Upper mantle and transition zone structure beneath Leizhou–Hainan region: Seismic evidence for a lower-mantle origin of the Hainan plume

Ba Manh Le a, Ting Yang a,⇑, Shenyi Gu b

a State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China
b Seismological Bureau of Hainan, Haikou 570203, China

ARTICLE INFO
Article history:
Received 26 February 2015
Received in revised form 25 May 2015
Accepted 9 June 2015
Available online 23 June 2015

Keywords:
Hainan plume
Mantle transition zone
Upper mantle
Lower-mantle origin
Synthetic seismograms

ABSTRACT
The origin of the widespread volcanism at the Leizhou–Hainan (Leiqiong) region in the Southern China remains obscure. We take advantage of the highly active seismicity and dense seismic networks surrounding this region to investigate its upper mantle and Mantle Transition Zone (MTZ) structure. Over 5000 P-wave waveforms whose raypaths bottom at depths around the MTZ are collected, and traveltimes of their first arrivals are hand-picked. By matching the traveltime curve variation over the epicentral distance range from 10 to 35°, we first construct a 1-D upper mantle and MTZ velocity structure for the region. This initial model is then refined by forward modeling, in which the observed triplicated waveforms from selected earthquakes are compared with the synthetic seismograms with varying velocity structure. In our preferred model for Leiqiong, the P-wave velocities deeper than 200 km at the upper mantle are 0.8–1.2% lower than the IASP91, and 0.6% slower in the MTZ, while the top and bottom boundaries of the MTZ depresses 12 km and slightly uplifted, respectively, compared to the global averages. This model provides independent constraints on the structure beneath Leiqiong, suggesting a thermal anomaly within the MTZ and a lower mantle origin for the volcanism seen in this region.

1. Introduction

The region of Leizhou Peninsula and Hainan Island in Southern China (Fig. 1), or Leiqiong for short hereinafter, has seen extensive volcanic activities since late Cenozoic (e.g. Tu et al., 1991; Flower et al., 1992; Ho et al., 2000). The origin of the widespread intraplate basaltic magmatism remains controversy. Earlier works attribute it to the lithospheric stretching along the southeastern China (Zhu and Wang, 1989; Flower et al., 1992), or mantle escape from Eurasia in response to lithospheric thickening in the Indo-Eurasian collision zone (Hoang and Flower, 1998; Liu et al., 2004). More recent geochemical studies (e.g. Van et al., 2008; Zou and Fan, 2010; Wang et al., 2011, 2013), however, point to a deep mantle origin, with the source region being the transition zone or even the core-mantle boundary. These findings are in line with most seismic tomographic studies (e.g. Lebedev and Nolet, 2003; Montelli et al., 2004; Zhao, 2007; Lei et al., 2009, 2013; Li and van der Hilst, 2010; Huang, 2014), which imaged low-velocity anomalies in the mantle beneath this region extending to upper mantle, the transition zone or even deeper. Nevertheless, previous seismic studies in this region are inevitably undermined by the fact that there is essentially no seismic station in areas to the south, including the vast region of the South China Sea (SCS) and the Indochina block. Therefore, many features of the low-velocity anomaly such as its location, origin depth and strength of anomaly vary significantly in tomographic models from different groups. For example, Lei et al. (2009) resolved a narrow low-velocity body tilting to the center of SCS, while recent models either show much broader anomalies (Li and van der Hilst, 2010), or a focused anomaly shifted to northeast at deep mantle (Wang and Huang, 2012; Huang, 2014). Therefore, there is no clear consensus currently on many features of this seismic velocity anomaly beneath Leiqiong, and other constraints are needed to address the remaining controversy.

The Mantle Transition Zone (MTZ), bounded by two discontinuities between 400 km and 700 km depths where the seismic velocity and the density increase rapidly, is of key importance for constraining the thermal state of the mantle. These discontinuities are thought to be due to phase changes of olivine and other minerals as pressure increases with depth (Jackson, 1983; Ringwood, 1975). The thermal variation in the mantle causes the respective phase changes to occur at different pressures (or depths) controlled by Clapeyron slopes of opposite signs (Bina and Helffrich, 1994), giving rise to the thickening or thinning of the MTZ. The topographic variations of 410- and 660 km discontinuities, or
changes in the MTZ's thickness, have been used as a proxy of the mantle thermal structure. For example, a thickening of the MTZ near cold subducted slabs (e.g., Shearer et al., 1999) and a thinning of the MTZ beneath warm upwelling plumes (e.g., Shen et al., 1998; Li et al., 2003) have been widely reported.

Due to the strong vertical velocity variations near the MTZ, the seismic raypaths turning at these depths disturb strikingly, leading to triplications in the traveltime curves across both discontinuities (Fig. 2). The traveltimes and waveforms of those triplicated waves, therefore, are sensitive to the depth and velocity contrasts across the discontinuities, and they are important tools to investigate the structure of the MTZ (e.g., Nowack et al., 1999; Song et al., 2004; Wright and Kuo, 2007; Chu et al., 2012).

In this study, we take advantage of the highly active seismicity around Leiqiong and the dense seismic network in Mainland China and Taiwan, and use them to construct the 1-D velocity model of the region. We hand-pick first arrivals for thousands seismograms sampling the upper mantle and the transition zone beneath this region, and obtain the 1-D velocity structure of the upper mantle and transition zone based on the variation of the travel times. We further refine the initial velocity structure by modeling triplicated waveforms. Our result for the upper mantle and transition zone structure of the region can provide independent constraints on the origin of its volcanism and shed lights on the regional tectonic events including the evolution of the SCS.
Leiqiong is surrounded by several seismically active regions including Manila and Philippine subduction zones, Sumatra subduction zone and Taiwan collisional zone. On the other hand, the southern China, Taiwan and the Indochina block have recently deployed dense seismic networks. As shown in Fig. 1, the distributions of earthquakes and seismic stations provide tremendous amount of raypaths that sample the upper mantle and the transition zone beneath the Leiqiong region.

We select earthquakes from the period of 2007–2011 with magnitude greater than 5.0. Seismic stations are mainly in the southern China including those at provinces of Guangdong, Guangxi, Yunnan and Hainan. Other networks include permanent stations in Taiwan, Thailand and Philippines, as well as a temporary seismic array in Vietnam deployed by Tongji Seismology group (Yang et al., 2015). In total there are 142 stations used in this study. To select high quality waveform data from such a huge dataset for our analysis, we set up the following criteria: first, each earthquake has at least 10 stations receiving its signals, and its depth is less than 50 km so that we can correct the depth to the Earth’s surface with minimum error; second, seismograms have to pass the automated data selection in which a threshold value of signal-to-noise ratio is specified to ensure a clear P-wave first arrival. We define the signal-to-noise ratio as the ratio of the peak-to-peak amplitude of the predicted arrival to the standard deviation of the time series in a 20 s window before the predicted arrival; Finally, to ensure the raypaths propagate through the upper mantle and the transition zone, the epicentral distances of seismograms have to fall in the range of 5–40°. With such criteria, we selected 270 earthquakes from over 1200 events, and more than 5000 high quality seismograms were considered. They provide a fairly good azimuthal coverage for the Leiqiong region, and their turning points sample the upper mantle, the transition zone and the top of the lower mantle with relatively uniform density (Fig. 1).

In the following analysis, two techniques are applied to this dataset to construct a velocity model for this region. First, we determine the variation of traveltime of first arrivals over a long epicentral distance range, through which an initial 1-D velocity model is yielded. Second, we perform synthetic waveform modeling of triplicated arrivals on selected events to refine the initial 1-D velocity structure.

2.2. First arrival traveltimes

Waves that are most sensitive to velocities at the transition zone are those turning at those depths. Depending on the epicentral distance and the focal depth, the P-wave first arrivals in the epicentral distance of 10–35° could have turning points in the upper mantle, the transition zone or in the lower mantle due to strong velocity changes (Fig. 2). The traveltime curve of the first arrivals over a prolonged range of epicentral distance depends on the velocity structure in the upper mantle and around the MTZ. The variation of the curve, therefore, can provide constraints on the 1-D average velocity structure at those depths.

In order to construct an average traveltime curve for this region, we select waveforms with clearly identifiable first arrival from the dataset that pass our criteria mentioned above, and pick their arrival times by hand. Multiple frequency band filters are applied to the waveforms in the picking process to reduce the uncertainty of arrivals, which is estimated to be less than 0.3 s. A total number of 4050 waveforms are processed and their first arrival times are picked. The inset map in Fig. 1 shows the map view of the turning points of those raypaths.

Corrections are needed for hand-picked arrivals before they can be used to construct an average traveltime curve for Leiqiong. Waveforms are from different earthquakes and stations, and their traveltimes depend on the focal depth and station elevation. So, we first correct all picked traveltimes to those with zero focal depth and zero station elevation based on the IASP91 model (Kennett and Engdahl, 1991). In addition, the raypaths of earthquakes and stations shown in Fig. 1 sample a much larger area than the Leiqiong. The heterogeneities at shallow depths outside Leiqiong also contribute to the traveltime anomalies of the first arrivals. To reveal the velocity anomaly just beneath Leiqiong, we need to remove anomalies accrued due to heterogeneities at the shallow depths outside Leiqiong. To perform this correction, we did the 3-D ray-tracing (Zhao et al., 1992) based on a pre-existing regional 3-D model (Li and van der Hilst, 2010), and calculated the traveltime anomaly accumulated at structure shallower than 200 km outside our study region, which is then removed from the traveltime anomaly after the depth and station elevation corrections. As shown in Fig. 3, after this correction, the deviations of first arrival traveltimes between hand-picked and predicted become more focused on the average traveltime curves.

After these corrections, the traveltimes of seismic rays with different epicentral distances are used to construct an average traveltime curve for the region (Fig. 4). The average curve is obtained by finding a polynomial of degree 6 that fits most of the data (those within the two limiting lines in Fig. 4) in a least-squares sense with 10% outliers removed. Fig. 4 shows the comparison between the average curve and the one calculated from the IASP91. While at short epicentral distances (5–15°), the average first arrival traveltimes from Leiqiong are comparable with or slightly shorter than predictions based on the IASP91, in the distance range of 15° to about 35°, the average traveltimes are systematically larger than that from the IASP91, especially from 18° to 28°, the range in which the triplicated waves are generated. These comparisons indicate that the P-wave velocities at the upper mantle, the transition zone and uppermost part of the lower mantle are slower than those in the IASP91.

Based on the average traveltime curve of the first-arrivals derived, we first construct an initial 1-D velocity structure of the upper mantle and the MTZ for Leiqiong. We employ the trial-and-error approach to match the average curve with the predicted ones by systematically changing the velocities near the IASP91. In this process, we break the model into limited number of parameters, including the gradient in the upper mantle, the depths of 410- and 660-discontinuities and their velocity increments across them, and two velocity gradients within the MTZ separating at 520 km, where another discontinuity is presumably located (Shearer, 1996). Fig. 5 shows examples of different velocity model and their corresponding traveltime curves. The best fitting model we obtained is the one from which the corresponding traveltime curve is within ±1.5% error range of the observed average curve (Fig. 5). In this model, the P-wave velocities are 1.0% on average slower than those of IASP91 at depths greater than 200 km in the upper mantle. Within the MTZ, the 410-discontinuity depresses 6 km while the 660-discontinuity is up 12 km with the
velocity jumps are notably less than those in the IASP91 but larger velocity gradient at depths shallower than 520 km (Fig. 5).

2.3. Synthetic seismograms

Although the traveltime curve of first-arrival P waves can provide constraints on the velocity structure around the MTZ, some portion of the transition zone will never be sampled by first-arrival P phases due to the discontinuities near the 410 and 660 km depths. For example, waves that sample the deeper part of transition zone (from ~550 km to 660 km) always arrive as secondary arrivals regardless of the focal depth [Tajima and Grand, 1998]. The traveltime curve of the first arrivals alone, therefore, cannot fully constrain the velocity variation within the transition zone.

On the other hand, the amplitudes of all arrivals from the transition zone and the time intervals between them, namely the waveforms of the triplicated waves, are sensitive to the depths of discontinuities and the velocity gradient within the transition zone. For instance, the time intervals between reflections off the 410- and 660-km discontinuities depend on the average velocity.

![Fig. 3. The differences between observed and predicted first arrivals as a function of the distance before (a) and after (b) the correction for shallow heterogeneities outside the study region; (c) comparison of the averaged differences before (dashed line) and after (solid line) the correction.](image)

![Fig. 4. The picked and corrected traveltimes of first arrivals (circle), the average traveltime curve (red line) derived from them, and predicted curve (green line) from the IASP91 model. The average curve is generated from the traveltimes between two limiting lines (dashed lines), which account for 90% of the total data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)

![Fig. 5. The different velocity models of the MTZ and their corresponding first-arrival traveltime curves. The best average model (red) is founded by matching its traveltime curve with the observed average curve (blue) within the ±1.5 % error range (shadow zone). Also shown are the IASP91 model (black), examples of high and low velocity models (dashed lines) and their traveltime curves. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)
of the MTZ while its gradient is closely related to timing among rays turning at different depths. Therefore, the tripled waveform modeling, through which synthetic and recorded waveform can be directly compared, is an indispensable tool to constrain the velocity structure of the transition zone in a variety of tectonic settings (e.g., Grand and Helmberger, 1984; Lefevre and Helmberger, 1989; Melbourne and Helmberger, 1998; Obayashi et al., 2006; Chen and Tseng, 2007).

To further refine the best fitting velocity model derived from the first arrival traveltime curve, we performed the synthetic waveform modeling for the tripled waves to compare them with the real waveforms from selected earthquakes. The reflectivity code (Fuchs and Müller, 1971) is used in the modeling to calculate the complete synthetic seismograms for a flat-layered (1-D) velocity model. Four earthquakes with high quality recordings are selected (Table 1), and their seismic rays sample the transition zone beneath Leiqiong with different azimuths. The earthquake focal mechanisms from Harvard CMT catalog (Ekström et al., 2012), locations of stations and the azimuths to the center of the stations are shown in Fig. 6. To direct compare the synthetic seismogram to the observed waveform, we remove the instrument response for all waveforms, and both observed and synthetic seismograms are band-filtered with the same frequency bands.

Because a profile of all stations with varying distance can reveal the systematic variations in amplitude and timing among the arrivals, and we assume the lateral change of the transition zone structure in the region is small (a 1-D, flat-layered model), we group all ray paths into three profiles (P1, P2 and P3 in Fig. 7) based on the average back-azimuths of stations in the network. The P1 profile includes waveforms from two earthquakes in Philippine with stations at Yunnan Province while the other two profiles involve earthquakes beneath the Luzon arc and at the northern Indochina, respectively. The stations we selected have epicentral distances in the range of 17–23°. At these distances, discontinuities and high velocity gradients in the MTZ result in tripled arrivals that sample successive depths near the transition zone (Figs. 2 and 6).

Using the velocity model constructed by the traveltime curves of the first arrivals as the starting model, we fine-tune the 1-D velocity structure, especially those across the discontinuities and the deeper part of the MTZ, where the first arrival traveltime curve is not sensitive to the velocity. Again, the final model is found through a trial-and-error approach in which we test different models near the starting model until we obtain the one that fits the observed waveforms best. To limit the number of parameters in the process of model construction, we only consider the depths of two discontinuities, their velocity increments at discontinuities and two linear segments within the transition zone.

Fig. 7 shows synthetic waveforms from the initial model and our preferred model with increasing epicentral distance for three profiles, as well as their comparisons with the observed seismograms. While the first arrivals fit the onsets of the seismograms equally well for both models (Fig. 8a), the waveform fittings are significantly improved for our final model, especially the amplitude of the later arrivals, indicating the velocity increments at the two discontinuities are better constrained. In addition, the later arrivals within the first few seconds in observed seismograms, including the forward and wide-angle branches above the top interface of the transition zone (AB and BC) and the wide-angle and forward branches above the bottom of the transition zone (AC and DE), have been well matched by synthetic seismograms.

Based on these waveform modelings, we derived our final model (Fig. 8), which is slightly different from that we obtained from the traveltime curve of the first arrivals. The depths of the two discontinuities are changed: the top boundary of the MTZ depress further to 422 km and the bottom boundary uplift only 6 km from the IASP91 model, while the velocity jumps are closer to those in the IASP91. Within the transition zone, the velocity structure, on average, is 0.6% lower than the global average with only one uniform velocity gradient.

We note that even there is a change in velocity gradient within the transition zone would lead to better fit for the first arrivals, our waveform modeling shows that one uniform velocity gradient within the transition zone generate waveforms fit the observations better. Therefore, a 520-km discontinuity, which has been proposed by many workers for a global feature in the MTZ (Shearer, 1996), is invisible at Leiqiong based on our study.

In Fig. 9 we combine all waveforms into one gather regardless of earthquakes and azimuths. Despite the fact that there are a few poorly fitted traces in Fig. 8, the theoretical traveltime curves for both first and later arrivals from our final model overall match well with the observed waveforms.

3. Discussion

In our preferred 1-D model for the Leiqiong region, the P-wave velocity is 0.8–1.2% slower than the IASP91 model in the depth range of 200–422 km; an average 0.6% slow anomaly within the MTZ, and a 12 km depression of the 410-discontinuity, as well as a slight uplift (6 km) for the 660-discontinuity. In this section, we discuss implications of this model for the nature of the Hainan plume and regional tectonic evolution including the opening of the South China Sea.

3.1. 3-D velocity variation verses 1-D model

Our analysis is based on an assumption that the upper mantle velocity of the region is 1-D in nature. However, with a history of extensive riftings and possible presences of deep mantle upwelling (Wang et al., 2013) as well as a late Mesozoic subduction zone (Yan et al., 2014), the mantle structure beneath Leiqiong is of course a complex 3-D structure. As shown in Fig. 8, fittings of synthetic and observed seismograms with different epicentral distances are not equally well even in the same profile, indicating there exist lateral velocity variations in its upper mantle and MTZ. The fact that arrival time of seismic rays having the same distance fall into a broad range of over 10 s (Fig. 4) also suggests there are strong horizontal velocity changes. Nevertheless, our dataset, which include a great number of raypaths with large azimuthal coverage, would smooth the lateral variations in velocity structure. The average model we derived is still representative of the dominantly 1-D feature of the structure.

3.2. The nature of the Hainan plume

The implication of our 1-D velocity model is that, an upwelling originated from the lower mantle, or a mantle plume, likely generates the reduction of the MTZ thickness and the thermal anomaly in the upper mantle (Ringwood, 1975; Bina and Helffrich, 1994). With the limitation mentioned above in mind, it is nonetheless useful to explore the constraints provided by this model on the mantle dynamics in the region.

An important feature we can derive from our model is the strength of thermal anomaly beneath Leiqiong implied by the MTZ thinning. The thickness based on our model is thinner than the global average by 18 km. This reduction is significantly less than the one derived from the receiver function study by Wang and Huang (2012). They found a thinned MTZ beneath the region northeast of Hainan Island with 25 ± 5 km reduction. This discrepancy can be explained by the fact that the receiver function can reveal the lateral variation of the discontinuity while our study
can only reveal the 1-D feature. In Wang and Huang's model, the thinned MTZ is limited at a region of \( \frac{C}{24} \) km in dimension, which is much less than our study region. Given Clapeyron slopes of 2.9 and \( \frac{C}{25} \) MPa/K for the 410- and 660-km discontinuities (Ringwood, 1975), respectively, the reduction in the thickness (18 km) is equivalent to an excess temperature of \( \frac{C}{26} \) K. However, the 1-D approach tends to average and smooth lateral variations in discontinuity depths, and thus decreases the apparent reduction in the thickness. Our estimate of the excess temperature should therefore be regarded as only an apparent value and most likely a lower bound. With these factors taken into consideration, an apparent excess temperature of at least \( \frac{C}{27} \) K is in agreement with estimates of the thermal anomaly at the depth of melt generation (<200 km) (White et al., 1995), values that reflect averages of the melt-generation and melt-migration processes.

On the other hand, the magnitude of velocity anomaly in our 1-D model (0.6–1.2% in P wave velocity) is comparable to or slightly less than those obtained through tomography, which fall in the range of 1–2% (Huang and Zhao, 2006; Montelli et al., 2006; Li et al., 2006, 2008; Zhao, 2007; Li and van der Hilst, 2010). As stated earlier, the decreased anomaly can be explained by the average effect of a large study region. By disregarding other factors than temperature affecting the seismic velocity, the slow velocity anomaly can be roughly converted to thermal anomaly based on laboratory measurements of the temperature derivatives of velocity in olivine (Isaak, 1992). The average strength of low velocity anomaly, 0.9%, would give rise to \( \sim 150 \) K increase in temperature. However, if we consider other factors, including composition, presence of partial melt and anelasticity, the estimate would be reduced. For example, taking into account the effect of anelasticity gives a lower excess temperature of \( \sim 100 \) K (Karato, 1993). Like the thickness of the MTZ and the strength of velocity anomaly, this range of excess temperature (100–150 K) is also less than previous estimates for Hainan plume (e.g. Wang and Huang, 2012; Huang, 2014). We emphasize that there is a large uncertainty associated with this estimation due to the 1-D nature of our model.

### 3.3. Implication to tectonic evolution of the South China Sea (SCS)

One of the tectonic enigmas in the region is the mechanism of the SCS evolution. While various models have been proposed for the opening mechanism of the South China Sea in \( \sim 32 \) Ma (Xu et al., 2012), there is no consensus on whether the mantle plume played a role in its rifting process. The generally accepted mechanism is the extrusion model, in which the opening of the SCS was mainly due to the movement of the Indochina block along the Red River Fault as consequences of India and Eurasia collision (Briais et al., 1993). Some workers modified this model by taking into account of the slab-pull of the proto-SCS subduction (Morley, 2002). Those models, however, are in contradiction with a few observations including the amount and the precise age of motion of Red River fault, as well as the kinematic evolution of the SCS spreading (Searle, 2006). Those models completely overlooked the possible presence of a deep mantle upwelling whose initiation likely coincided with the SCS opening (Yan et al., 2014). When a plume head impinges on the overlying lithosphere, the dynamic buoyancy associated with the upwelling will generate widespread uplift, and then give rise to rifting. The compiled catalog of global hotspots (Storey, 1995; Coffin and Eldholm, 1994)
indicates that the initial of mantle plume appears to be responsible for a number of continental rifts. The estimate of magma flux in Hainan Island reaches the range of 0.1–0.25 km$^3$/year (Zou and Fan, 2010), which is close to that of major flood basalt eruptions (Flower et al., 1992). In addition, the lower mantle origin supported by this study, along with various geochemical signatures (e.g. Yan et al., 2008; Zou and Fan, 2010; Wang et al., 2011, 2013), indicates the initiation of Hainan plume was a major regional event that would definitely enhance the rifting process, if not the primary driving force for the continent breakup (Ziegler and Cloetingh, 2004).

In addition to seismic tomographic images and geochemical signatures mentioned in the introduction section, there are a few more lines of evidence indicating that the deep origin of plume played a role in the rifting process of the SCS. For example, active-source seismic investigations found that there are widespread occurrences of lower crust high velocity (LCHV) layer up to 6 km in thickness in northern SCS (Lester et al., 2014). Even though the origin and timing are still in debate, but those with landward features have been attributed to pre-rift magmatism (Nissen et al., 1995). These observations suggest that magmatic activity occurred much earlier, and in much larger region than surface exposures. Therefore, they likely were associated with the mantle upwelling and impingement of the plume head.

The presence of a mantle plume would definitely interact with the mid-ocean-ridge of the SCS during it spreads and in the post-spreading stage. Based on the temporal and spatial distribution of volcanic activities in the SCS and surrounding regions through Cenozoic, Xu et al. (2012) proposed a ridge suction model in which, during the SCS spreading, the melt supplied by the plume preferentially fed to the ridge of the SCS, causing a significant drop in volcanic activity within the SCS basin and surrounding regions while volcanisms were well distributed in both pre- and post-spreading stages. The model provides an explanation for the post-spreading magma activities along the extinct ridge in the central sub-basin of the SCS, which had been active for as long as ~10 Ma after the cession of spreading. The latest study (Yang et al., unpublished report) found that there exists a very
curves calculated from our final P-wave velocity model for Leiqiong region. The observed waveforms between 15 Ma. This may indicate there has been a persistent melt supply from an active source even there is no passive spreading any more.

Central to this ridge suction model is whether there exists a channel beneath the lithosphere transferring melt from the plume center, presumably located at NW of the SCS to the ridge. It is difficult for seismic tomography to image such structure without seismic station coverage in the SCS. Therefore, a seafloor passive-source seismic experiment covering the northern and northwestern SCS would be required to validate the existence of the underneath channel and the ridge suction model.

4. Conclusions

To constrain the structure of the upper mantle and transition zone beneath Leizhou–Hainan (Leiqiong) region, we collect over 5000 seismograms turning at those depths from seismic stations surrounding the region, and hand-pick their first-arrival times. By inversing the traveltime curve of the P-wave first-arrivals, and modeling the triplication waveforms from the MTZ, we construct a 1-D velocity model for its upper mantle and the transition zone. In this model, the P-wave velocity is 0.8–1.2% slower than the IASP91 model in the depth range of 200–422 km; an average 0.6% slower anomaly within the MTZ, and a 12 km depression of the 410-discontinuity, as well as a slight uplift (6 km) for the 660-discontinuity. The significance of this model is that the temperature within the MTZ and upper mantle is higher than the global average (~140° exceed temperature), indicative of lower mantle origin of the volcanism seen in this region. This observation provides independent seismic evidence for the existence of Hainan plume, which likely enhanced the opening process of the South China Sea, and have interacted with the mid-ocean-ridge of the SCS.

Acknowledgements

We would like to thank several provincial seismological bureaus in China including Hainan, Guangdong, Guangxi, and Yunnan for providing us the waveform data collected at their networks. Thanks to two anonymous reviewers for their constructive reviews which improve the manuscript significantly. This study is funded by National Natural Science Foundation of China through Grants 41076019 and 91128209.

References
