt' (Stage I of the 'Himalaya' project) and using the joint inversion method on the regional earthquake and teleseismic data (Zhao et al., 1994), this article obtains the three-dimensional (3D) P -wave velocity structure of the crust and upper mantle beneath the southeastern margin of the Tibetan Plateau. On this basis, we can analyse and discuss scientific problems such as the existence of an environment for plastic flow in the middle and lower crust of the western Sichuan Plateau, the deep dynamic mechanism that promotes the internal and boundary tectonic deformation and strong earthquake activities of the Daliangshan Block the relationship between moderately and strong earthquakes, Earth surface deformation and deep processes in the Panxi region. The findings of this study have an important scientific significance for our understanding of the deep geodynamic mechanism for earthquake generation and the development of the southeastern margin of the Tibetan Plateau. In addition, we discuss the resulting seismogenic structure model and evaluate the likely seismic activity trend for the region in the future.

2 Observational Data and Tomography Methods

This study collected 18,530 regional earthquakes and 754 teleseismic events recorded by 634 stations (arrays) of regional digital seismic networks located in Sichuan Province, Yunnan Province and their perimeter zones, as well as the China earthquake scientific arrays (Institute of Geophysics, China Earthquake Administration, 2011), including observational data from 224 permanent regional digital seismic stations in regions such as Sichuan and Yunnan Provinces (duration: January 2009-December 2014); observational data of 356 flowing seismic arrays of the 'China Earthquake Scientific Array Detection-the South Section of the north-south Seismic Belt' (Stage I of the 'Himalayas' Project) (duration: August 2011-May 2013); observational data of 35 arrays of the Ms7.0 Lushan earthquake scientific investigations in Sichuan Province (duration: June 2013-September 2014) and observational data of 19 seismic situation flow tracking monitoring stations in Xichang, Sichuan Province (duration: May 2013-March 2015) (Fig. 2).

To achieve high-quality earthquake observational data and to avoid problems such as instrument polarity and azimuth angle deviations, primarily we selected seismological observational data obtained after the azimuth angle general survey of the seismometers used for the regional seismic measurements, i.e. observational data from the regional digital waveform network in Sichuan and Yunnan Provinces started in 2009. First, we performed P-wave picking with the regional earthquake waveform data. From the regional earthquake data from the regional digital seismic stations, we selected 17,734 earthquake events with earthquake magnitudes greater than M₁2.0 according to the seismic observation reports; from the regional earthquake data from the China seismic scientific arrays, we selected 796 earthquake events with



Fig. 2. Distribution of seismic stations used in this study area. The black square denote Chinese seismic array detection-the southern section of NorthSouth seismic belt, the black triangle denote the regional digital seismic network.

earthquake magnitudes greater than $M_L 3.0$ with at least 15 P-wave observational data points for the P-waves of each earthquake. Figure 3 shows that the regional earthquake event distribution within the studied region is relatively reasonable; in particular, there is a preferable earthquake event distribution on the boundary faults of the active blocks within the studied region and the surrounding areas. Figure 4 is a time–distance graph of the regional earthquakes. According to the relationship between the

regional earthquake travel time and the epicentral distance, we screened the data with large deviations in the P-wave error in the following way: first, we conducted the polynomial fitting calculation to the P-wave; then, we deleted the data with significantly deviating fitting curves to ensure the accuracy of the P-wave; and finally, we screened and picked 249,316 pieces of P-wave data for 18,530 regional earthquake events. When selecting the teleseismic events, to ensure the signal to noise ratio and



Fig. 3. Epicenter distribution of regional earthquakes used in this study.



Fig. 4. The relationship between travel time and epicenter distance.

the reliability of the earthquake data, we selected teleseismic events with an earthquake magnitude ≥ 5.0 to ensure the powerful energy and clear first motion of the seismic wave when arriving at the stations; at the same time, we required that the epicentral distance of the teleseismic events be $30^{\circ} \leq \Delta \leq 90^{\circ}$ to ensure that the seismic wave ray paths were primarily concentrated in the crust and upper mantle. In addition, each teleseismic event needed to be recorded by more than 20 seismic stations (arrays). According to the above principles, we conducted an analysis and screening of the teleseismic events to

finally obtain a total of 754 events. Figure 5 shows the locations and the distribution of the epicentres of the teleseismic events. It can be seen that the teleseismic events used for the inversion imaging have preferable azimuth angle distribution features. Next, we preprocessed the teleseismic data, including antitilting, mean removal correlation, anti-instrument response and band pass filtering, and we adopted the waveform crosscorrelation adaptive stacking method to pick the relative travel time residual of the P-waves of the teleseismic events (Rawlinson et al., 2004; Zhang Fengxue et al., 2013). Figure 6 shows that the teleseismic relative travel time differences adopted in this study are primarily distributed within 2 s and that we ultimately picked 103,902 pieces of P-wave data from 754 teleseismic events for the inversion.

By adopting the travel time tomography method proposed by Zhao et al. (1994), this article used the joint inversion of the regional earthquake and teleseismic data to obtain the velocity structure of the 3D P-waves in the crust and upper mantle beneath the southeastern margin of the Tibetan Plateau. This method allows for changes in the 3D space; in addition, by setting a series of 3D grid nodes in the model space, it solves for the velocity disturbance at the node and the velocity disturbance of any other point in the model can be derived from a linear interpolation of the velocity disturbances of the eight adjacent nodes. To rapidly and accurately calculate the theoretical travel time and the seismic ray path, this method improves on the approximate curving algorithm proposed by Um and Thurber (1987) during the ray-tracking process, which performs 3D ray tracking iteratively using pseudo bending technology and Snell's Law to make it applicable to the



Fig. 5. The distribution of teleseismic events.



Fig. 6. Relative residuals and the epicenter distance. The horizontal axis denotes epicenter distance, The vertical axis denotes relative travel time residual.

complicated velocity discontinuity. During the inversion process, the LSQR method with a damping factor was adopted to solve the large-scale sparse observation equation set (Paige and Saunders, 1982), and the damping satisfied the minimum model and data variance. According to the event distribution within the study area, the locations of the seismic stations and the seismic array coverage situations, we first divided the model of the study area (Figure 7) into a $0.5^{\circ} \times 0.5^{\circ}$ uniform grid in the horizontal direction and 19 layers in the depth direction. In

the depth direction from 10 km to 50 km, each layer is divided with equidistance intervals of 5 km; below 50 km, the depth layers are 60 km, 80 km, 120 km, 150 km, 200 km, 250 km, 300 km and 400 km. In addition, the Conrad and Moho velocity discontinuities are included in the initial model; the seismic sounding result is taken as the reference for the initial velocity in the crust; and the IASPEI91 model is adopted for the initial velocity structure under the Moho. The one-dimensional (1D) initial P-wave velocity model adopted in this study was

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Fig. 7. Meshing diagram of research area.

obtained according to the average velocity at different depths based on a comprehensive consideration of existing seismic sounding in this region and matches the Bouguer gravity anomaly inversion (Wang Chunyong et al., 2002, 2003; Lou Hai et al., 2008). To search for the best value of the damping parameter in the tomographic inversion, we conducted multiple inversions with different damping parameter values and determined the final value to be 15.0.

We adopted the checkerboard method to test the resolution of the inversion result (Zhao et al., 1994; Ding Zhifeng, 1999), which not only evaluates the reliability of the inversion result but also measures the crossing situations of the seismic rays within the space. The fundamental principle of the checkboard resolution test is to establish the 3D space grid points and add the interphase positive and negative velocity disturbances based on the 1D velocity model (the disturbance value adopted in this study is $\pm 3\%$), to calculate the theoretical travel time with the same ray path distribution of the observational data and to conduct the inversion on the generated theoretical travel time to obtain the imaging resolution of the observational data via comparisons between the velocity value of each node in the result and the theoretical value. Figure 8 gives the result of the data checkerboard resolution test, from which we can see that the relative changes in the positive and negative velocities can be restored correctly in the different depth layers of the study area; however, the recovery of the middle and lower crust in the northwestern part of the study area (the Songpan-Ganzi Block) is relatively poor. The test results for the boundary fault of the active blocks within the study region and the surrounding areas are preferable, primarily due to the relatively dense stations (arrays) near the fault structure zone and the concentrated distribution of a large amount of seismic events.

In addition to the checkerboard test, the ray density can be used to measure the reliability of the resolution. The seismic ray density refers to the total number of rays passing through the model grids, the distribution of which is closely related to the resolution ratio of the inversion result. Regions with large seismic ray densities have high resolution ratios in the inversion result. Figure 9 shows the distribution of the number of rays through all the nodes, from which we can see that the density of rays in most regions within the study area is more than 6000 pieces, which ensures the relatively high resolution of the inversion result in this region. The rays in the Longmenshan fault belt, the Lianfeng-Zhaotong fault belt, the Xianshuihe-Anninghe-Zemuhe-Xiaojiang fault belt, the Red River fault zone and nearby regions have relatively dense coverage densities, with general values as

high as 6000-8000 pieces, while the ray coverage density in other regions is relatively less. Within the range of the middle and upper crustal depths, the Longmenshan fault zone and the southern section of the Nujiang fault zone are the regions with the highest ray densities, with ray densities larger than 9000 pieces, which is primarily due to the dense distribution of the seismic stations (arrays) and the seismic events within this region. We performed relocation for the earthquakes during the velocity structure inversion process with alternate earthquake locations and velocity structure inversions, i.e. we performed relocation for the earthquakes according to the initial 3D velocity model and inversions to the velocity structure using the LSQR algorithm with damping on the basis of ray tracking according to the location result, and we iterated until the conditions were satisfied.

3 Inversion Results

Figure 10 gives the distribution diagram for the P-wave velocity abnormality at different depths in the crust and upper mantle beneath the southeastern margin of the Tibetan Plateau. It can be seen that the shallow P-wave velocity abnormality distribution features within the upper crust depth range are closely related to the surface geological structures and the formation lithology. In the velocity abnormality drawing at a depth of 1 km, there are local P-wave high-velocity abnormalities in the exposed surface area in the complex petrographical provinces of Baoxing and Kangding. According to the geological data, this region has zonally distributed basic volcanic rocks and volcaniclastic rocks, primarily of the Cathaysian Ordovician Period; therefore, the abnormality is related to the intrusive masses distributed in the Baoxing and Kangding Provinces. It can be seen from the velocity structure chart that the western margin of the Chengdu Cenozoic Foreland Basin has obvious low-velocity abnormality distribution features. There are local lowvelocity abnormality features in the Yanyuan Basin, the Xichang Mesozoic Basin and the Butuo Basin, and the low-velocity abnormality distribution is primarily related to the huge and thick sedimentary cover in the region. In the 10-km depth layer, the middle and upper crust velocity structures of the Sichuan-Yunnan and Songpan-Ganzi Blocks show significant horizontal heterogeneity and blocking structures with different scales and interphased high and low velocities. The low-velocity abnormalities are primarily distributed in Huidong and Huize near the Xiaojiang fault zone as well as in Daocheng, Jiulong and surrounding areas within the Northwestern Sichuan Block. The Yanyuan Basin also shows features of a low-velocity abnormality. There are significant high-velocity



Fig. 8. Map view of results of the checkerboard resolution test at different depths in the study area. The depth of the layer is shown at the upper left corner of each map. The velocity perturbation scale is shown at the bottom.

abnormalities west of the Longmenshan fault zone and northeast of the Fubianhe fault zone of the Chuanqing Block, which are primarily related to the overall uplift of the Minshan fault block (strong fault uplift) since the Cenozoic. Longquanshan and the surrounding areas at the eastern margin of the down-faulted Chengdu Basin also show high-velocity abnormalities. There are significant low-velocity features near the Yajiang–Jiulong region as well as along the Yunongxi fault zone within the Northwestern Sichuan Block. Since the Quaternary, the intense difference movement of the fault block boundary and the southward deflection of the Xianshuihe fault zone



Fig. 9. Distribution of the number of the P wave rays passing through each grid node (hit numbers). The depth of the layer is shown at the upper left corner of each map. The hit numbers scale is shown at the bottom.



Fig. 10. P wave velocity perturbation image of the southeastern margin of the Tibetan Plateau. Black lines denote main faults in the study region.

in this section has led to a landform effect conversion from a left-rotated horizontal shearing motion to a squeezing movement on the turning position. The long-term deformation of the Gonggashan fault block shows an intense uplifting state, which has resulted in the significantly different velocity feature differences within the surrounding mountains. In addition, it illustrates that the low-velocity abnormality region has relatively low-

medium strength, which easily leads to deformation and uplift in a compressive environment.

It can be seen from the 20-km depth drawing that the Minshan Block has significant low-velocity abnormality distribution features; in particular, the Songpan-Heishui-Ma Erkang zone on the NW side of the Longmenshan fault zone shows a large low-velocity abnormality distribution area. The three magnetotelluric (MT) sounding sections laid across the Longmenshan nappe structure zone reveal that the Chuanqing Block has highconductive electrical property structural features at a depth of 20 km, i.e. there is a crustal high-conductivity layer under the high-resistance layer of the upper crust of the Chuanging Block with an upper burial depth of approximately 20 km that is consistent with the tomography inversion result of this study. It can be seen that the low-velocity abnormalities at this depth are primarily distributed within the Daliangshan secondary Block and in Yanyuan-Ninglang within the Northwestern Sichuan Block. The crust in the Sichuan Basin shows a relatively high velocity, and there are some differences in the velocity abnormality distribution between different sections of the Zhaotong fault belt: the northeastern section and the southwestern section show low-velocity and high-velocity abnormality distribution features, respectively. Miyi-Panzhihua and the northwest regions within the Kangdian Earth axis, i.e. the region between the Anninghe fault and the Gold River-Jinghe fault zone, show significant high-velocity abnormality distribution features due to the mantle plume activities that led to an intrusion into the crust of basic and ultrabasic mantle sources. The Emei and Leshan regions, which are east of Yingjing-Mabian-Yanjin tectonic zone at the the southwestern margin of the anteklise in the middle of Sichuan Province, have significant high-velocity abnormality features, which are more significant at a depth of 30 km, with a range covering the Emei-Ziyang-Zigong -Yibin regions within the Sichuan Province.

There are some changes in the forms and ranges of the velocity abnormality at a depth of 30 km, and there are more significant low-velocity abnormality distributions in the Heishui–Xiaojin region. The leading edge of the positive abnormality near the Miyi–Panzhihua zone moves southward to the Yuanmou region and eastward to Qiaojia and Huidong, the range of which is limited by the Zemuhe fault belt. The velocity image at 40–60 km represents the velocity structure features of the middle and lower crust in the study area. According to the inversion result, the study area has significant horizontal heterogeneity in its velocity distribution at the middle and lower crust depths. The Northwest Block and the Songpan–Ganzi Block have large-scale low-velocity abnormality distributions, which

illustrates that they have relatively weak middle and lower crust materials. The Sichuan Basin, which is at the western margin of the Yangtze Platform, has significant highvelocity abnormality features; this high-velocity abnormality is caused by the continuous and stable middle and deep metamorphic rock crystalline basement that formed during the Archaean to Paleoproterozoic under the thick sedimentary cover of the basin; however, it also indicates the relatively stable status of the middle and lower crust of the Sichuan Basin at the western margin of the Yangtze Block. The velocity structure drawing for the upper mantle at a depth of 80-120 km reflects the influence of the complicated tectonic movements in the study area. The Yangtze platform region shows a large area of high-velocity abnormalities; the Western Sichuan Plateau region shows overall low-velocity abnormality distribution features; and the low-velocity medium of the upper mantle of the Songpan-Ganzi Block invades the upper part of the southern section of the Longmenshan fault belt. In addition, the Panxi region shows a large area of low-velocity abnormalities, which is nearly consistent with the idea of Li (1987) that the buried depth of the lowresistance layer of the upper mantle is 80-123 km and with the findings of Kong Xiangru et al. (1987) that the buried depth of the low-resistance layer of the upper mantle in the Panxi region is approximately 89 km.

4 Discussion

The southeastern margin of the Tibetan Plateau is located in the eastern section surrounding the collision zone between the India Plate and the Eurasian Plate and is one of the regions with the strongest lithospheric deformation in the Chinese mainland since the Neogene Period. The crustal movement and interactions with the deep media have a global tectonic significance as well as uniquely regional evolutionary characteristics. In addition, due to the strong seismicity at the southeastern margin of the Tibetan Plateau with frequent moderately strong earthquakes, a detailed study of the velocity structure features of the crust and upper mantle in this region is not only helpful to reveal the deep driving processes of the plate convergence boundaries and to expand our understanding of the deep dynamic mechanisms that promote tectonic deformation and seismic activities in this region but also has important scientific significance for studies of crustal movement models of the southeastern margin of the Tibetan Plateau.

4.1 Plastic flow of the middle–lower crust and the deep seismogenic environment of the western Sichuan Plateau

According to our 3D P-wave velocity structure result, the middle and lower crust of the Songpan-Ganzi Block and the northwestern Sichuan secondary Block have wide significant low-velocity abnormality distributions, illustrating that they have relatively weak middle and lower crustal media. The middle and lower crust of the western Sichuan Plateau has conditions for plastic flow, and the middle and lower crust of the Sichuan Basin shows significant high-velocity abnormality areas without a low-velocity layer. Geologic and geothermal-based studies and different deep physical geographical sounding methods and imaging results in recent years have revealed that the areas west of the Longmenshan nappe structure belt, Songpan-Ganzi orogenic zone and Chuan-Dian Block have low-velocity low-resistance abnormalities related to middle and lower crust channel flows (Royden et al., 1997; Huang et al., 2002; Wang et al., 2003; Yao et al., 2006, 2008; Bai et al., 2010). Wang et al. (2010) showed that the Songpan-Ganzi Fold System, to the northwest of the basin, has low-velocity anomalies in its upper mantle; Yang et al. (2014) showed that a lowvelocity anomaly is located primarily in the eastern and southeastern regions of the Tibetan Plateau; and Huang et al. (2015) revealed low-velocity zones in the mid-lower crust under SE Tibet and a high-velocity body in the upper mantle beneath South China representing the root of the Yangtze Craton. In combination with the latest 3D

apparent density inversion results (Fig. 11), this implies that the Songpan–Ganzi and northwestern Sichuan secondary Blocks have low-density abnormality regions (Li Jun et al., 2017). Therefore, the existence of lowvelocity and low-density regions is the basis for the deep dynamic effect on the western Sichuan Plateau at the southeastern margin of the Tibetan Plateau. The plastic flow of the middle and lower crust of the western Sichuan Plateau drives the deformation and fault movements of the upper brittle crust, which leads to the accumulation and release of strain in the fault zones, forming strong earthquakes (Zhang Peizhen, 2008).

4.2 The deep dynamic mechanism promoting the Daliangshan Block and the surrounding tectonic deformation and strong earthquake activities

The Daliangshan Block at the southeastern margin of the Tibetan Plateau appears to have significant transition zone features on its terrain in addition to large changes in its crustal thickness, fault development and frequent block and surrounding seismic activities, which are closely related to the active fault distribution pattern. The Ms \geq 6.0 earthquakes of the Yingjing–Mabian–Yanjin fault zone on the northeastern boundary of the Daliangshan fault block are concentrated on the Mabian–Leibo– Daguanbei line, forming a northwest directed strong earthquake intensive zone with a basically anastomotic



Fig. 11. 3D apparent density inversion of the southeastern margin of the Tibetan Plateau (Li et al., 2017).

direction. In addition, the fault zone has twice experienced $Ms \ge 7.0$ earthquakes and several times has experienced Ms6.0-6.9 earthquakes. Therefore, what is the dynamic mechanism promoting and restraining the structural deformation and strong seismicity in the Daliangshan Block at the southeastern margin of the Tibetan Plateau as well as the Yingjing–Mabian–Yanjin fault belt?

According to our P-wave imaging result, at a depth of 10 km in the upper crust, the Shimian-Hanyuan-Yuexi zone in the Daliangshan fault uplift region shows a highvelocity abnormality distribution (Fig. 10), illustrating that the medium of the upper crust in this region has brittleness features, which easily accumulate the earthquake energy necessary for crust movement. At a depth of 20 km, the northern Daliangshan section shows a low-velocity abnormality distribution and this special velocity structure difference is closely related to the seismic activity features in this region. At 09:23 on October 1, 2014, the Ms5.0 Yuexi earthquake (102.8° E 28.4° N) occurred near the north section of the Daliangshan fault belt. In combination with the existing magnetotelluric MT sounding section result for Shimian-Leshan and Mianning-Yibin, the 2D electrical property structure of the MT section of Shimian-Leshan illustrates that the Shimian-Hanyuan zone includes a high-resistance layer with an electrical resistivity of more than thousands of Ω .m and a thickness that gradually diminishes from 15 km at the western end towards the east. The electrical resistivity under the highresistance layer is a low-resistance layer in the crust of several to dozens of Ω .m. According to studies of the electrical property structure of the MT section in the Mianning-Yibin belt, Wan Zhansheng et al. (2010) obtained similar conclusions. Wan Zhansheng et al. (2010) speculated that on both sides of the western boundary of the Daliangshan Block, i.e. the Anninghe fault zone and the Daliangshan fault belt, the low-resistance layers in the crust are mutually connected, the high-conductivity layer in the Daliangshan Block has a north-south distribution range of at least 100 km and the north-south distribution of the high-conductivity layer is nearly the same as the orientation of the Daliangshan Block. There are continuous high-conductivity layers in the lower parts of the Daliangshan Block and the Sichuan and Yunnan Blocks in the east-west direction with relatively better conductivity in the lower part of the Daliangshan Block.

Figure 12 shows the P-wave velocity disturbance vertical section for Jiulong, Eeryi-Muchuan and Liujia. A comparison of the P-wave section results between the two MT measuring lines reveals that the Daliangshan secondary Block has a low-velocity layer distribution: the low-velocity abnormality advantage distribution direction is approximately in the SN direction within the middle and lower crust depth ranges of the Daliangshan secondary Block, which is nearly the same as the direction of the Daliangshan fault. In the EW direction, the Songpan-Ganzi and Daliangshan Blocks have a continuous lowvelocity layer distribution within the middle and lower crust depth ranges (Han Zhujun et al., 2009); therefore, we believe that the low-velocity layer crosses the Daliangshan fault in the west-east direction, which ends within the region near the Yingjing-Mabian-Yanjin fault tectonic belt. In addition, the result of the latest tectonic deformation form of the Yingjing-Mabian-Yanjin seismic tectonic zone supports the plastic flow model of the middle and lower crust media under the control of gravitation and the plastic flow in the middle and lower crust in the Daliangshan secondary Block provides a dynamic source for the latest tectonic activities of the Yingjing-Mabian-Yanjin seismic tectonic zone Therefore, no large-scale fault is needed in the near surface to connect the seismic zone to the margin or interior of the Tibetan Plateau.



Fig. 12. P wave velocity perturbation vertical profile of Eryi-Liujia.

4.3 The seismicity, surface deformation and deep processes in the Panxi region

Located at the southeastern margin of the Tibetan Plateau, the Panxi region is an important part of the boundary zone in the ladder pattern landform in the eastern and western parts of China due to its extremely complicated geological tectonic features. frequent seismicity and intense Mesozoic-Cenozoic tectonic deformation; therefore, long-term and thorough studies are necessary to obtain a correct understanding of the region. The traditional range of the Panxi region extends from Mianning in Sichuan Province to the north and continues through Xichang, Miyi and Panzhihua until Yuanmou in Yunnan province, spanning approximately 300 km from south to north and limited by the Ganluo-Xiaojing fault and the Chenghai-Jinghe boundary fault zone to the east and west with a width of dozens to hundreds of kilometres.

According to our 3D P-wave velocity structure, the velocity features in the crust of the Panxi tectonic zone have significant heterogeneity, especially in the Miyi, Panzhihua and Huidong regions, which are in the core of the tectonic zone. The 10-km velocity structure drawing reveals the local high-velocity abnormality features of the Shimian-Xichang-Panzhihua regions (Fig. 10), and both sides of the Xiaojiang fault are located in the low-velocity abnormality region with the low-velocity abnormality on the east side of the fault being especially significant. As the boundary of the third-level tectonic unit, both sides of the Pudu River fault have different velocities and structures. The Wuding-Yimen and Kunming-Jianshui folded uplift regions show relatively high-velocity and low -velocity abnormality distributions, respectively. At a depth of 20 km, the low-velocity abnormality range near the Xiaojiang fault zone is further expanded and the upper crust shows overall low-velocity features, which is consistent with the results revealed by body wave imaging, background noise and deep seismic sections (Wu Jianping et al., 2013; Liu et al., 2014). At a depth of 30 km, the forms of some abnormalities experience significant changes and the primary direction of the highvelocity abnormality near 102° E shows an approximate SN direction distribution and extends to the Yuanmou region in the south. The abnormality boundaries on the eastern and southern sides are limited by the Zemuhe and Gold River-Jinghe faults, and Panzhihua and Miyi show high-velocity abnormalities, which are particularly significant at depths of 40-60 km. The positive abnormality on the western side of Qiaojia and Huidong is gradually connected to the positive abnormality near Panzhihua with increasing depth; at the same time, the leading edge of the abnormality is extended to the south.

The depth of 80 km reveals the high- and low-interphase velocity structure feature of the Panxi tectonic zone, where the high-velocity abnormality near Panzhihua disappears and is replaced by a low-velocity abnormality feature, which is more extruded at a depth of 120 km, nearly consistent with the idea of Li (1987), who believes that the buried depth of the low-resistance layer of the upper mantle is 80-123 km, and with Kong Xiangru et al. (1987), who revealed that the buried depth of the lowresistance layer of the upper mantle in the Panxi region is approximately 89 km. Due to the existence of the lowvelocity layer in the upper mantle of the Panxi tectonic zone and its location in the upper mantle uplift region of the Panxi tectonic zone, the uplift of the upper mantle and the existence of deep fractures provide conditions for an invasion of the thermal mantle media and the deep tectonic setting is formed for the moderately strong seismic activities in the Panxi region.

Our P-wave velocity structure illustrates that there are a large range of high-velocity abnormality distributions in the crust of the Panxi tectonic belt, which is thought to be related to the intrusion of large amounts of basic and superbasic mantle source medium into the crust during the mantle plume activity period of the Neopaleozoic. During the crustal doming process, the intrusion of large amounts of mantle sources increased the mechanical strength of the crustal medium and formed the hard block within the crust with Panzhihua as its core. As evidence, the axis region has a series of layered basic and ultrabasic intrusion rock masses from the Hercynian Period. The existence of the hard medium in the crust of the Panxi region plays a role in obstructing the SE directional escape of the medium of the Tibetan Plateau, leading the primary neotectonic movements in the Panxi area and in the middle of Yunnan Province to be intermittent uplift movements. The uplift range since the Quaternary has been approximately 2000 m. The intense uplift movement in this region has formed deep river valleys and alpine and gorge region features with exposed bedrock; at the same time, the region has a newer difference fault depression, forming the fault depression basins of Yuanmou and Kunming.

5 Conclusions

This study collected 18,530 regional earthquakes events and 754 teleseismic events recorded by 634 stations (arrays) of the regional digital seismic networks set in Sichuan Province, Yunnan Province and perimeter zones, as well as the China earthquake scientific arrays. By adopting the travel time tomography method proposed by Zhao et al. (1994), this study used the joint inversion of the regional earthquake and teleseismic data to obtain the velocity structure of the 3D P-waves of the crust and upper mantle under the southeastern margin of the Tibetan Plateau. We found the following.

1) According to the imaging results, the P-wave velocity abnormality distribution features of the shallow crust are closely related to the geological structure, landforms and formation lithology. The upper crust velocity structure of the Sichuan and Yunnan Blocks and the Songpan-Ganzi Block show significant horizontal heterogeneity, forming blocking structures with different sizes and interphased high and low velocities. The P-wave inversion result also illustrates the large range of lowvelocity abnormality distributions in the northwest Sichuan secondary Block and the Songpan-Ganzi Block in the middle and lower crustal depth range, illustrating that they have relatively weak middle and lower crusts, that the middle and lower crust media of the western Sichuan Plateau have conditions for plastic flow and that the Sichuan Basin has a significant high-velocity abnormality at the western margin of the Yangtze platform, in which the middle and lower crust is in a relatively stable state.

2) The P-wave imaging result also reveals that the lowvelocity abnormality distribution direction is in the approximately SN direction within the middle and lower crust depth ranges of the Daliangshan secondary Block, which is nearly the same as the direction of the Daliangshan fault. In the EW direction, the Songpan-Ganzi Block and the Daliangshan Block have continuous low-velocity layer distributions within the middle and lower crust depth ranges. It is thought that the lowvelocity layer crosses the Daliangshan fault in the westeast direction, ending in the region near the Yingjing-Mabian-Yanjin fault tectonic zone at the western margin of the Sichuan Basin. In addition, the low-velocity layer in the crust medium is the deep dynamic source for the internal and boundary fault tectonic deformation and seismic activities in the Daliangshan Block.

3) Our P-wave velocity structure illustrates that there are a large range of high-velocity abnormality distributions in the crust of the Panxi tectonic belt, which is likely related to the intrusion of large amounts of basic and superbasic mantle source media into the crust during the mantle plume activity period of the Neopaleozoic. During the crustal doming process, the intrusion of large amounts of mantle sources increased the mechanical strength of the crustal medium and formed a hard block within the crust with Panzhihua as its core. The evidence of this is that the axis region has a series of layered basic and ultrabasic intrusion rock masses from the Hercynian Period. The 3D P-wave velocity structure also reveals a low-velocity layer in the upper mantle at a depth of 80– 120 km in the Panxi region and that the Panxi tectonic zone is located in the uplift region of the upper mantle. The uplift of the upper mantle and the existence of the deep fracture allows the intrusion of mantle thermal media, which sets the deep tectonic setting for the moderately strong seismic activity in this region.

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