The lithospheric structure beneath southeast Tibet revealed by P and S receiver functions

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ABSTRACT

Yunnan is located at the margin of southeast Tibet, where dramatic tectonic activities occur. In this study, we calculated the P and S receiver functions by the deconvolution of three-component seismic data from 48 permanent broad-band stations deployed in Yunnan region. In order to improve signal-noise ratios of the receiver functions, we move-out corrected receiver functions to a reference epicentral distance of 67°, and then stacked them to one trace for each station. Finally, the stacked traces were converted to the depth domain to obtain the crustal and lithospheric thicknesses beneath each station. In southwestern Yunnan (at the west side of the Jinshajiang-Red River Fault), the crustal thicknesses from the P-wave receiver functions (PRFs) and from the S-wave receiver functions (SRFs) are in the ranges of 30–36 km, and of 33–39 km, respectively. But in northwestern Yunnan, the crustal thicknesses from PRFs and SRFs are from 66 to 69 km and from 63 to 66 km, respectively. Our results show that the crustal thicknesses in Yunnan from PRFs and SRFs are consistent, with a maximum deviation of 3 km; and increase gradually from ~30 km in the south to ~68 km in the northwest. Besides, the lithospheric thickness from PRFs is also similar to that from SRFs, with the largest difference of 15–20 km in southeastern Yunnan. At the west side of the Jinshajiang-Red River Fault in western Yunnan, it is only about 80–100 km, and increases to 140–150 km regionally in northern and southeastern Yunnan. The thinned lithosphere extends eastward from western Yunnan to eastern Yunnan. We attribute the thinned lithosphere to the upwelling of hot upper mantle materials associated with the eastward subduction of the Indian plate.

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1. Introduction

The continuous collision between the Indian and Eurasian plates began about 50 Ma ago, and has resulted in the uplift of the Tibetan plateau and at least 1500 km of crustal shortening within the collision region (Molnar and Tapponnier, 1975; Royden et al., 2008). Yunnan is located at the southeastern margin of the Tibet Plateau. Due to the influence of eastward subduction of the Myanmar micro-plate, as well as southeastward extrusion of the Tibet Plateau, the regional deformations are characterized by the thickening of the underlying crust, formation of a series of Cenozoic strike-slip faults, and eastward escape of the Tibetan plateau's crustal materials (Royden, 1996; Royden et al., 2008; Clark and Royden, 2000; Klemperer, 2006). As shown in Fig. 1, the topography elevation of our study area is about 4000 m in the northern region, but only around 700 m in the southern region. Our study

area is part of the transition zone between the Tibetan Plateau and the Yangtze Craton, and is in the path of the escape flow from the Tibetan plateau. The large strike-slip faults, e.g. the Nujiang Fault, the Lancangjiang Fault, the Jinshajiang-Red River Fault, the Lijiang-Xiaojinhe Fault, and the Xianshuihe-Xiaojiang Fault, divide the region into four blocks: the East-Yunnan Block, the Central Yunnan Block, the Indochina Block, and the Yunnan-Myanmar-Thailand Block. This special tectonic setting leads to strong earthquake activities and strong lithospheric deformations. Eight strong earthquakes with the magnitudes above Ms 7.0 have occurred in the region since 1970s. Furthermore, these earthquake epicenters were clustered dominantly along the boundary faults (Fig. 1). The focal mechanisms suggest that these large strike-slip faults may absorb most of the lithospheric deformation, and could be the first-order tectonic boundary separation of different blocks.

The lithosphere is seismologically divided into two parts: the crust and the mantle lid above the asthenosphere. The depth and the topography of Moho discontinuity and the lithosphere-asthenosphere boundary (LAB) are the most important parameters

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Fig. 1. Topography, faults and earthquakes in Yunnan and its adjacent region. Red circles represent the epicenters of $6.0 \leq M_s \leq 8.0$ earthquakes from 1500 to 2013. Beach balls represent earthquakes with $M_s > 7.0$ since 1970. Solid lines represent major active faults while the black triangles represent broadband seismic stations. Major faults and geological blocks: F1 – Nujiang Fault; F2 – Lancangjiang Fault; F3 – Jinshajiang–Red River Fault; F4 – Lijiang–Xiaojinhe Fault; F5 – Xianshuihe–Xiaojiang Fault. I – Eastern Yunnan Block; II – Indochina Block; III – Central Yunnan Block; IV – Yunnan–Myanmar–Thailand Block. Inset map: Contour of smoothened elevations of southeastern Tibet, with interval being 1000 m. The red rectangle on the inset map is showing the study region.

for understanding lithosphere structural evolutions. The main seismological characteristics of these discontinuities in the upper mantle are the abrupt changes of the P- and S-wave velocities. Though the first order features in geodynamic Earth models, the LAB is only a weak interface in seismic Earth models (Dziewonski and Anderson, 1981; Kennett and Engdahl, 1991). The main characteristic of wide angle observation technique is that the vertical part of a travel path is smaller than the horizontal part, thus only effective to explore crustal structures (Kind et al., 2012). Seismic tomography techniques (body waves or surface waves) are usually used to study the structural characteristics of the upper mantle (e.g., Kanamori and Press, 1970; Knopoff, 1972). But they are more sensitive to gradual velocity variations than rapid changes, which hinders their applications to determining sharp discontinuities (Kind et al., 2012). Meanwhile, lateral resolutions of regional surface wave tomography are in general around 300–400 km, nearly an order of magnitude lower than the vertical resolution (Rychert and Shearer, 2009). Teleseismic body wave tomographies have better lateral resolutions, but the vertical resolution is limited (McKenzie and Priestley, 2008; Priestley and Tilmann, 2009). For these reasons, it is difficult to obtain high-resolution seismic observations of the lithosphere thickness (Kind et al., 2012).

In the past 30 years, several thousand kilometer sounding profiles have been established in Yunnan region (Kan and Lin, 1986; Zhang et al., 2002, 2009; Xu et al., 2015; Pan et al., 2015). Many other geophysical observations, such as surface wave tomographies (Hu et al., 2008; Yao et al., 2008), receiver functions (Hu et al., 2008; Wu and Zhang, 2011; C. Li et al., 2008; Bao et al., 2015; Chen et al., 2015), teleseismic P wave travel time tomographies (Lei et al., 2009; C. Li et al., 2008), and magnetotelluric sounding (Bai et al., 2010; Cheng et al., 2015; Li et al., 2014) have been carried out. These results provide important information on the crust structure in Yunnan region, but lower-lithosphere struc-

tures are still poorly understood due to limited observation conditions and spatial resolutions.

In the last decades, the receiver function technique has become one of the most powerful tools for investigating the lateral variation of discontinuities in the crust and the upper mantle. Its main principle is to use the delay time of the Ps and Sp phases in the P and S receiver functions to measure the depth of the interfaces, respectively. Though there are successful applications of the P receiver functions to the LAB (Rychert et al., 2005), the method is generally limited for detecting interfaces in the mantle lithosphere due to interference of its primary conversions with strong crustal reverberations. The recent developed S receiver function technique seems able to overcome this problem, because it analyses S-to-P converted phases that arrive earlier than the incident S phase and are therefore separated from the later arriving S reverberations (Farra and Vinnik, 2000; Yuan et al., 2006). In this study, we used both the P and the S receiver functions from 48 permanent broad-band seismic stations deployed in Yunnan region to estimate the crustal and the lithospheric thicknesses. We then use the observed variation of the lithospheric structures to discuss the kinematics and the dynamics of the interaction between the Yunnan and its adjacent geological blocks.

2. Method

Receiver functions are commonly used to image crustal structures beneath seismic stations. This technique takes advantage of the fact that what buried in the P wave coda is many P to S wave conversions (Ps) from discontinuities directly beneath a seismic station (Langston, 1979).

When teleseismic P waves arrive at the surface, it is possible to isolate these Ps conversions by deconvolving the P wave signal

from the horizontal components (Langston, 1979; Owens et al., 1984). This process removes the source and the far-field effects. The resulting receiver function would contain primarily the Ps arrivals. As shown in Fig. 2, to further reduce the direct P waves and enhance the Ps phases, the vertical, north-south and west-east (ZNE) components of the ground motion are rotated into the local ray coordinate system (LQT components). The L component is mainly dominated by the P waves (the incident P or Sp waves), while the S waves (the incident S or Ps waves) are mainly contained in the Q and T components. P receiver functions (PRFs) are usually computed by deconvolving the L component from the Q component (Yuan et al., 1997); while S receiver functions (SRFs) are usually computed by deconvolving the Q component from the L component (Yuan et al., 1997). SRFs are free of S multiples and therefore can be very useful for detecting the mantle lithosphere where PRFs are sometimes dominated by crustal multiples. Additionally, the S-to-P converted waves cannot be observed over all epicentral distances since they do not occur at overcritical incidence angles (Yuan et al., 2006; Li et al., 2007), thus we have to select appropriate teleseismic events for calculation of SRFs.

As shown in Fig. 3, we assume that the Moho and the LAB are two discontinuities in the upper mantle. Raypaths of the P_M s and S_{MP} denote the conversions from the Moho, and those of the P_{LS} and S_{LP} denote the conversions from the LAB. P_{LS} and S_{LP} phases from the LAB do not denote the response directly under stations due to certain offset from the station. According to the IASP91 model (Kennett and Engdahl, 1991), given an LAB depth of 100 km, when a seismic wave arrives at the station from an epicentral distance of 67°, lateral distances sampled by P_{LS} and S_{LP} converted phases are 25 and 52 km, respectively.

In order to enhance weak signals in receiver functions and improve the signal-to-noise ratios, one effective method is to stack a large amount of receiver functions. However, the arrival-time of converted waves depends on the wave incidence angle and the horizontal slowness. In order to apply the stacking technique to enhance weak signals from the same discontinuity, we need to ensure the same arrival-time for these phases. We accomplished

Fig. 2. Rotation scheme for the three component waveform data of incident P and converted seismic phases. The north (N) and east (E) components are rotated to the radial (R) and transversal (T) components, where R is pointing to the event epicenter and T is perpendicular to R (lower-right inset shown the horizontal plane). Z and R components are then projected to the orthogonal L and Q components (both in the same vertical plane). BAZ is the back azimuth of the event-station pair with respect to the north direction. The angle i is the incidence angle of the incoming P-wave. Ps represents the converted P-to-S phases at the Moho.

Fig. 3. P-to-s (Ps) and S-to-p (Sp) ray paths in lithosphere. Thick black lines show the raypaths of Ps (P_{LS}) and Sp (S_{LP}) direct conversions from the base of the lithosphere. Grey lines indicate the Ps (P_Ms) and Sp (S_MP) direct conversions from the Moho, and the first-order Ps reverberation on the Moho that also appears in the data: P_{Mpps} , P_{Mpss} and P_{Msps} (dashed black line for clarity).

this requirement by using a move-out correction. The delay-time of the Ps converted phases T_{Pds} from a discontinuity at depth d , is given by (Dueker and Sheehan, 1997, 1998):

$$T_{Pds} = \int_{-d}^0 \left(\sqrt{V_s^{-2} - p^2} - \sqrt{V_p^{-2} - p^2} \right) dz, \quad (1)$$

where p is the corresponding ray parameter; V_p and V_s describe the P and S wave velocities, respectively. Both velocities are also functions of the depth z . Once a velocity model is set, the time delay of the Ps conversion at the conversion depth d depends only on the ray parameter p . In other words, a conversion depth d may be associated with multiple delay times. Giving a ray parameter p , we can transform the receiver functions into the depth domain by using Eq. (1). The Tau-P method (Crotwell et al., 1999) was employed to get p according to the epicentral distance. For instance, we computed the delay time difference between the Ps conversion phase and the direct P from the IASP91 model (Kennett and Engdahl, 1991), with respect to the ray parameters 8.89, 6.40 and 4.70 s/deg (epicentral distances 30°, 67° and 90°), respectively. As shown in Fig. 4, the arrival time difference of the Ps phase from the 660 km discontinuity is close to 10 s for $p = 8.89$ and 4.70 s/deg (corresponding to the epicentral distance 30° and 90°). Therefore, to enhance weak phases from the same discontinuity, it is necessary to move-out correct different events to a reference distance (e.g., a reference distance of 67°, corresponding to a slowness of $p = 6.40$ s/deg for P wave, and $p = 12.07$ s/deg for S wave).

3. Data and the results

In this study, waveform data for 211 teleseismic earthquakes with $M_s > 6.5$ recorded at 48 permanent broadband stations in Yunnan are collected (see Fig. 5). The events with the epicentral distance of 28–95° are used to calculate PRFs; and those with the epicentral distance between 55° and 150° are used for computation of SRFs. The algorithm for PRF evaluation is composed of the following steps: (1) the waveforms are cut from 10 s before the direct P-wave to 100 s after the direct P-wave; (2) the ZNE components

Fig. 4. Relationship between conversion depth (km) and time delay (s) of the Ps phase for different ray parameters computed from the IASP91 model. Ray parameters for the curves a, b and c, are 4.70, 6.40 and 8.89 s/deg, corresponding to epicentral distances of 90°, 67° and 30°, respectively. Additionally, the ray parameter for curve d is 12.07 s/deg, which corresponds to S wave incidence from epicentral distances of 67°.

Fig. 5. Locations of the earthquakes used in this study. Events with epicentral distance between 28° and 95° are used for computation of PRFs, while those events with epicentral distance between 55° and 150° are used for computation of SRFs. The small triangle in the center of the figure marks the location of the study region.

are rotated into the ZRT coordinates; (3) the ZR components are rotated to the LQ components; (4) an iterated deconvolution algorithm (Ligorria and Ammon, 1999) is applied to deconvolve the L component from the Q component in the time domain; (5) an 1 Hz width Gaussian filter is applied to remove the effects of high frequency noises. Finally, a total of 7407 PRFs are obtained, and the average number of the PRFs is 154 per station.

Results at two particular stations are shown in Fig. 6. One is from the broadband seismic station TOH (Fig. 1), located at the junction of Xiaojiang and Jinshajiang Fault where the Ms 7.6 Tonghai earthquake occurred in January 5, 1970. The other station is GEJ, located in eastern Yunnan that belongs to the stable southern China block. These two stations were added to the Yunnan Seismic Network in late 1998. After processing the all teleseismic waveforms with the epicentral distances ranging from 28° to 95°, we obtained 165 and 180 PRFs at the GEJ and TOH, respectively (the lower panel in Fig. 6). To remove the time delays of different incidence angles, all individual seismic traces were move-out corrected to a reference distance of 67° using the IASP91 model (Kennett and Engdahl, 1991) before stacking.

The radial (R) and the vertical (Z) components are rotated into the ray coordinate system (LQ). Theoretically, S-waves are only contained in the Q-component, and P-waves are in the L-component. The incidence angle of a P-wave is calculated from a reference earth model. And we assume that the focal depth is zero in the calculation process. After the coordinate rotation, however, part of the P-wave energy still remains in the Q-component, and part of the S-wave energy is left in the L-component, mainly due to the tilted Moho and strong crustal anisotropy in Yunnan region (Chen et al., 2013). As shown in Fig. 6, the positive phase right behind P is marked as P_{MS} and interpreted as the conversion phase from the Moho. The P_{MS} converted phases beneath GEJ and TOH stations appear at the time of 5.4 s and 5.5 s, respectively (Fig. 6). By looking up the table in Fig. 4, the crustal thicknesses beneath GEJ and TOH station are 45 km and 46 km, respectively. In addition, an obvious negative polarity P_{LS} phase appears after the P_{MS} in either individual traces or the stacked trace, and occurs at the time of 8.5 and 9.0 s, respectively. Here we interpreted the negative polarity P_{LS} phase as the conversion phase at the LAB, and estimated that the depths of the LAB beneath GEJ and TOH station are 75 km and 79 km, respectively.

Similarly, the main steps of getting SRF are as follows: (1) the waveforms are cut from 100 s before the S-wave to 20 s after the direct S wave, then the time axis is reversed so that the Sp converted phases appear at positive arrival times; (2) the ZNE components are rotated into the ZRT coordinates; (3) the ZR components are transformed into the LQ components; (4) in the time domain, the S receiver function is obtained by the deconvolution of the Q component from the L component (Ligorria and Ammon, 1999); (5) an 1 Hz width Gaussian filter is finally used to remove the effects of high frequency noises. In order to compare the SRFs with the PRFs, the amplitudes of the SRFs are reversed, so that the S_{MP} phases in the SRFs retain positive polarity. In this study, a total of 1512 S receiver functions are computed.

In order to analyze differences between the PRFs and the SRFs, we also present the SRFs for GEJ and TOH, respectively. As shown in Fig. 7, we obtained 23 and 28 SRFs at the two stations from all available data with epicentral distances from 55° to 150°, respectively (Fig. 7 lower panel). Individual SRFs are summed into one trace, after move-out corrected to the reference distance of 67° with the IASP91 model (Kennett and Engdahl, 1991). The S_{MP} and the S_{LP} converted phases at the Moho and the LAB beneath the two stations are clearly distinct in the stacked traces. Though the coherency of the SRFs is poorer than that of the PRFs, the stacked traces still have a high signal-to-noise ratio. The S_{MP} converted phases beneath GEJ and TOH stations occur at the arrival

Fig. 6. Individual PRFs and stacked traces for (a) GEJ and (b) TOH stations. The individual traces are displayed by sequential, and has been move-out corrected to a reference epicentral distance of 67° before stacking (bottom panel). The top panel of each plot is the stacked trace, and the converted phases at the Moho and the LAB are labeled as P_{Ms} and P_{Ls} , respectively.

Fig. 7. Individual SRFs and stacked traces for (a) GEJ and (b) TOH stations. All these individual traces are displayed by sequential, and have been move-out corrected to a reference epicentral distance of 67° before stacking. The top panel of each plot is the stacked trace, and the converted phases at the Moho and the LAB are labeled as S_{Mp} and S_{Lp} , respectively.

time of 6.5 s and 5.8 s (Fig. 7), implying 48 km and 43 km crustal thicknesses via the table in Fig. 4, respectively. The delay times of the S_{Lp} phases are 12.48 s and 11.08 s, corresponding to the depth of 90 km and 81 km, respectively. From the PRFs and the SRFs, we found that the crustal thicknesses are 45 km and 48 km, and the LAB depths are 75 km and 90 km beneath GEJ station, respectively; the crustal thicknesses are 46 and 43 km, and the LAB depths are 79 km and 81 km beneath TOH, respectively. The comparisons demonstrate that the crustal thicknesses from the PRFs are consistent with those from the SRFs. But the deviation in the LAB depths from the PRFs and the SRFs reaches 15 km beneath GEJ station, perhaps because the SRFs sample a larger lateral structure with a lower resolution than the PRFs. This example indicates that LAB depths from the SRFs can be divergent when they vary dramatically around a station.

One key for obtaining a reliable depth of a discontinuity is to pick up an appropriate conversion to the stacked trace. In order

to assess the summation of the PRFs and the SRFs, we collected all stacked traces from 48 permanent stations in Yunnan, and scaled them with the same normalized factor. As shown in Fig. 8, the P_{Ms} (with the positive polarity) and the P_{Ls} (with the negative polarity) are interpreted as the conversion phases at the Moho and the LAB, respectively. Generally, the P_{Ls} phases are quite weak, but also clearly visible (except at a few stations). As shown in Fig. 9, despite that the amount of the SRFs is less than that of the PRFs for a given station; the stacked traces have a high signal-to-noise ratio. The positive S_{Mp} and negative S_{Lp} phases are interpreted as the conversion phases from the Moho and the LAB, respectively. These phases stand out clearly in the stacked traces, implying the high signal-to-noise ratio in the SRFs.

In order to get the Moho and LAB topographies, we first picked up the delay time of the converted phases from the stacked receiver functions, and then obtained the corresponding depths for each station by looking up the table in Fig. 4. After that, the crustal

Fig. 8. Stacked PRFs at each station in Yunnan. The dash line represents the positive P_{MS} converted phase, which are interpreted as the conversion phase at the Moho. The upper letters L indicate a negative phase and represent the P_{LS} conversion phases from the LAB. The question-marks represent the stations with controversial P_{LS} phases. Station name is shown at the left of each stacked trace (see Fig. 1).

thicknesses beneath all stations are applied to the spline interpolation in GMT software (Wessel and Smith, 1998). As shown in Fig. 10, the contour map of the crustal thickness from the PRFs is consistent with that from the SRFs. In general, the crustal thickness varies from about 30 km in southern Yunnan to 68 km in north-western Yunnan. An important structural feature is that there is a transition belt near the 26°N latitude, and the crust thickness increases dramatically across the belt toward the north: from ~40 km under central Yunnan to ~50 km near the Lijiang-Xiaojinhe Fault.

Similarly, the contour map of the lithospheric thickness can be obtained with a spline interpolation beneath each station. As shown in Fig. 11, the LAB thickness changes dramatically: it is only about 80–100 km on the west side of the Jinshajiang-Red River Fault, and extends from western Yunnan to eastern Yunnan. It reaches to 140–150 km locally in the northern and southeastern regions in Yunnan. In general, the LAB variations derived from the PRFs and the SRFs are consistent. The maximum variation reaches 15–20 km. The dominant period of the S receiver functions is longer than 5 s, corresponding to a wavelength of ~20 km. Synthetic tests (Li et al., 2007) show that a 10 km LAB depth variation can be clearly identified. The resolution for the LAB sharpness is about 20 km, close to the dominant S-wave wavelength (Li et al., 2007). Our results from the P and S receiver functions support the previous conclusions, and confirm that there exists an LAB depth transition belt in Yunnan near the latitude 26°N, where the lithospheric thickness increase rapidly from 100 to 150 km across the belt.

4. Discussion

For decades, the receiver function technique has been developed as one of the most powerful tools to observe seismic discontinuities in the crust and the upper mantle (e.g. Vinnik, 1977; Langston, 1979). Multiple reverberations at the Moho in the PRFs usually arrive later than 10 s and are separated from the LAB converted phase. However, it may appear in the same time window with the P_{LS} phase at the LAB due to complex crustal structures, which will cause interference between the crustal multiple reflections and the LAB conversions in the PRFs, and would result in difficulties in recognizing the Moho and the LAB phases. On the contrary, the S_{LP} phases at the LAB can be clearly identified in the SRFs, because the Sp waves travel faster than the incoming S waves and the SRFs are free of contamination from the multiples. The P-wave impulse is significantly narrower (~2 s) than the S-wave impulse (~5 s). Thus the corresponding PRFs have a higher resolution than the SRFs (Li et al., 2007).

In this study, the PRFs and the SRFs are converted from the time domain into the depth domain using the IASP91 earth model (Kennett and Engdahl, 1991), and are then used to determine the depths of discontinuities. Utilization of 1-D reference models could cause errors in the receiver function conversions; but such errors should be systematic, and therefore do not affect the characteristics of local anomalies. Our results show that the crustal thicknesses from the PRFs are generally consistent with those from the SRFs. But the thickness deduced from the SRFs is generally 1–3 km (in some locations) thicker than that from the PRFs. For

Fig. 9. Stacked SRFs at each station in Yunnan. The dash line represents the positive S_{Mp} converted phase, which is interpreted as the conversion phase at the Moho. The upper letters L indicate a negative phase and represent the S_{Lp} conversion phases from the LAB. Station name is shown at the left of each stacked trace (see Fig. 1).

example, in southwestern Yunnan (to the west side of the Jinshajiang-Red River Fault), the crustal thickness from the PRFs is in the range of 30–36 km, while that from the SRFs is about 33–39 km. Our results are about 2–3 km less than those from the joint inversion of Rayleigh waves and the PRFs (Y. Li et al., 2008), but are closer to the results of Bao et al. (2015).

Our results indicate that the lithosphere thicknesses from the PRFs are globally consistent with those from the SRFs, except some local differences. The discrepancies may be resulted from the differences in sample regions, frequency bands and incidence angles. When the lithosphere thickness is more than 100 km, the SRFs sample areas are larger than those of the PRFs, leading to a wider S_p impulse in the stacked trace. This could cause less accurate picking-up of discontinuity depths. In some cases, the negative polarity P_{LS} phase from the LAB and the positive polarity multiples at the Moho will occur in the same time window. Consequently, the amplitude of the P_{LS} phase will be partially or completely neutralized in the PRFs. When the lateral heterogeneity is strong, e.g. dipping layers, the SRFs could lose coherence for individual traces. Thus the results may be biased from variable piercing point locations. Despite good consistencies between the crustal thicknesses derived from the PRFs and from the SRFs, the LAB depths from the two techniques could differ as much as 15–20 km, similar to those suggested by Li et al. (2007).

The crustal thicknesses obtained from the PRFs and the SRFs allow us to understand better the regional geodynamic processes. The elevated topography of the eastern margin of Tibet has been explained as a direct result of the crustal thickening by lower-crustal flow evacuated from central Tibet (Royden et al., 1997; Clark and Royden, 2000). An important crustal structure feature

is that the crustal thickness increases rapidly from ~40 km under central Yunnan to ~50 km near the Lijiang-Xiaojinhe Fault. Previous gravity measurements have revealed an approximately 150 km wide and 900 km long, NE-SW Bouguer anomaly belt that extends along the Longmenshan Fault and the Lijiang-Xiaojinhe Fault into the interior of Yunnan (Wang et al., 2003). This anomaly decreases from –200 mGal in southeastern Yunnan to –460 mGal in east Tibet. The strong gravity gradient pattern fits well with our crustal thickness results (Fig. 10), and is consistent with other previous results (Y. Li et al., 2008; Bao et al., 2015; Liu et al., 2014). However, the crust thickness gradient belt from the SRFs seems varying more rapidly than that from the PRFs. The reason could be coherency loss and larger errors in the SRFs from a tilted Moho. Regardless, both suggest strong crustal thickness variation from south to north across Yunnan.

Continental lithosphere thickness variations are genetically related to deformation and magma histories (Vedran and Fischer, 2014). At the west side of the Jinshajiang-Red River Fault, the LAB depth derived from the PRFs ranges from 80 to 100 km, very close to that from the SRFs. In southeastern Yunnan, however, the depth from the PRFs is ~20 km less than that from SRFs, and is only in a range of 100–120 km. In addition, the thinned lithosphere formed a transition belt near 26°N latitude, and increases to 120–140 km southeast ward across the belt. Lei et al. (2014) found that the low velocity zone in the upper mantle is primarily distributed along the Lijiang-Xiaojinhe Fault, and is on the west of the Jinshajiang-Red River Fault. As shown in Figs. 11 and 12, there are clear coherent patterns between the thinned lithosphere and the low velocity zone of the P_n waves (Lei et al., 2014). Obviously, the temperature variation within the upper mantle can sig-

Fig. 10. The contour map of crustal thicknesses in Yunnan from (a) PRFs and (b) SRFs, respectively. The dash lines represent the faults and the black triangles are permanent broad-band stations (see Fig. 1). The unit of numbers is km.

nificantly change the wave velocity. The Tengchong volcanic area (near TEC station, see Fig. 1) located in the western Yunnan is adjacent to Myanmar. This area is associated with a high heat flow of 75–85 mW/m² (Wang et al., 1990). Hot springs and volcanic eruptions in the area are related to the hot mantle material upwelling caused by the northeastward subduction of the Indian plate (Lei et al., 2009). The upwelling hot mantle material could heat up the bottom of the lithosphere, resulting in removal of the lithosphere bottom and reduced velocity in the upper mantle. Tomography results (Huang et al., 2002; Huang and Zhao, 2006; Wang et al., 2003; Wang and Huangfu, 2004; C. Li et al., 2008; Lei et al., 2009) showed that there exists a large scale low velocity zone in the crust and the upper mantle beneath western Yunnan. These techniques are sensitive to gradual velocity changes, but less so to discontinuities, therefore do not give the thickness of lithosphere.

The XKS (SKS, SKKS and PKS) splitting observations from 350 portable and 90 permanent broad-band seismic stations (Chang et al., 2015) indicate that the fast wave polarization direction is approximately N-S in the north of the 26°N latitude, and rotates to approximately E-W in the south of the 26°N latitude (see

Fig. 11. The contour map of lithospheric thicknesses in Yunnan from (a) PRFs and (b) SRFs, respectively. The dash lines represent the faults and the black triangles are permanent broad-band stations (see Fig. 1). The unit of numbers is km.

Fig. 12). This polarization direction change may be related to changes of the mantle dynamics. Because of the northeastward subduction of the Indian plate beneath western Yunnan (Lei et al., 2009; Hu et al., 2008), the crust beneath western Yunnan is westward rollback and the crustal material rotates clockwise around the East Himalaya Syntaxis (Chen et al., 2013). The resulting deformations are associated with many northeast strike-slip faults and high seismicity in the Yunnan-Myanmar-Thailand Block. However, the upper mantle beneath Myanmar remains eastward extrusion, when the northeastward asthenosphere beneath southern Yunnan meets the southeastward extrusion flow from east Tibet. Finally, the fast wave polarization direction starts to rotate from N-S to E-W near 26°N latitude. In this process, hot mantle material also extends eastward, thinning the lithosphere above.

Because the LAB is only a weak feature in seismic Earth models (Dziewonski and Anderson, 1981; Kennett and Engdahl, 1991), the Ps and Sp conversions at the LAB should be also weak. However, our observations indicate very clear conversions in either the stacked or individual traces, implying a significant jump in physical parameters such as velocity or temperature across the LAB. The high seismicity and tectonic activities in Yunnan also support that

Fig. 12. Pn velocity tomographic image (Lei et al., 2014) and SKS splitting results (Chang et al., 2015) in Yunnan and its adjacent region. Thick solid lines represent faults (see Fig. 1).

the lithospheric deformation may be dramatic. The XKS-phase splitting measurements support the existence of an eastward material flow across the southern part of our research region, which primarily reflects the deformation mechanism in the upper mantle. Therefore, the variation trend of the LAB depth shown in our results should be reliable.

5. Conclusions

The LAB is usually a weak interface, not as sharp as the Moho discontinuity. The P_{LS} conversion phase from the bottom of the lithosphere is so weak that it can be easily contaminated by the multiple conversion phases at the Moho. Thus the PRFs are rarely used to detect the thickness of the lithosphere. In this study, we computed the PRFs and the SRFs at 48 permanent broad-band stations deployed in Yunnan. Our result shows a negative polarity phase behind the conversions at the Moho in the PRFs and the SRFs, which is interpreted as the LAB. Our results also show that both the P_{LS} and the S_{LP} conversion phases from the LAB are clearly distinguishable on the stacked traces of most stations, implying a significant velocity jump at the LAB beneath Yunnan. The crustal thickness increases gradually from about 30 km in southern Yunnan to 68 km in northwestern Yunnan. The thicknesses from both the PRFs and the SRFs agree well with each other: their differences are less than 3 km.

The SRFs are especially suitable to detect the LAB with a spatial resolution of order 20 km for the LAB sharpness. This resolution is close to the dominant S-wave wavelength. Our observations show that the lithosphere thickness from the SRFs is 15–20 km thicker than those from the PRFs in some local areas. The lithosphere thickness beneath Yunnan varies significantly, from about 80–100 km in the west side of the Jinshajiang–Red River Fault (in western Yunnan), to 140–150 km in northern and southeastern Yunnan. The thinned lithosphere extends from western Yunnan eastward across the Jinshajiang–Red River Fault and the Xiaojiang Fault into eastern Yunnan. We suggest that this east–west distribution of the thinned lithosphere in Yunnan is related to hot mantle material

associated with the northeastward subduction of Myanmar macro-plate and the southeastward extrusion from east Tibet.

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