Imaging 3-D crustal P-wave velocity structure of western Yunnan with bulletin data*

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Abstract Western Yunnan is a region with intensive tectonic activity and serious earthquake risk. It is of significant importance to study three dimensional crustal structure of this region to understand the tectonic setting and disaster mechanism. Densification and digitalization of seismic networks in this region provides an opportunity to study the velocity structure with bulletin data. In this study, we collect P-wave data of 10 403 regional earthquakes recorded by 79 seismic stations from January 2008 to December 2010. In addition to first arrivals data (Pg with epicentral distance less than 200 km and Pn), the Pg (or $\bar{P}$) data with epicentral distance more than 200 km are also considered as later direct arrivals in the tomographic inversion. We also compare the quantity and the quality of the seismic data before 2010 and after 2010. The test results show that adding the follow-up Pg phase can effectively improve the inversion ability of crustal imaging, and quantity and the data quality are significantly improved since 2010. The tomographic results show that: (1) The Honghe fault zone, which is the major fault systems in this region, may cut through the entire crust, and the velocity contrasts between two sides at lower crust beneath the Honghe fault are estimated at higher than 10%, while the velocity difference below Nujiang fault zone extends only in the upper crust; (2) Most of the earthquakes in the region occurred at the interface of high-velocity media and low-velocity media, i.e., the areas with high velocity gradient, which has been validated in other areas.

Key words: regional earthquake; 3-D velocity structure; later phase; Yunnan region

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1 Introduction

Western Yunnan is located in the eastern edge of the Tibetan Plateau, an area with unique geological environment. It is not only an important part of the world famous Alps-Himalayan orogenic zone, but also an area suffering intense compression from the collision between Gondwana continent and Eurasian continent (e.g., Wang et al., 2002; Ma et al., 1989). Since the late Paleozoic, western Yunnan experienced lots of tectonic processes, frequent magmatic activity, varying degrees metamorphism and multi-stage mineralization

(Chen et al., 1987). In addition, western Yunnan is an area with highest seismicity in China. Earthquakes in this region have large magnitude and high frequency, which cause great loss of people's lives and properties. According to statistics, in western Yunnan since the 1900s earthquakes with magnitude $M \geq 5$ occurred two times every year, earthquakes with magnitude $M \geq 6$ occurred once every 2 to 3 years (Yan et al., 1985), and some of the strong earthquakes with magnitude $M > 7$ caused tremendous casualties and property losses. Complex underground structures as well as numerous and large earthquakes make Yunnan, western Yunnan region in particular, being one of the focus of geophysical researches (e.g., Kan and Lin, 1986).

Understanding the fine structure of western Yunnan is of great significance for understanding the tectonic settings and disaster mechanism of the region. Frequent and widely distributed earthquakes make it feasi-

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ble to image the underground structures in this region. The earthquake bulletin data is usually reported by experienced technicians, which is a good starting point for tomographic studies (e.g., Wang et al., 2002; Liu et al., 1989). In general, both first arrivals and later phases are reported in the bulletin data. However, in most cases only the first arrivals are considered in previous tomographic studies due to the poor picking precision of later phases. During the past few years, the number of digital seismic stations has been prominently increased in the region, resulting in a great improvement in the precision of earthquake locations as well as the quantity and the quality of the bulletin data, which provides an opportunity to cast more lights on the subsurface structure in this region. In this study, we conduct seismic tomography using the bulletin data from January 2008 to December 2010 in western Yunnan area, and we try to include both the first arrivals and later phases in

the tomographic inversion.

2 Data and method

2.1 Data

We collect bulletin data from 79 seismic stations (Figure 1a) of Yunnan and Sichuan seismic networks in the period of January 2008 to December 2010. The original data set includes about 12 000 local and regional earthquakes. We use the following criteria to further data screening: on one hand, the number of P wave observation should be no less than three for one earthquake; on the other hand, the maximal travel-time residual (the difference between the observed and calculated travel times) is 2.0 s. After data selecting, the number of events involved in the inversion is 10 403 (Figure 1b), and the total number of the P-wave observations is 59 669, where the numbers of Pg and Pn phases are 55 669 and 3 539, respectively.

Figure 1 (a) Locations of seismic stations (solid triangles), new three stations after 2010 (delineated by rectangular), major faults (thick lines), prominent historic earthquakes with $M > 6.0$ (open circles). The dashed line shows the location of the profile AA' from Zhenyuan to Binchuan. F_1 . Xiaojiang fault; F_2 . Honghe fault; F_3 . Zemuhe fault; F_4 . Jinshajiang fault; F_5 . Lancangjiang fault; F_6 . Nujiang fault; F_7 . Anninghe fault. (b) Epicentral distribution of the events used in the 3-D inversion.

The reduced travel times of all phases used are shown in Figure 2a. It is clearly shown in Figure 2a that the Pg data scatters around the average velocity of 6.0 km/s. And starting from about 200 km, Pn begins to appear as first arrival phase. Since the first arrivals (Pg wave before 200 km and the Pn wave after 200 km)

are not interfered with other phases, so they have high picking precision and have been widely used in previous tomography studies. However, as indicated in Figure 2a, the seismic bulletin of the study area reports Pg wave phase data reach to the epicentral distance ~ 600 km. According to IASPEI standard seismic phase list, a Pg

also appears at larger distances caused by multiple P-wave reverberations inside the whole crust with a group velocity around 5.8 km/s. To further check the physical background of the Pg phase at larger distance in the study area, we collected waveform data of an earthquake occurred on November 28, 2011 at the boarder between China and Myanmar (Figure 2b) with magnitude 5.2 recorded by permanent and recently deployed portable stations (Figure 2b) within the azimuthal range of 60°–

130°. The Pg phases recorded at all distances keep in consistence, which may indicate that the marked Pg phases share the similar ray path at all distances, i.e., we may also treat the Pg phase at large distances as direct arrival from earthquake to station. It is also shown in Figure 2c that Pg phases have relatively higher amplitude than Pn phases, which ensures reasonably high picking accuracy of the latterly arrived Pg phase. But in this study we only have 4 007 Pg after 200 km.

Figure 2 (a) Reduced travel time data of all P wave used in the study. (b) Distribution of seismic stations and the earthquake (denoted by star) with magnitude 5.2 occurred on November 28, 2011 at the boarder between China and Myanmar. (c) Waveforms of the earthquake (Figure 2b) recorded by permanent and portable stations. The Pn and Pg phases reported by bulletin are marked with triangles and vertical bars, respectively, and the manually picked Pn and Pg at portable stations are marked with squares and circles, respectively. fxn denotes permanent station corresponding to the solid triangle in Figure 2b, and pxn denotes portable station corresponding to the open triangle in Figure 2b.

2.2 Method

Method used in this study is 3-D tomography code developed by Zhao et al. (1992), and further improved by Zhao et al. (1994) and Zhao (2001). The method can be applied in the velocity models with complex discontinuities and it adopts effective 3-D ray tracing method

to calculate travel time and ray path. LSQR method is used to calculate the data from large inverse problem (Paige and Saunders, 1982), and nonlinear problems are linearized with iterative approach, and the source parameters and velocity structure can be jointly inverted in each iteration step.

Several deep seismic sounding (DSS) experiments were carried out in the study area and adjacent region in last century (e.g., Hu et al., 1986; Kan and Lin, 1986; Yan et al., 1985; Lin et al., 1993). Results from the active exploration and seismic tomography (Wang et al., 2002) suggested the study area shows strong lateral velocity heterogeneity. Also the DSS experiments revealed that from the south part to north part of the study area the depth of Conrad discontinuity increases from 21 km

to 24 km and the Moho depth increases from 38 km to 58 km. Such strong lateral variations of two discontinuities definitely should be considered into the tomographic inversion. The contours of Conrad and Moho discontinuities summarized by Wang et al. (2002) are also used in this study. A localized 1-D velocity model (Figure 3a) obtained by averaging DSS results (Hu et al., 1986) is used as the initial velocity model.

Figure 3 1-D initial model of velocity structure (a), Conrad interface (b), as well as Moho interface (c) in western Yunnan.

3 Inversion for 3-D velocity structure

In our study the velocity structures are represented with grid nodes, and the velocity at any point is calculated with linearly interpolation from its eight neighbors (Zhao et al., 1992). Prior to tomographic inversion, we conduct checkerboard resolution tests (Zhao et al., 1992) with different grid space. Firstly, we discrete the study area with grid setting, and we assign positive and negative 3% velocity perturbation to all grid nodes alternatively. Then we calculate the synthetic arrival times for checkerboard models with the same numbers of stations, earthquakes and ray paths as those in the real data set. Finally, we invert the synthetic data with the same algorithm as for the real data. The grid setting with 0.5 degree by 0.5 degree grid horizontally, and –200 km, 1.00 km, 10.00 km, 30.00 km, 50.00 km, 250 km in the vertical direction are taken as the grid setting for real data inversion where most of the assigned perturbations are resolved. The resolvability of all Pn

and Pg data is shown in Figure 4. In general the central parts of the study area at all depths are well resolved, which indicates that the data set is adequate to resolve structures with scale no less than 0.5 degree. The poor resolvability at the northwest and southwest parts is mainly caused by sparsely distributed earthquakes and seismic stations (Figure 1). The resolvability also decreases with depth due to the decrease of seismic rays.

We conduct the tomographic with two iterations, in total 58 478 data are involved in the inversion, and the root mean square residual decreases from 2.0 to 0.612 33. The resultant P-wave images at different depths are shown in Figure 5. Velocities at depth shallower than 10 km are more diffused and are likely to be controlled by the surface structure such as basin and mountain. While at layers deeper than 10 km tomographic images clearly show a feature of bi-material, clear boundaries from NW to SE segment high and low velocity zones, which is consistent with previous studies (e.g, Wang et al., 2002; Li et al., 2008), yet, to the west of the Honghe fault in the deeper region, our results are

Figure 4 Checkerboard resolution test with all Pg and Pn data at different depths.

Figure 5 Final P wave model with velocity perturbations obtained from all observations at different depths.

in contradiction with Wang et al. (2002), while coincident with the results of Lei et al. (2009), from new data; at shallower depths our results are more scattered than those of Wang et al. (2002) and Lei et al. (2009), which may be due to the more western stations and data that we used.

4 Discussion

4.1 Effects of long distance Pg phase

The checkerboard resolution tests shown in Figure 4 are obtained by using all Pg and Pn phases (Figure 2a). To check the effect of the Pg data at long distance, we carry out checkerboard tests by using only first arrival phases (Figure 6). Although the main body of research area is well resolved by both data sets (Figure 1b), the results of checkerboard test with all phases included show better resolvability in the upper crust (layers of 1.0 km and 10 km). Although direct arrival assumption may be an oversimplification of the actual ray path of long distance Pg phase, it still can be

inferred from checkerboard resolution test even with a small number (4 007) of later arrival Pg phases involved, the ray coverage improves significantly in certain areas. Deep seismic sounding results indicate several reflected crustal phases exist in this region (e.g., Kan and Lin, 1986; Hu et al., 1986; Lin et al., 1993), those reflected phases sample the crust different from the direct phases which may provide further information about the crust structure (Zhao et al., 2005). We take some examples in Table 1 that compare the travel time from phases report and the theoretical travel time.

Table 1 A comparison of the travel times from phases report and the theoretical travel time

Station name	Epicentral distance /km	Pg travel time from phases report/s	Theoretical travel time of direct arrival/s
TNC	99	16.01	17.56
BAS	161	25.88	26.83
DAY	382	62.27	63.84
CUX	402	65.47	67.00

Figure 6 Checkerboard resolution by using only first arrival waves Pg and Pn at different depths.

4.2 Consistence of tomographic results

Many digital stations have been built in Yunnan since 2008, and this region now owes one of the densest seismic stations in Chinese mainland. In order to compare the data in recent years, we divide the earthquakes into two equal halves: from January 1, 2008 to September 2, 2009 and from January 1, 2010 to December 31, 2010, each half with 4 900 events. The inversion outputs are summarized in Table 2, and the tomographic results are shown in Figure 7. After 2010, there are three new stations, all located at Tengchong region (Figure 1a). The increase of seismic stations may have two effects on the observation. The increase in station number directly increases the data number, since one event could be recorded by more stations. At the same time, the newly added three stations densify the station coverage in the west part of the research area, which in turn will improve the earthquake location precision. Those two effects can be inferred from Table 2: there is a sub-

stantial increase in data number for the same earthquake number; and the residual of the second half data is much smaller than the first, indicating an improvement in the data quality after 2010. The comparison of the checkerboard of the two halves (not shown) shows that, at all depths, checkerboard of the second half is clearer, indicating a better ray coverage. Tomographic images from two images are similar in general pattern (Figure 7), even if they show some differences in detail. But the differences are in the places where the data have poor resolution and the differences may come from differences in data quality as we compared in Table 2, event and station distributions. But the comparison with the first half tomography results (Figure 7a) shows that the velocity anomalies in the second half tomography results (Figure 7b) are more coherent, especially at 30 km depth, and coherence is one of the judgment standards of good tomography result (Zhou, 2004).

Table 2 Comparison of P wave data and tomographic circumstances before and after 2010

	Earthquake number	Ray number	Station number	Data usage rate		Residual	
				First iteration	Second iteration	First iteration	Second iteration
First half	4 900	21 073	76	96.85%	98.178%	0.640 25	0.636 49
Second half	4 900	34 419	79	97.29%	99.13%	0.579 53	0.581 92

4.3 Tectonic implication of the P-wave velocity structures in western Yunnan

Tomographic results (Figure 5) obtained from the whole data set are somehow average results from two halves (Figure 7). In the tomographic results (Figures 5 and 7), the velocity distribution in the upper crust (1.0 km and 10 km) are more diffused which is likely contributed to the shallow structure as sediment basins and local magma activities. All results indicate that the Honghe fault is the boundary of strong velocity contrast. Honghe fault is a major boundary of the crustal structure, and lateral variation of Moho is very obvious, which is consistent with the seismic results and the gravity anomaly results (Kan and Lin, 1986). Materials NE to the Honghe fault show negative anomaly and materials SW to the Honghe fault appear to be high velocity. To the depth of 50 km, the boundary of velocity contrast moves about 1 degree to the southwest, this may suppose that the Honghe fault may cross the whole crust (Li et al., 2009) with nearly vertical to slightly NNE dipping. Also shown in Figure 5 are earthquakes with magnitude $M > 4.0$ occurred from 1970 to 2010. Most

earthquakes occurred within the upper to middle crust. Most of the epicenters extend along deep faults and are located in the transitional zones between high- and low-velocity areas, i.e., the areas with high velocity gradient, which is similar with previous findings (e.g., Huang et al., 2000).

A vertical profile from NE to SW of the study area (AA' in Figure 1a) is shown in Figure 8, and this vertical section crosses over several main faults in this region. It can be seen that most of the earthquakes in the upper crust are located in negative anomaly boundary, beneath which there is a positive anomaly column in depth. Earthquakes in the lower crust are located in positive anomaly blocks, indicating the junction of high- and low-velocity media is a main place for stress accumulation and energy gathering (e.g., Zhang et al., 2005; Lei et al., 2009). The velocity anomaly beneath Nujiang fault only extends in the upper crust, and other faults have even smaller range in velocity anomaly. Lancangjiang fault shows a clear display in 12 km depth, which coincides with the previous result (He et al., 2004).

Figure 7 P-wave model with velocity perturbations at several depths from data before (a) and after 2010 (b).

Figure 8 Velocity tomography of AA' profile from NE to SW of the study area.

5 Conclusions

In this study we conduct 3-D P-wave velocity tomography by using the seismic bulletin data reported by China Earthquake Networks Center. Our tomographic images are generally similar to previous results (e.g., Wang et al., 2002; Huang et al., 2000). Prominent earthquakes in this region are prone to occur in the region with high velocity gradient, which is also consistent with previous observations. The main fault, Honghe fault zone, is imaged as a sharp boundary of velocity contrast through the lower crust. The velocity contrast across the Honghe fault is estimated at higher than 10%. The reported Pg at long distances is used as later phases in our tomographic inversion, which can significantly improve the resolvability of the data in certain area. It is found that both the data quantity and quality are improved with time.

Recently, more than 250 portable stations have been deployed in Yunnan by Institute of Geophysics, China Earthquake Administration and Earthquake Administration of Yunnan Province. And seismic network in western Yunnan area now is one of the densest networks in the world (Wang et al., 2012), which provides an unprecedented opportunity to explore the 3-D structure of this area.

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