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Research on the Crustal Velocity Model of the Yunnan Region and Its Application[1]

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Abstract

This paper selects the records of 7,412 earthquakes,each recorded by more than 10 stations in Yunnan between 2009 and 2014 to acquire the traveltime curves.Meanwhile,for improving precision,linear analysis,reduced traveltime curve and interval stability analysis are conducted focusing on the records of 83 earthquakes with $M_L \geq 3.0$ recorded each by≥80% of the stations,and by combining predecessors' research results,the initial crustal velocity model of the study area is obtained. By selecting 200 earthquakes with M≥3.0 occurring in Yunnan between 2010 and 2014, using the Hyposat batch location processing method to iterate the initial velocity model,and performing fitting to S waves layered velocity structure,we obtain the crustal velocity model for the Yunnan region,namely,the 2015 Yunnan model,with: v_{P1}= 6.01km/s,v_{P2}=6.60km/s,v_{Pn}=7.89km/s, H_1=20km,H_2=21km,v_{S1}=3.52km/s,v_{S2} =3.86km/s,v_{Sn}= 4.43km/s. Analysis on earthquake relocations based on the new model shows that most earthquakes occurring in Yunnan are at a depth of 10k-20km of the upper crust. The March 10,2011M_S5.8Yingjiang and August 3,2014 M_S6.5 Ludian earthquakes are relocated,and the focal depths determined with the new model are respectively close to the precise positioning

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result and hypocentral distance to the strong motion stations at the epicenters,indicating that the new one-dimensional velocity model can better reflect the average velocity structure of the study area.

Keywords: The Yunnan area; Crustal velocity model; Earthquake location

INTRODUCTION

Yunnan is located in the southeast margin of the Qinghai-Tibetan Plateau,on the east side of the collision between the Indian plate and the Eurasian plate,where the geological structure is complex,a series of fault zones,such as the Nujiang fault,Ailaoshan-Honghe fault and Xiaojiang fault,are formed and developed (Deng Qidong et al. ,1994; Cai Linsun et al. ,2002) . The seismic activity noted as its great intensity,high frequency,severe disaster and wide distribution, which is one of the provinces with frequent destructive earthquakes and the most serious geological disasters in China. Accurate determination of the earthquake epicenter and focal depth has always been a hot issue for seismologists (Zhu Yuanqing et al. ,1997a) ,and a suitable crustal velocity model can help seismologists accurately determine the precision of seismic parameters (Zhu Yuanqing et al. ,1997b; Zhang Tianzhong et al. ,2007) .

For a long time,lots of studies have been done in this area by geoscientists,such as artificial seismic sounding (Hu Hongxiang et al. ,1986,1993,1994; Zhang Xiankang et al. ,2002; Wang Fuyun et al. ,2005; Zhang Zhongjie et al. ,2005a; Wang Chunyong et al. ,2009) ,body wave and surface wave tomography (Wang Chunyong et al. ,2002; Bai Zhiming et al. ,2003; Huang Jinli et al. ,2002; He Zhengqin et al. ,2005; Zhang Zhongjie et al. ,2011; Huang Jing et al. ,2012) and receiver function inversion (Hu Jiafu et al. ,2003; Li Yonghua et al. , 2009) ,which provides important data for studying tectonic background and crustal velocity model of Yunnan.

In this paper, the velocity model is measured and corrected by the use of abundant observation data from the Yunnan Digital Seismic Network,and the results are applied to the observation of seismic networks in practice, in order to improve the quality of earthquake locating.

1. ESTABLISHMENT OF REGIONAL VELOCITY MODEL

1. 1 Data Selection

The 49 fixed stations of the Yunnan Digital Seismic Network are distributed evenly according to the land area of Yunnan Province,about 50km-200km apart. Among them,stations are relative densely distributed in Kunming,in central Yunnan,and Dali in western Yunnan,which are about 50km-100km apart,and relatively sparse in Zhaotong in northeast Yunnan,Shangri-la in northwest Yunnan and southwest Yunnan,which are about 100km- 200km apart.

The 7,412 earthquakes recorded at least by 10 seismic stations during 2009-2014 since the establishment of digital networks of the 10th "Five-year Plan"are selected for the research,and epicenter distribution is shown in Fig. 1. Among them,83 earthquakes are recorded by more than 80% of these stations,with M_L greater than 3. 0.

1. 2 Determination of Initial Crustal Velocity Model

The 95,116 Pg seismic phases,1,813 Pb seismic phases,8,674 Pn seismic phases,98,570 Sg seismic phases,19 Sb seismic phases and 573 Sn seismic phases are extracted from selected data of 7,412 earthquakes,and their travel time and epicentral distances are used respectively for linear fitting to acquire corresponding fitting velocity,which is as below.

$$T = A + (\Delta/v) \qquad (1)$$

Where,T denotes seismic phase travel time,Δ is epicentral distance,v is fitting velocity,A is constant.

Velocities fitted by curves of Pg,Pb,Pn,Sg,Sb and Sn seismic phase travel time are respectively v P1 (P-wave velocity in the upper crust) = 6.04km/s， v_{P2} (P-wave velocity in the lower crust) =6.68km/s,v_{Pn} (P-wave velocity at the top of upper mantle) =7.89km/s,v_{S1} (S-wave velocity in the upper crust)=3.53km/s,v_{S2} (S-wave velocity in the lower crust) =3.93km/s and v Sn (S-wave velocity at the top of upper mantle) =4.51km/s.

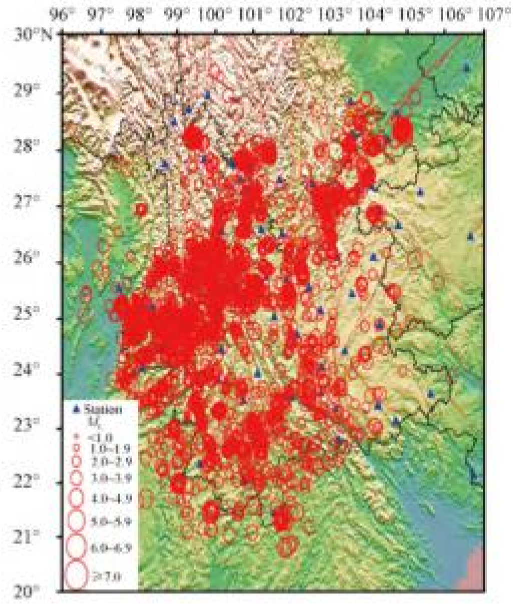

Fig. 1 Distribution of selected earthquakes

To improve the accuracy,seismic data with high positioning accuracy,that is,each of the 83 earthquakes with ML≥3.0 recorded at more than 80% stations,are selected for further analysis,and corresponding velocities fitted by Pg,Pb and Pn seismic phase travel time curves are v_{P1} =6.03km/s,v_{P2} =6.68km/s and v_{Pn} =7.91km/s (Fig.2).

According to velocity results of straight line fitting,reduced travel time method is used to adjust initial model and determine trial and error scope of model,that is,to provide variation range of parameters of crustal velocity model and ensure that real crustal model parameters are included in the range of variable parameters.

Reduced travel time is calculated according to Pg,Pb and Pn seismic phases of the 83 earthquakes.

$$T_Z = T_G - (\Delta/v) \qquad (2)$$

where,T_Z represents reduced travel time,T_G observed travel time,v wave velocity.

In order to investigate the fitting of actual travel time and theoretical travel time in velocity fitting straight line for v_{P1} ,v_{P2} and v_{Pn} at different focal depths,focal depths of 5km,10km,15km and 20km are selected and upper crust thickness H_1 and lower crust thickness H_2 are adjusted,and it is found that the focal depths of earthquakes in Yunnan are basically concentrated in 5km-20km,the theoretical travel time of Pg,Pb and Pn seismic phases are roughly parallel to the observed travel time,and data points are also concentrated. Studies of the seismic location carried out based on small and moderate earthquakes (Wu

Jianping et al. ,2004) also show that earthquake focuses are generally located in brittle middle-upper crust in this region,less than 20km deep,and the initial crustal velocity model thus obtained in Yunnan is as shown in Table 1.

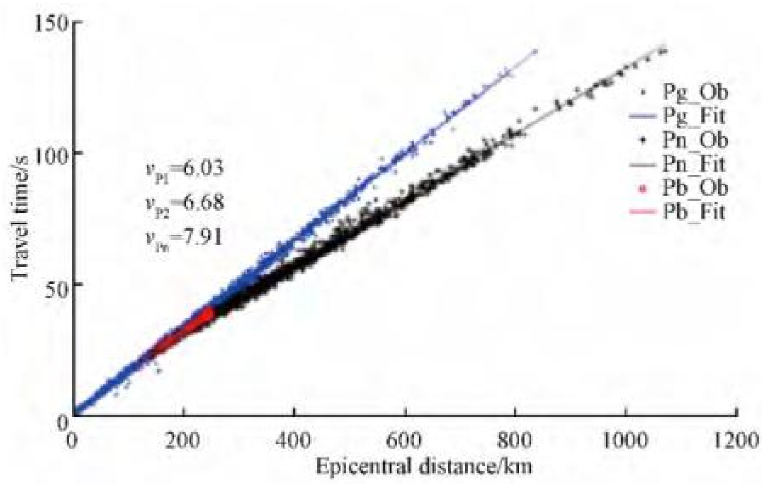

Fig. 2 Travel time curves

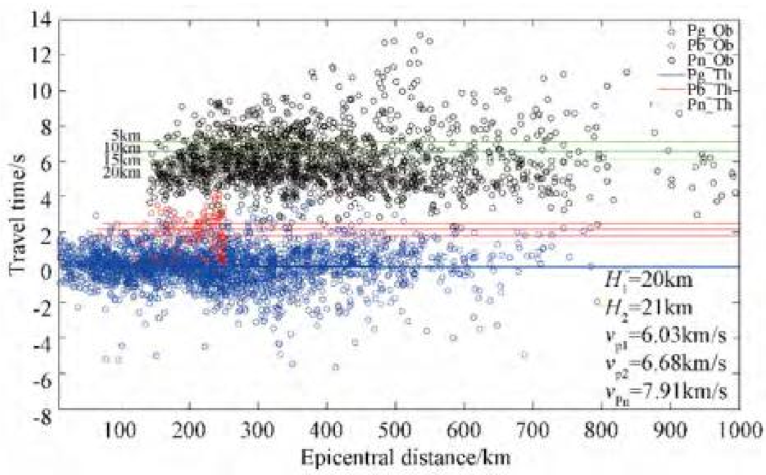

Fig. 3 Reduced travel time curves

Table 1 Initial model

Crust layering	v_P (km/s)	Thickness (km)
Upper crust	6. 03	20
Lower crust	6. 68	21
Top of the upper mantle	7. 91	

1. 3 Analysis of Velocity Stability

Velocity stability of the initial model is analyzed.The stability of v_{P1},v_{P2} and v_{Pn} under the following conditions is investigated (Fig.4):changes as epicentral distance increases; changes in different area coverage (150km as window and 50km as step length); changes in different area coverage (200km as window and 50km as step length) . It can be seen from Fig. 4 that v_{P1} ,v_{P2} and v_{Pn} are relatively stable in different area coverage.

1. 4 Determination of Optimal Velocity Model

The 200 earthquake events with M≥3.0 in Yunnan between 2010 and 2014 are selected, and radiation coverage of selected earthquakes and seismic stations is shown in Fig.5. The Hyposat batch location method is used for iteration for the initial velocity model,and computation limits are as below. v_{P1}=5.8-6.4km/s,v_{P2}=6.5-6.9km/s,v_{Pn}=7.8-8.2km/s,depth of Conrad discontinuity=16-24km and depth of Conrad discontinuity=38-42km.Calculation results are obtained (Table 2) .

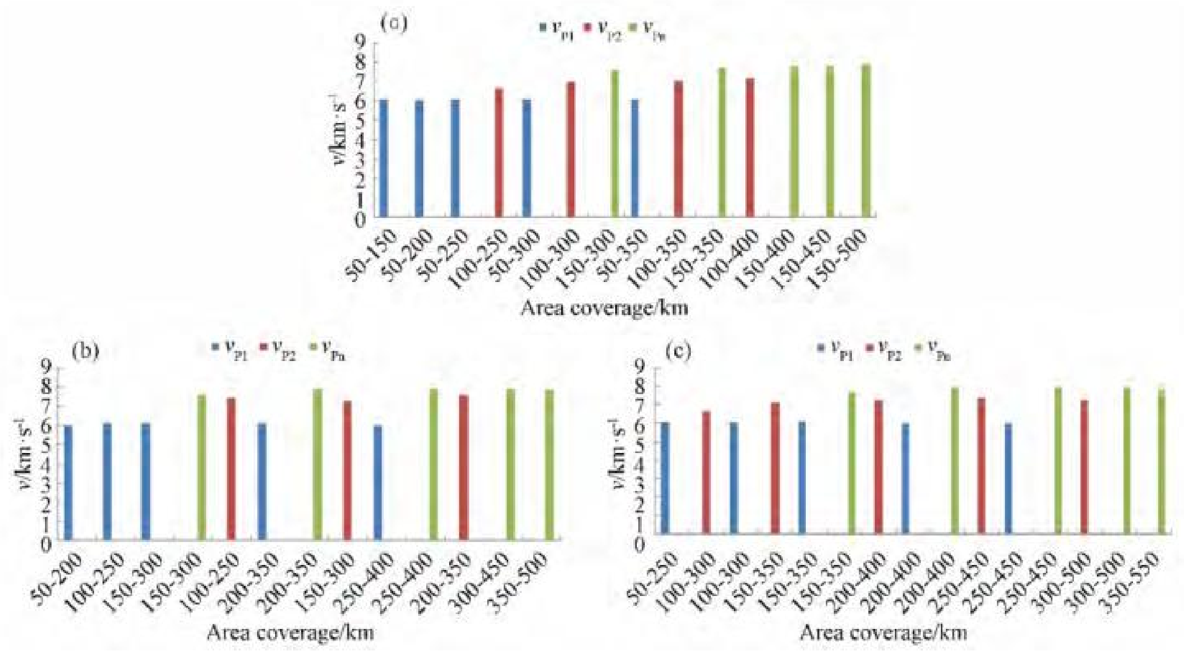

Fig. 4 Changes of v_{P1} ,v_{P2} and v_{Pn} in different area coverage

(a) Changes as epicentral distance increases. (b) Changes in different area coverage (150km as window and 50km as step length) . (c) Changes in different area coverage (200km as window and 50km as step length)

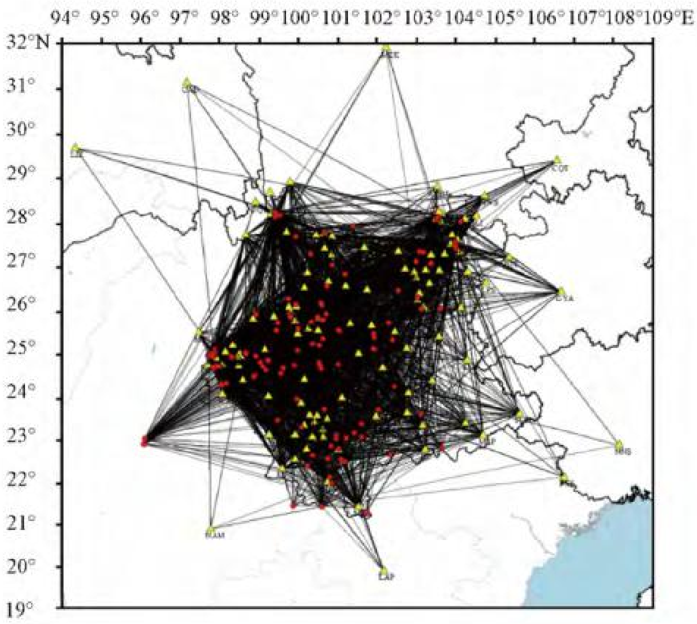

Fig.5 Distribution of P-wave propagation paths

Table 2 Results obtained by 2 iterations with Hyposat batch processing

	v_{P1} (km/s)	v_{P2} (km/s)	v_{Pn} (km/s)	Conrad depth(km)	Moho depth(km)	RMS
The first computation	6.00	6.60	7.90	20	41	0.469
The second computation	6.01	6.60	7.89	20	41	0.469

The results obtained by the second computation is taken as the optimal model,which, together with the daily catalogue model,are used to calculate 200 earthquake events using the Hyposat batch location approach (Fig. 6 and Fig. 7) ,to obtain RMS of the average travel time residual of positioning,which is 0.459 for the optimal model and 0.528 for the catalogue model. There are only 3 earthquakes with a difference in epicenter location of more than 10km between the two,and according to the recheck,it is concluded that the earthquakes with large errors have less seismic phases and the gap angle of seismic stations is large.

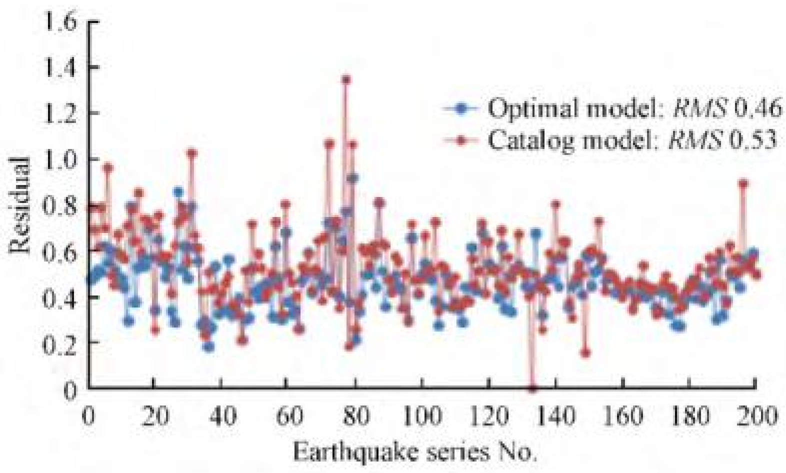

Fig. 6 Residual comparison between optimal model and catalog model after batch processing

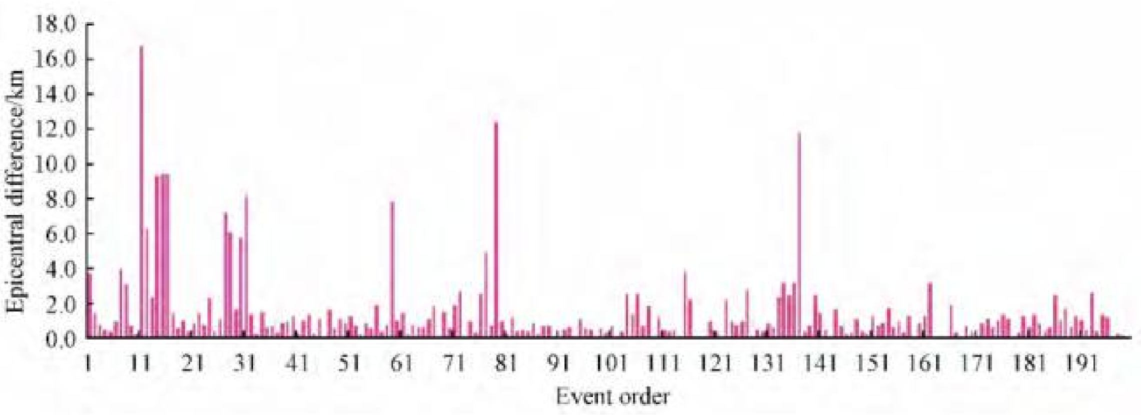

Fig. 7 Comparison of epicenter difference between optimal model and catalog model after batch processing

1. 5 Establishment of a Complete Regional Velocity Model

The S-wave velocity obtained by the method of uniform wave velocity ratio mainly reflects S-wave velocity in the upper crust (v_{S1}) . In order to further obtain S-wave velocity in the upper crust,lower crust and the top of the upper mantle (v_{S1},v_{S2} and v_{Sn}) ,keeping the epicenter location within the original error range,the obtained P-wave layered velocities and thickness of each layer,as well as the same seismic phase data used in original batch processing,are used to continuously adjust wave velocity ratio of each layer to try out v_{S1} ,v_{S2} and v_{Sn} of S-wave in stratified layers,and the complete crustal velocity model of Yunnan is obtained through further testing in trial calculation (the 2015 Yunnan model) ,which is shown in Table 3.

Table 3 Crustal velocity model of Yunnan (the 2015 Yunnan model)

Crustal layering	v_P (km/s)	v_S (km/s)	v_P/v_S	Crustal thickness(km)
Upper crust	6. 01	3. 52	1. 71	20
Lower crust	6. 60	3. 86	1. 71	21
Top of the upper mantle	7. 89	4. 43	1. 78	

2. EARTHQUAKE RELOCATION ANALYSIS BASED ON THE NEW MODEL

2. 1 Analysis of Focal Depth

The 2015 Yunnan model is adopted to remeasure the depths of 322 $M_L \geq 4.0$ earthquakes occurred in Yunnan and its adjacent areas during 2008-2016 using the PTD method (Zhu Yuanqing et al. ,1990) ,which are compared with the distribution of focal depths in catalogue reports (Fig. 8) .

Fig. 8 (b) and Fig. 8 (c) show respectively projections of focal depths along the longitude and latitude. It can be seen from the graph that most of the focal depth values calculated from the catalogue model are concentrated around 5km and 15km,and obviously distributed in two bands, while depth values calculated from the 2015 Yunnan model show a wide distribution,which are uniformly distributed within 20km. It is therefore clear that the depth distribution measured by the new model is more reasonable.

2. 2 Analysis of Typical Earthquake Location

(1)The new model (the 2015 Yunnan model) is used to locate the Yingjiang M5.8 earthquake on March 10,2011,and the result is compared with catalogue results and fine positioning results (Fang Lihua et al. ,2011) (Table 4) . Obviously,the positioning depth of the new model is the closest to fine positioning results.

Table 4 Comparison of measurement results for the Yingjiang earthquake

Model	N(°)	E(°)	Depth (km)	RMS
Fine positioning	24.680	97.903	13.4	
New model positioning	24.736	97.874	14.8	0.484
Catalog results	24.726	97.856	7.0	0.400

(2)The new model is adopted to locate the Ludian M_S6.5 earthquake on August 3,2014 using the PTD and Hyposat method respectively,and the measured depths are 7km and 8. 1km.Both of them are smaller than the hypocentral distance of Longtoushan strong motion network in the epicentral area,which is 8. 3km (Table 5,Fig. 9) ,indicating that the new one-dimensional velocity model can better reflect the average velocity structure of the study region. Longtoushan station of Yunnan strong motion network well documented this earthquake (Table 6,Fig. 10) .

Table 5 Comparison of measurement results for the Ludian earthquake

Origin time of earthquake		N(°)	E(°)	Depth/km	M_S	Residual	Illustration
(a-m-d)	(h: m: s)						
2014-08-03	16: 30: 11. 0	27.101	103.381	13.0	6.5	0.734	Catalog results
2014-08-03	16: 30: 11. 0	27.101	103.381	7.0	6.5	0.734	PTD positioning
2014-08-03	16: 30: 12. 3	27.107	103.422	8.1	6.5	0.658	Hyposat positioning

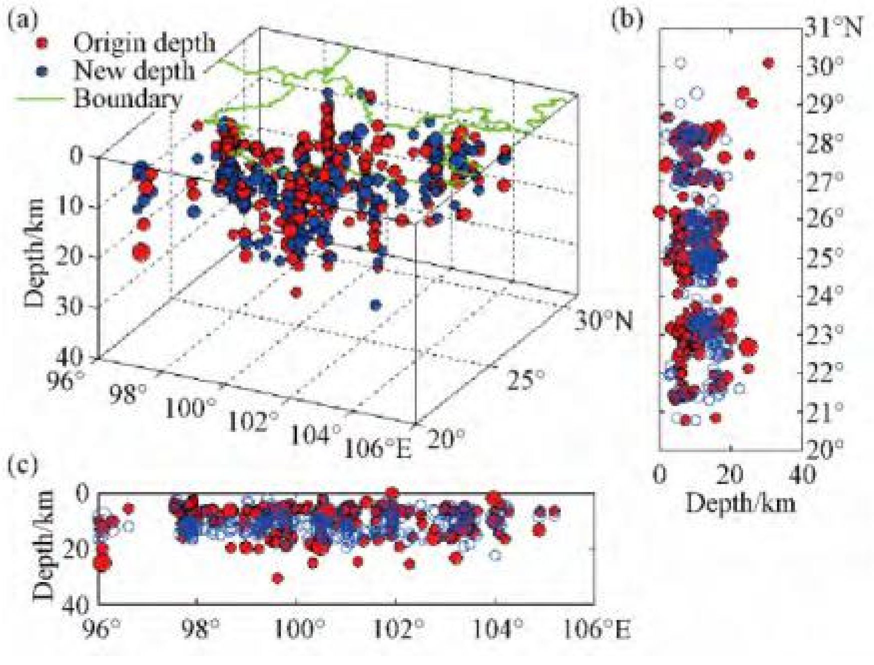

Fig. 8 Distribution of focal depths measured by new and old models

(a) Three-dimensional distribution of focal depths; (b) Focal depth projection along latitude; (c) Focal depth projection along longitude

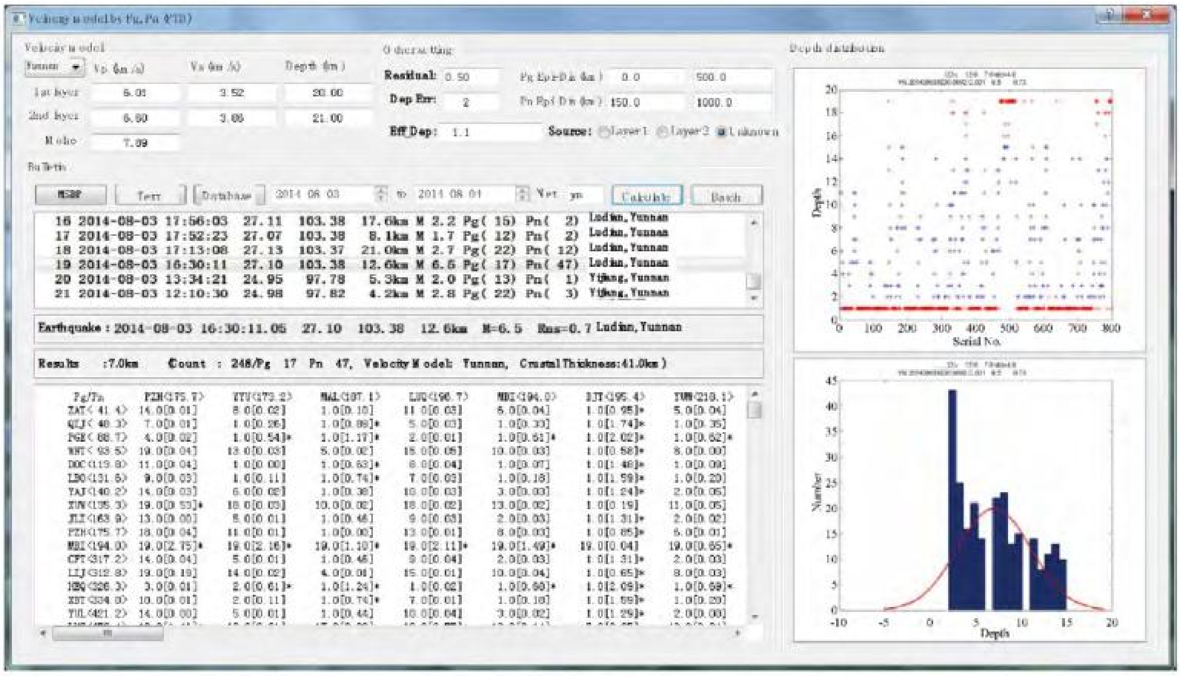

Fig. 9 PTD relocating for the Ludian earthquake

Table 6 Parameters of Longtoushan station

Station	N(°)	E(°)	Elevation (m)	Hypocentral distance(km)	Site	Observing objects	Instrument model	Instrument No.
Longtoushan of Ludian	27. 104	103. 384	1873	8. 3	Soil layer	Free surface	ETNA	4917

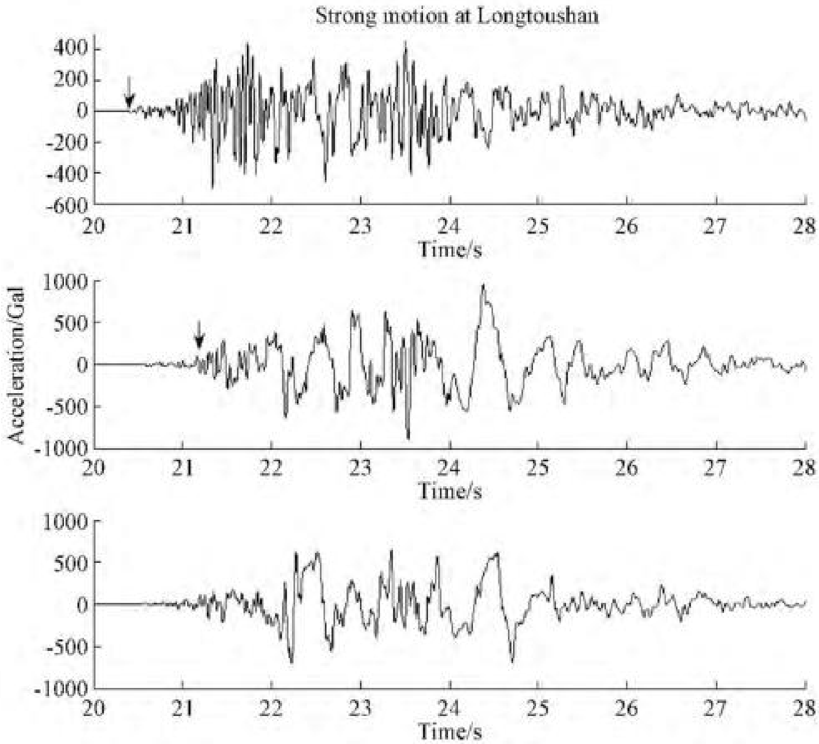

Fig. 10　Waveform records at Longtoushan station

3. DISCUSSION AND CONCLUSION

(1) The 7 ,412 earthquakes recorded by at least 10 seismic stations in Yunnan during 2009-2014 are used for linear fitting.　Meanwhile,to improve accuracy,seismic data with high positioning accuracy of 83 earthquakes with $M_L \geq 3.0$ recorded by more than 80% of stations were selected for further analysis,and their theoretical reduced travel time and actual reduced travel time are calculated. By selecting different focal depths and adjusting the thickness of both the upper and lower crust,it is found that the focal depths of earthquakes in Yunnan are basically concentrated in 5km-20km. The theoretical travel time of Pg,Pb and Pn seismic phases are roughly parallel to the observed travel time,and data points are also concentrated,and thus the initial crustal velocity model of Yunnan is obtained: v_{P1}=6. 03km/s,v_{P2}=6.68km/s,v_{Pn}=7.91km/s,H_1=20km,H_2=21km.By setting different sliding windows,it is observed that v_{P1} ,v_{P2} and v_{Pn} of the initial model are relatively stable.

(2) The 200 earthquake events with M≥3.0 in Yunnan are selected and the Hyposat batch location method is used for iteration for the initial velocity model,and better results are obtained and taken as the optimal model. In the meantime,by continuously adjusting the wave velocity ratio of each layer to try out v_{S1} ,v_{S2} and v_{Sn} of S-wave in stratified layers,the

complete crustal velocity model of Yunnan is obtained through further testing in trial calculation (the 2015 Yunnan model):v_{P1}=6.01km/s,v_{P2}=6.60km/s,v_{Pn}=7.89km/s,H_1= 20km,H_2 =21km,v_{S1}=3.52km/s,v_{S2} =3.86km/s,v_{Sn} =4.43km/s.

(3) Based on the 2015 Yunnan model obtained in this study,322 M≥4.0 earthquakes in Yunnan between 2008 and 2016 are relocated using the PTD method. The obtained depths are no longer distributed in two bands at depths of around 5km and 15km,but evenly distributed within 20km. The depth distribution measured by the new model is more reasonable. The new model is adopted to relocate the Yingjiang M_S5.8 earthquake on March 10,2011,and the focal depth is calculated to be 14.8km,which is the closest to the fine positioning result of 13.4km. The new model is adopted to locate the Ludian M_S6.5 earthquake on August 3,2014 using the PTD and Hyposat method,and the measured depths are 7km and 8.1km respectively. Both of them are smaller than the hypocentral distance of the Longtoushan strong motion network in the epicentral area,which is 8.3km,indicating that the new one-dimensional velocity model (the 2015 Yunnan model) can better reflect the average velocity structure of the study region,which provides basis for more detailed work in future.

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