Crustal thickness and Poisson’s ratios of South China revealed from joint inversion of receiver function and gravity data

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A B S T R A C T

Crustal thickness and Poisson’s ratio are two important parameters for understanding the crustal structure, composition, and deformation of the South China block. Due to the complicated crustal structure and poor signal-to-noise ratio of teleseismic data at dozens of stations in South China, the receiver-function H–x stacking produces large uncertainty and deviation when estimating these two crustal parameters. In this paper, we improve the technique of joint inversion of receiver function and gravity data and utilize it to improve the estimates of crustal thickness and Poisson’s ratio in South China. We calculate the receiver functions of 245 permanent seismic stations from the teleseismic data recorded during 2013–2015 and then carry out the joint inversion on the receiver functions and the complete Bouguer gravity anomalies data. The joint inversion reduces the uncertainty of each single-method inversion and enhances the accuracy of estimation. Our results demonstrate that the crustal thickness, ranging 26.1–46.5 km, is large in the NW (38–46.5 km) and small in the SE (26–34 km) with a NNE-trending gradient zone along the line of Yichang–Jishou–Baise in central South China. The crustal Poisson’s ratio, ranging 0.20–0.31, is high (0.28–0.31) in most of the northern South China, intermediate (0.26–0.29) around the eastern coastal area, very low (0.20–0.24) within the Jiangnan orogenic belt and around the southern coastal area, and slightly low (0.22–0.26) in other places. With the constraints of previous geological and geophysical studies, we suggested that the notable low-value belt of crustal Poisson’s ratio (between the lines of Shitai–Jiujiang–Yiyang–Jishou–Baise and Shaoxing–Jiangshan–Pingxiang–Yongzhou–Guigang–Beihai) represents the possible suture zone between Yangtze and Cathaysia sub-blocks in South China during the Neoproterozoic.

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1. Introduction

The South China block is located at the convergence of the Eurasian, Pacific and India–Australian plates. It was formed by collision and amalgamation of two Precambrian sub-blocks during the Neoproterozoic: Yangtze block in the NW and Cathaysia block in the SE (Fig. 1). The tectonic deformation and geodynamics of South China have drawn the attention of numerous geoscientists since the last century (Shu, 2012; Zhao and Cawood, 2012; Charvet, 2013; Zhang et al., 2013; Guo and Gao, 2018; and reference therein).

Detailed information about crustal structure and composition is crucial for a better understanding of crustal deformation and dynamic mechanism in South China. Several studies based on seismic tomography have been carried out in recent years to image the crustal and mantle structure in or covering South China (Huang and Zhao, 2006; Zhao et al., 2012; Zhou et al., 2012; Chen et al., 2015; Shen et al., 2016; Sun and Kennett, 2016; Shan et al., 2017). These results benefit in revealing velocity anomalies or variations among Yangtze and Cathaysia blocks and tracing the high-velocity zone of the Pacific slab subduction during the Mesozoic. However, most of these studies emphasized more on the upper mantle structure and less on crustal structure and composition.

Crustal thickness and Poisson’s ratio are two important parameters to characterize crustal structure and composition (Zandt and Ammon, 1995; Christensen, 1996; Zhu and Kanamori, 2000; Chevrot and van der Hilst, 2000; Ji et al., 2002). Crustal thickness describes the crustal deformation of thickening and thinning,
and crustal Poisson’s ratio features the crustal composition of felsic and mafic minerals. According to Zandt and Ammon (1995), Christensen (1996), Zhu and Kanamori (2000) and Ji et al. (2002), a low Poisson’s ratio to a value less than 0.26 implies high content of felsic and low content of mafic mineral within the crust. An intermediate Poisson’s ratio to a value between 0.26 and 0.28 indicates that the felsic and mafic contents of the crust differ little. High Poisson’s ratio to a value between 0.28 and 0.30 indicates high content of mafic and low content of felsic mineral within the crust. When the value of Poisson’s ratio exceeds 0.3, it could be inferred that there probably exists partial melting of rocks, or fracture zone with fluid infiltration, or serpentinitized fault zone within the crust (Zandt and Ammon, 1995; Christensen, 1996; Ji et al., 2002).

Telesismic receiver-function H–κ stacking technique (Zhu and Kanamori, 2000) is a popular way to obtain crustal thickness (H) and Vp/Vs ratio (κ), the latter of which can be further transformed to crustal Poisson’s ratio according to their relationship (Christensen, 1996). By using this technique, Ai et al. (2007), Li et al. (2013) and Huang et al. (2015) found that the crustal thicknesses decrease and the Poisson’s ratios increase from inland to offshore in the southeastern South China, Wang et al. (2017) demonstrated that the crustal thicknesses increase northwestern and the Poisson’s ratios increase northeasterly or northwestern in the southwestern South China, and He et al. (2013) claimed that the crustal thicknesses and Vp/Vs ratios in the Jiangnan orogenic belt are identical to those in Cathaysia block but are different from those in Yangtze block. Chen et al. (2010), Li et al. (2014) and He et al. (2014) used this technique to obtain or compile the maps of crustal thickness and Vp/Vs ratio in Chinese mainland. The above results from various authors present a roughly similar trend of crustal thickness and Poisson’s ratio of South China, but they also present distinct difference in quite a few stations. One reason for the difference is the variation in telesismic data and analysis procedure utilized by various authors in their studies. Another is the uncertainty of receiver-function analysis, especially in the case of the complicated crustal structure (e.g. the dipping intracrustal interface and anisotropic structure) beneath some seismic stations. The complicated crustal structure usually decreases the signal-to-noise ratio of telesismic data and makes the multiple reverberated phases absent or unable to be clearly identified, resulting in the large uncertainty of receiver-function H–κ stacking (Luo, 1986; Shi et al., 2018). Chen and Niu (2016) outlined the permanent seismic stations with “abnormal” receiver functions in China, most of which in South China are located in the sedimentary basins of Yangtze block.

Combination of receiver-function analysis and other geophysical methods could reduce the uncertainty. One alternative way is the joint inversion of receiver function and surface waves, which has been increasingly popular in recent years (Chen and Niu, 2016; Guo et al., 2018). Another alternative way is the joint inversion of receiver function and gravity data (Lowry and Pérez-Gussinyé, 2011; Shi et al., 2018). The complete Bouguer gravity anomalies reflect both the undulation of Moho depths and the heterogeneous density distribution within the crust (Blakely, 1995). The crustal thickness is equal to the summation of Moho depth and elevation. The crustal Vp/Vs ratio describes crustal composition, which can be also characterized via the heterogeneity of crustal density (Christensen, 1996; Lowry and Pérez-Gussinyé, 2011). Hence, the inversion of gravity data could estimate crustal thickness, density and Vp/Vs ratio, and thus provides constraints on the receiver-function H–κ stacking. Lowry and Pérez-Gussinyé (2011) proposed the joint inversion of receiver function, gravity, and heat flow data, and utilized this technique to improve the estimate of crustal thickness and Vp/Vs ratios in the western United States. Unfortunately, heat flow data is not always available or is incomplete or is in poor resolution to many other places, while gravity data is available with high resolution to many places. Hence, Shi et al. (2018) simplified the technique of Lowry and Pérez-Gussinyé (2011) by proposing the joint inversion of receiver function and gravity data without consideration of the geothermal effects, making it easy for applications. This is valid to some extent for two reasons. One is that the gravity inversion is carried out in a small sliding window and the gravity anomalies within such a small window mainly
reflect the undulation of Moho depths and the heterogeneous density distribution in the crust. Another is that the mantle geotherm variation in such a small window usually is small and could be neglected.

In this study, we employ the joint inversion of receiver function and gravity data to improve the estimates of crustal thickness and Poisson’s ratio in South China. We further improve the technique of joint inversion of receiver function and gravity data by utilizing gravity vertical gradient rather than gravity anomaly. Compared with gravity anomaly, gravity vertical gradient is less sensitive to the mantle sources (such as the mantle geotherm variations) and is suitable for neglecting the mantle geothermal effects within a small window. Our joint inversion is iterative and could gradually reduce the uncertainty of the conventional receiver-function analysis and improve the accuracy of the estimation. Based on the results of joint inversion, we analyze the similarities and differences of crustal structure and composition between Yangtze and Cathaysia blocks, and discuss the possible suture zone between the two blocks during the Neoproterozoic.

2. Geological background

During the Neoproterozoic, Yangtze block in the NW of South China and Cathaysia block in the SE collided and amalgamated together to form the unified South China block (Shu, 2012; Zhao and Cawood, 2012; Charvet, 2013; Zhang et al., 2013). The Jiangnan orogenic belt, an exposed NE-trending arc-shaped metamorphic rock system of the Late Precambrian (Fig. 1), is the product of the collision of the two blocks. During the Late Neoproterozoic, the unified South China block took place an extension-riifting and glacial event, leading to the formation of Nanhua rift basins and Nantuoglacial strata on the eastern and central sections of the Jiangnan orogenic belt (Shu, 2012; Zhao and Cawood, 2012; Charvet, 2013; Zhang et al., 2013). In Early Paleozoic and Early Mesozoic, the South China block underwent two intra-continental orogenic events (Shu et al., 2014, 2015), resulting in reactivation of the sedimentary cover in the western South China block and planar-distributed orogenic deformation and magmatic activity in the eastern South China block (Charvet et al., 2010; Charvet, 2013; Shu, 2012; Shu et al., 2014, 2015; Zhang et al., 2013; Song et al., 2015). During the Mid-Late Mesozoic, the South China block experienced tectonic reworking related to intracontinental tectonics and northwestern subduction of the western Pacific Plate, giving rise to progressively northwestward deformation in the western South China block while widespread deformation with magmatic intrusions (Fig. 1) in the eastern South China block (Li and Li, 2007; Shu, 2012; Zhang et al., 2013).

3. Data and methods

3.1. Data selection

We collected the broadband teleseismic data recorded between 2013–2015 at 245 permanent seismic stations in South China (triangles in Fig. 2) from China Seismic Array Data Management Center (Data Management Centre of China National Seismic Network, 2007; Zheng et al., 2010). These stations are distributed in a range of 104°–122°E, 21°–32°N with an average spacing about 70 km. We selected the teleseismic events with Ms > 5.5 and the epicentral distance between 30°–90° from all the 245 stations, and initially windowed the waveforms by 10 seconds before and 80 seconds after the arrival time of the P-wave.

We also collected the complete Bouguer gravity anomalies data in South China from the grid database of world gravity map WGM2012 released by the world geological map committee (Balmino et al., 2012), which cover the range of 104°–122°E, 21°–34°N with a grid spacing of 10 km. The complete Bouguer gravity anomalies in the WGM2012 database were derived from the available Earth gravity models EGM2008 and DTU10 by using the spherical harmonic approach. This calculation included 1° × 1° resolution terrain corrections derived from ETOPO1 model that consider the contribution of most surface masses (atmosphere, land, oceans, inland seas, lakes, ice caps and ice shelves). Since the Bouguer data (Fig. S1(a)) presents high-frequency noise produced mainly by high-resolution terrain corrections, we suppressed the noise via the low-pass filtering with a cut-off wavenumber of 100 km, which yielded the denoised complete Bouguer gravity anomalies in South China shown in Fig. 2(a). The difference between the original and denoised Bouguer gravity anomalies mainly presents the high-frequency noise, as shown in Fig. S1(b). Although some small-scale short-wavenumber anomalies are also suppressed unexpectedly by the low-pass filtering, they can be neglected since the seismic stations spacing (roughly 70 km) is too large to resolve them. Fig. 2(b) shows the gravity vertical gradient transformed from the denoised complete Bouguer gravity anomalies in South China by using the frequency-domain derivative filter (Blakely, 1995), which presents higher resolution of gravity-field features than the original Bouguer anomalies.
3.2. Data processing and receiver-function $H$–$\kappa$ stacking

We first removed the mean and trend of each waveform and tapered the end of each waveform from the collected telesismic data. Subsequently we filtered the waveform data for a band range of 0.02–2 Hz. Then we rotated the three components of all waveform data in $E$-, $N$- and $Z$-directions into the three components in $R$-, $T$- and $Z$-directions. In the next processing step we performed the iterative deconvolution (Ligorria and Ammon, 1999) on these waveform data to obtain their receiver functions at each station. In this process, a Gaussian filter coefficient of 2.5 and the standard volume factor of 0.01 were used. Finally, we chose those receiver functions of relatively high signal-to-noise and carried out the receiver-function $H$–$\kappa$ stacking (Zhu and Kanamori, 2000) for estimating the crustal thickness and Vp/Vs ratio at each station. For that an average Vp of 6.3 km/s of 1-D crustal model was utilized, and the weight coefficients for the amplitudes of Ps, PPs, and PSSs+PPSs were set to 0.7, 0.2, and 0.1, respectively. A range of crustal thickness of 20–60 km and a range of Vp/Vs ratio of 1.55–2.1 were adopted for scanning. The variances of crustal thickness and Vp/Vs ratio at each station can be calculated according to the formula presented by Zhu and Kanamori (2000). Although these variances are estimated from the flatness of the $H$–$\kappa$ stacking map at the maximum and are not the global errors, they provide a significant reference to evaluate the local uncertainty of the receiver-function $H$–$\kappa$ stacking (Zhu and Kanamori, 2000).

3.3. Joint inversion of receiver function and gravity data

After the above receiver-function $H$–$\kappa$ stacking, we carried out the joint inversion of receiver function and gravity data to improve the estimates of crustal thickness and Vp/Vs ratios in South China. We utilized the technique of joint inversion of receiver function and gravity data presented by Shi et al. (2018) rather than the technique of joint inversion of receiver function, gravity and heat flow data by Lowry and Pérez-Gussinyé (2011). There are several reasons for us to neglect the gravity effects of the mantle geothermal variations. First, the heat flow data is incomplete and low-resolution in South China to employ the joint inversion technique of Lowry and Pérez-Gussinyé (2011). Secondly, since the gravity inversion is carried out in a small sliding window, the gravity field within such a small window mainly reflects the undulation of Moho depths and the heterogeneous density distribution of the crust, and the mantle geothermal variations in such a small window usually are small and produces a weak or negligible gravity effect. Furthermore, we replace the gravity anomaly in the joint inversion with the gravity vertical gradient to reduce the gravity effects caused by the mantle sources (including the mantle geothermal variations). Compared with the regular gravity anomaly, the gravity vertical gradient emphasizes more on the crustal sources and less on the mantle sources.

According to Blakely (1995), the complete Bouguer gravity anomaly is composed of the Moho gravity anomaly $\Delta g_{\text{Moho}}$ caused by the undulation of the Moho interface and the crustal gravity anomaly $\Delta g_{\text{Crust}}$ due to the heterogeneous distribution of density of the crust. Hence, the complete Bouguer gravity anomaly can be derived as (Shi et al., 2018, modified after Lowry and Pérez-Gussinyé, 2011),

$$\Delta g = \Delta g_{\text{Moho}} + \Delta g_{\text{Crust}},$$

(1)

where,

$$\Delta g_{\text{Moho}} = \Delta \rho_{\text{Moho}} \cdot F^{-1} \{2 \pi G \cdot F(D - D) \cdot e^{-jD} \},$$

(2)

$$\Delta g_{\text{Crust}} = \Delta \rho_{\text{Crust}} / \partial \kappa \cdot F^{-1} \left\{ \frac{1 - e^{-jD}}{f} \left[ F(k - \bar{k}) - c \cdot e^{-jD} \right] \right\},$$

(3)

where, $\Delta \rho_{\text{Moho}}$ is the density contrast to the Moho interface, $\Delta \rho_{\text{Crust}} / \partial \kappa$ is the partial derivative of the ratio between crustal density and Vp/Vs ratio, $D = H - E$ is the Moho depth, $H$ is the crustal thickness, $E$ is the elevation, $\bar{D}$ is the average Moho depth, $\bar{k}$ is the average Vp/Vs ratio, $F(\cdot)$ and $F^{-1}(\cdot)$ are the Fourier and inverse Fourier transformations, respectively, $G$ is the gravitational constant, $f$ is the wavenumber, and $c = F((D - D) \cdot (k - \bar{k}))$ is the correction factor for the variation of crustal thickness.

Then, the vertical gradient $g_{z}$ of the complete Bouguer gravity anomaly can be derived as,

$$g_{z} = g_{z, \text{Moho}} + g_{z, \text{Crust}},$$

(4)

where,

$$g_{z, \text{Moho}} = \Delta \rho_{\text{Moho}} \cdot F^{-1} \{2 \pi G f \cdot F(D - D) \cdot e^{-jD} \},$$

(5)

$$g_{z, \text{Crust}} = \Delta \rho_{\text{Crust}} / \partial \kappa \cdot F^{-1} \left\{ \frac{1 - e^{-jD}}{f} \left[ F(k - \bar{k}) - c \cdot e^{-jD} \right] \right\}.$$  

(6)

Let $g_{z}^\text{real}$ be the real gravity vertical gradient (can be transformed from the gravity anomalies via derivative filtering), $g_{z}^\text{pre}$ be the prediction of gravity vertical gradient related to the crustal thickness and Vp/Vs ratio (can be calculated according to Equations (4)–(6)), and $g_{z}^\text{dev} = g_{z}^\text{real} - g_{z}^\text{pre}$ be the deviation between the real and calculated gravity vertical gradient (which come from the noise, shallow interference, or mantle geothermal variations). Assuming that the deviation obeys a Gaussian distribution, its probability density function is defined as

$$p = \frac{1}{\sqrt{2\pi} \sigma} \cdot e^{-\left(\frac{g_{z}^\text{dev} - \mu}{2\sigma}\right)^2},$$

(7)

and its likelihood function is calculated from

$$L(\mu, \sigma^2) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi} \sigma} \cdot e^{-\left(\frac{g_{z}^\text{dev} - \mu}{2\sigma}\right)^2} = \left(\frac{1}{\sqrt{2\pi} \sigma^2}\right)^{\frac{n}{2}} \cdot e^{-\sum_{i=1}^{n} \frac{(g_{z}^\text{dev} - \mu)^2}{2\sigma^2}},$$

(8)

where, $\mu = \frac{1}{n} \sum_{i=1}^{n} g_{z}^\text{dev}$ and $\sigma^2 = \frac{1}{n-1} \sum_{i=1}^{n} (g_{z}^\text{dev} - \mu)^2$.

The framework of the joint inversion of receiver function and gravity data is as follows.

1) Prepare the real gravity vertical gradient data and the initial values of crustal thickness and Vp/Vs ratio for the gravity inversion in the study area. We regard the gravity vertical gradient (Fig. 2(b)) transformed from the denoised complete Bouguer gravity anomalies as the real gravity vertical gradient data, and apply it into the joint inversion. In addition, we use the results of crustal thickness and Vp/Vs ratio from the conventional receiver-function $H$–$\kappa$ stacking as the initial values for the gravity inversion.

2) Calculate the parameters of $\Delta \rho_{\text{Moho}}$ and $\Delta \rho_{\text{Crust}} / \partial \kappa$ (in Equations (5) and (6)) for the gravity inversion in the study area. We interpolate the initial crustal thickness and Vp/Vs ratios and the real gravity vertical gradient data onto a regular grid. Then we substitute the three gridded data into Equations (4)–(6), and solve the parameters of $\Delta \rho_{\text{Moho}}$ and $\Delta \rho_{\text{Crust}} / \partial \kappa$ in the study area by using a linear regression algorithm.

3) Carry out the gravity inversion at the i-th station to obtain its gravity $H$–$\kappa$ likelihood map. We utilize the algorithm based on a sliding window centered at the i-th station for carrying out the gravity inversion. After setting the size of sliding window and...
the grid spacing within the window, we search the initial crustal thickness and Vp/Vs ratios and the real gravity vertical gradient data distributed among the window centered at this station, and then interpolate them on a regular grid. For each set of crustal thickness and Vp/Vs ratio in the receiver-function H–κ stacking map, we substitute the solved $\Delta \rho_{\text{Moho}}$ and $\partial p_{\text{Crust}}/\partial k$ into Equations (4)–(6) to calculate the prediction of gravity vertical gradient $g^e_{2\sigma}$ within the sliding window centered at the i-th station. Then we subtract the prediction $g^e_{2\sigma}$ from the real one $g_{2\sigma}$ to yield the deviation $g_{2\sigma}^e$, which is mainly contributed by the noise, shallow interference, and mantle geothermal variations. We substitute the $g_{2\sigma}^e$ into Equations (8) to obtain the likelihood value. We repeat the above work for each set of crustal thickness and Vp/Vs ratio in the receiver-function H–κ stacking map and finally obtain the gravity H–κ likelihood map at the i-th station.

4) Obtain the joint H–κ map and joint estimates of crustal thickness and Vp/Vs ratio at the i-th station. Following the work of Lowry and Pérez-Gussiñyé (2011), we multiply the receiver-function H–κ stacking map by the gravity H–κ likelihood map to yield the joint H–κ map at the i-th station. Then we pick out the optimum values of crustal thickness and Vp/Vs ratio from the joint H–κ map. We use an algorithm similar to Zhu and Kanamori (2000) to estimate the variances of crustal thickness and Vp/Vs ratios improved by the joint inversion for evaluating the uncertainty. These variances are estimated from the flatness of the joint H–κ map at the maximum and are not the global errors, but they will provide a significant reference to evaluate the local uncertainty of the joint inversion.

5) Replace the original values of crustal thickness and Vp/Vs ratio at the i-th station by using the estimated values from the joint inversion and repeat steps 3) to 5) for the next station, until the joint inversion at all the stations has been carried out.

Shi et al. (2018) have verified that various sliding window size and grid spacing play low impacts on the joint inversion, while initial values of crustal thickness and Vp/Vs ratio make certain impacts on the joint inversion. We suggest choosing a small window size for densely distributed stations and choosing a relatively large window size for sparsely distributed stations, and ensuring each window containing at least five seismic stations. We also suggest choosing the grid size obeying the rule of $S_1/4 < S_2 < S_3$, where $S_1$ is the average seismic spacing between and $S_2$ is the grid spacing within the sliding window. On the other hand, it is necessary to carefully prepare for the initial values of crustal thickness and Vp/Vs ratio for the joint inversion. In addition, it is worthy of utilizing an iterative algorithm for the joint inversion to gradually improve the initial values of crustal thickness and Vp/Vs ratio and enhance the inversion accuracy (Lowry and Pérez-Gussiñyé, 2011; Shi et al., 2018). Thus, we carry out the above joint inversion iteratively for the entire study area till the standard deviations of crustal thickness and Vp/Vs ratio between the last two iterations reach the given threshold or the iteration number gets the given threshold.

In the real application of South China, we firstly evaluated the influence of the parameters of the Gaussian filter coefficient, crustal average Vp value, sliding window size, grid spacing and density contrast to Moho interface $\Delta \rho_{\text{Moho}}$ on the joint inversion. The station of JX.YIC was used for the evaluation and the results are shown in Table S1, which indicate that all these parameters play little role in the joint inversion. Based on the evaluation, we chose the following parameters for all the stations in South China: the Gaussian filter coefficient of 2.5, the crustal Vp value of 6.3 km/s, the grid spacing of 20 km. We chose the window size of ~300 km for densely distributed stations in the eastern South China and the window size of ~400 km for sparsely distributed stations in the western South China. We carried out the joint inversion iteratively and used the results of crustal thickness and Vp/Vs ratio by the last iteration as the initial values for the next iteration. We set the threshold of the standard deviation of crustal thickness between the last two iterations as 0.5 km and the threshold of the standard deviation of crustal Vp/Vs ratio as 0.01 for stopping iteration. After four iterations, the standard deviation of crustal thickness between the last two iterations decreased to 0.1801 km and that of crustal Vp/Vs ratio decreased to 0.0044, implying an effective reduction of inversion error. Thus, we stopped the joint inversion after four iterations and obtained the improved estimates of crustal thickness and Vp/Vs ratio at 245 stations in South China. The solved value of $\Delta \rho_{\text{Moho}}$ is 392 g/cc in the study area, and that of $\partial p_{\text{Crust}}/\partial k$ is 401 g/cc (smaller than the expected value of 1500 g/cc presented by Lowry and Pérez-Gussiñyé, 2011, and slightly smaller than the inverted value of 600 g/cc in the western United States by Lowry and Pérez-Gussiñyé, 2011).

Then we transformed the crustal Vp/Vs ratio to the crustal Poisson’s ratio for all 245 stations according to their relationship of $\sigma = 0.5 \times [1 - 1/(\kappa^2 - 1)]$ (Christensen, 1996), where $\kappa$ is Vp/Vs ratio and $\sigma$ is Poisson’s ratio.

4. Results and uncertainty

4.1. Results

We chose three stations (red triangles in Fig. 2) to demonstrate the results of the joint inversion of receiver function and gravity data: JX.YIC in the eastern South China, HN.JIS in the central South China, and SC.AYU in the western South China. Fig. S2 shows the receiver functions at station JX.YIC and the results from the receiver-function H–κ stacking and from the joint inversion. The H–κ map from the receiver-function H–κ stacking at this station (Fig. S2c) presents one extreme value and is easy to pick out, whose estimates of crustal thickness and Vp/Vs ratio are 31.5 ± 2.31 km and 1.73 ± 0.07, respectively. While, the H–κ map from the joint inversion at this station (Fig. S2e) presents one focused extreme value and is easier to pick out, whose estimates of crustal thickness and Vp/Vs ratio are 31.5 ± 1.45 km and 1.73 ± 0.05, respectively. Fig. S3 shows the receiver functions at station HN.JIS and the results from the receiver-function H–κ stacking and from the joint inversion. Due to the complicated Jiangnan orogenic structure around this station, the signal-to-noise ratio of teleseismic data is poor and the multiple reverberated phases cannot be clearly identified and cannot be enhanced by stacking. Hence, the H–κ map from the receiver-function H–κ stacking (Fig. S3c) at this station presents one extreme-value belt and is difficult to pick out, whose preliminary estimates of crustal thickness and Vp/Vs ratio are 42.5 ± 5.01 km and 1.86 ± 0.10, respectively. While, the H–κ map from the joint inversion at this station (Fig. S3e) presents one focused extreme value and is much easy to pick out, whose estimates of crustal thickness and Vp/Vs ratio are 35.5 ± 1.59 km and 1.84 ± 0.04, respectively. Fig. S4 shows the receiver functions at station SC.AYU and the results from the receiver-function H–κ stacking and from the joint inversion. Again, due to the complicated crustal structure (including the thick sedimentary cover) beneath this station, the H–κ map from the receiver-function H–κ stacking (Fig. S4c) presents one extreme-value belt and is difficult to pick out, whose preliminary estimates of crustal thickness and Vp/Vs ratio are 44.6 ± 3.08 km and 1.77 ± 0.06, respectively. While, the H–κ map from the joint inversion (Fig. S4e) presents one focused extreme value and is quite easy to pick out, whose estimates of crustal thickness and Vp/Vs ratio are 40.5 ± 2.36 km and 1.85 ± 0.04, respectively. Therefore, the joint H–κ maps produced by our joint inversion are more focused than the H–κ stacking maps from the conventional receiver-function H–κ stacking, making the pickup of the optimum values of crustal thickness and Vp/Vs ratio easier and the uncertainty smaller.
Fig. 3 and Table S2 show the estimates of crustal thickness and Vp/Vs ratio in South China from the conventional receiver-function H–κ stacking. The crustal thickness in South China, ranging from 26.0–50.9 km, is large in the NW and small in the SE, and varies abruptly in some local places (such as Yichang, Guiyang, and so on). A NE-trending gradient zone of crustal thickness is roughly along the line of Yichang–Jishou–Guiyang, but is inconsistent with the gradient zone of gravity anomaly shown in Fig. 2(a). The crustal Vp/Vs ratios, ranging from 1.51–1.95, vary more strongly in the entire South China region, and exhibit relatively long and low wavelength variation along the Jiangnan orogenic belt and around the southern coastal areas. Fig. 4 illustrates the histograms of the variances of crustal thickness and Vp/Vs ratio in South China by the conventional receiver-function H–κ stacking. The variances of crustal thickness are mostly of 1.5–5.5 km, and those of crustal Vp/Vs ratio range mostly around 0.04–0.15. The large uncertainty at some stations is mainly due to the poor signal-to-noise ratio of teleseismic data and the absent or unclear multiple reverberated phases caused by the complicated crustal structure (e.g. the dipping intracrustal interface and anisotropic structure) below these stations.

Fig. 5 shows the final model of crustal thickness and Vp/Vs ratios in South China improved by the joint inversion after four iterations, and Fig. 6 shows the transformed crustal Poisson’s ratios in South China. On a whole, the improved crustal thickness in South China, ranging from 26.1–46.5 km, is high in the NW and low in the SE and varies smoothly in the entire study area. A NNE-trending gradient zone of crustal thickness is presented along the line of Yichang–Jishou–Baise (white dashed line in Fig. 5(a)), and is consistent with the gradient zone of gravity anomaly shown in Fig. 2(a). The improved crustal Vp/Vs ratios of South China, ranging 1.63–1.91, are relatively high in the NW and low within the Jiangnan orogenic belt and around the southern coastal areas. The crustal Poisson’s ratios of South China, ranging 0.20–0.31, present a similar feature to the crustal Vp/Vs ratios.

4.2. Uncertainty

Figs. 7(a) and (b) show the histograms of the variances of crustal thickness and Vp/Vs ratio improved by the joint inversion. The variances of crustal thickness from the joint inversion are mostly of 1.0–2.5 km and those of crustal Vp/Vs ratio are mostly of 0.02–0.08, both of which are much smaller than those (Fig. 4) from the conventional receiver-function H–κ stacking. The deviations (Fig. S5(a)) between the crustal thickness from the joint inversion (Fig. 5(a)) and that from the conventional receiver-function H–κ
Fig. 5. The maps of crustal thickness (a) and Vp/Vs ratios (b) in South China improved from the joint inversion of receiver function and gravity vertical gradient data. The white dashed line in (a) represents the gradient zone of crustal thickness. The white dashed line (S1) and white dotted lines (S2) in (b) respectively denote the possible leading edge of Cathaysia block buried in the deep and the possible leading edge of Yangtze block buried in the shallow inferred in this study.

Fig. 6. The map of crustal Poisson’s ratios in South China transformed from the crustal Vp/Vs ratios improved from the joint inversion of receiver function and gravity data. The white dashed line (S1) and white dotted lines (S2) respectively denote the possible leading edge of Cathaysia block buried in the deep and the possible leading edge of Yangtze block buried in the shallow inferred in this study.

stacking (Fig. 3(a)) range mainly from −3–3 km, and the deviations of crustal Vp/Vs ratio (Fig. S5(b)) range mainly from −0.1–0.1. With the gravity constraints, the joint inversion slightly decreases the values of crustal thickness and increases the values of crustal Vp/Vs ratio in most places, but significantly decreases the values of crustal thickness and increases the values of crustal Vp/Vs ratio around the Sichuan basin. The deviations (Fig. S6(a)) between the crustal thickness from the joint inversion (Fig. 6(a)) and that from previous receiver-function H–κ stacking by He et al. (2014) mainly range −5–5 km, and the deviations (Fig. S6(b)) of crustal Vp/Vs ratios mainly range −0.1–0.1. On a whole, the uncertainty of the estimates of crustal thickness and Vp/Vs ratio has been reduced significantly by the joint inversion.

It is worth mentioning that the crustal thickness and Vp/Vs ratios from the joint inversion overlap within the variances of crustal thickness and Vp/Vs ratios from the receiver-function H–κ stacking at most stations but may not overlap at several stations. For example, the crustal thickness (35.5 ± 1.59 km) from the joint inversion at HNJS does not overlap with that (42.5 ± 5.01 km) from the receiver-function H–κ stacking. One reason for the non-overlapping is that there are quite a few crustal models fitting the receiver-function data because of the large uncertainty of the receiver-function H–κ stacking at these stations, while the crustal model estimated from the joint inversion is the one fitting both the receiver function and gravity data at these stations. Another reason is that, for both the joint inversion and the receiver-function H–κ stacking, the variances of crustal thickness and Vp/Vs ratio are estimated from the flatness of each H–κ map at the maximum and are not the global errors. Hence, at these stations, the maximum in the joint H–κ map from the joint inversion may be far from the maximum in the H–κ stacking map from the receiver-function H–κ stacking, causing their variances non-overlapping.

According to Equations (1)–(3), we calculated the prediction of gravity vertical gradient and gravity anomalies caused by the final crustal model from the joint inversion after four iterations. Fig. 8 displays the gravity predictions of the final crustal model and its deviation from the real gravity vertical gradient at 245 stations. It is clear that the gravity predictions fit both of the real gravity anomalies and the vertical gradient on the trend and most of the vertical gradient deviations are distributed randomly within the range of −0.0005–0.0005 mGal/m (Fig. 7(c)). One reason for the deviations between the real and calculated gravity vertical gradient (and gravity anomalies) is the large seismic stations spacing in the study area (roughly 70 km), which makes the gravity predictions presenting more of long-wavenumber signal and less of short-wavelength signal. Another reason may be the neglect of mantle geothermal variations, which could also cause gravity effects.

5. Interpretation and discussion

5.1. Crustal thickness and isostasy of South China

There is a notable NNE-trending gradient zone of crustal thickness along the line of Yichang–Jishou–Baise in the central South China (Fig. 5(a)). The crustal thickness across this gradient zone decreases by about 4 km from west to east, consistent with previous studies (Li et al., 2006; Guo and Gao, 2018). To the NW of the gradient zone, the crustal thickness is relatively large with values of 38–46 km (nearly 40 km on average), implying a fairly stable crust. Whereas, the crustal thickness increases from 42 km steeply to 46 km to the west of Guiyang (in the midwest of Yangtze block), which is likely associated with the southeastward extrusion of the Tibetan plateau in this region (Tapponnier et al., 2001). To the SE of the gradient zone, the crust thins to values of 26–34 km, which are
less than the global average of crustal thickness, and indicate a re-worked crust (Shu, 2012; Zhao and Cawood, 2012; Charvet, 2013; Zhang et al., 2013). The crust even thins to 26–29 km around the southern coastal area (such as Nanning, Beihai and Guangzhou in Fig. 5(a)). This thinning of the crust SE of the gradient zone is related to the long-distance (>1000 km) flat-slab subduction of the Western Pacific plate during the Mesozoic (Li and Li, 2007).

By using the crustal thickness improved from the joint inversion, we obtained the apparent density distribution of the crustal layer in the study area (shown in Fig. S7) via the space-domain mapping (Guo et al., 2016). Wherein, the sea level is set as the top surface of the crustal layer, and the undulant Moho depth calculated by subtracting the crustal thickness (obtained from the joint inversion) from the elevation is set as the bottom surface of the crustal layer. The apparent density values of the crust are high in Cathaysia block and low in Yangtze block, and the transition zone between high-low crustal density values is just along the Jiangnan orogenic belt. Using the apparent density distribution of the crustal layer and the elevation data, we calculated the isostatic crustal thickness in the study area based on the Airy’s hypothesis (Blakely, 1995), the result of which is shown in Fig. 9 along with its deviation from the crustal thickness improved by the joint inversion. The deviation is positive in most of Yangtze block, indicating an overbalance of the crust, and is negative in the Jiangnan orogenic belt and most of Cathaysia block, implying an underbalance of the crust. Wang et al. (2017) also found the overbalance of the crust around the Sichuan basin in the western Yangtze block.

5.2. Crustal Poisson’s ratios in South China

To the NW of the line of Shitai–Jiujiang–Yiyang–Jishou–Baise (white dashed line in Fig. 6), the crustal Poisson’s ratios are relatively high with values of 0.25–0.31. Wherein, high crustal Poisson’s ratios (0.28–0.31) appear in the NW of Yangtze block (surround Chongyang, Dazhou, Yichang, Dayong and Jishou), indicating high content of mafic mineral within the crust and possible existence of intermediate-mafic rocks within the Precambrian basement. Previous seismic tomography (Zhou et al., 2012) demonstrated thick high-velocity zone in the middle and lower crust around the Sichuan basin, supporting high mafic mineral within the crust. Several previous hydrocarbon drillings in this area (Luo, 1986; Gu and Wang, 2014) supported the existence of intermediate–mafic volcanic rocks, mafic–ultramafic intrusive rocks and volcanic eruption rocks at the top of the Precambrian basement. The large-scale high gravity and high magnetic anomalies in this area (Gu and Gao, 2018) also support the possible existence of intermediate–mafic magmatic rocks of high density and high magnetism within the crust.

Intermediate crustal Poisson’s ratios (0.26–0.28) occur to the NE of Yangtze block (around Xiamen and Tongling in the middle and lower reaches of the Yangtze River), implying the balance contents of mafic and felsic mineral and the existence of intermediate–mafic rocks within the crust. This area hosts polymetallic metallogenic belt along the middle and lower reaches of the Yangtze River. Previous seismic tomography (Jiang et al., 2013; Ouyang et al., 2014) and the deep seismic reflection profiles (Lü et al., 2013) suggested that asthenospheric melt promoted mantle magma to rise up and to underplate the crust–mantle boundary.
leading to large-scale magma activity and mineralization via faults, fracture zones and detachment belts within the crust.

To the SE of the line of Shaoxing–Jiangshan–Pingxiang–Yongzhou–Guigang–Beihai (white dotted line in Fig. 6), the crustal Poisson’s ratios are generally lower than those in Yangtze block with most values of 0.22–0.26, implying high content of felsic mineral within the crust. They are mostly due to the planer-distributed silicic granites and volcanic rocks in the shallow (Fig. 1) and crustal thinning (Fig. 5a). The granite generally contains much quartz causing much felsic mineral, and the thinning of lower crust causes less mafic mineral. Previous seismic tomography (Zhou et al., 2012) illustrated thin high-velocity lower crust in this area, supporting low mafic minerals within the crust. The crustal Poisson’s ratios are low with values of 0.21–0.24 around the southern coastal area, which is partly because the crust is thinned to 26–30 km there (Fig. 5a). Intermediate-high values (0.26–0.29) of crustal Poisson’s ratio arise from the eastern coastal area, indicating that the content of mafic mineral is comparable to (or slightly higher than) that of felsic mineral within the crust. They are associated with polytype magmatic rocks of the Late Mesozoic in the shallow (Fig. 1). The NE-trending high gravity and high magnetic anomalies in this area (Guo and Gao, 2018) imply possible existence of intermediate-mafic magmatic rocks within the crust.

Between the line of Shitai–Jiujiang–Yiyang–Jishou–Baise and the line of Shaoxing–Jiangshan–Pingxiang–Yongzhou–Guigang–Beihai (between the white dashed line and the white dotted line in Fig. 6), there is a distinguished belt of intermittent low values of crustal Poisson’s ratio, ranging 0.20–0.24 and lower than on both sides of the belt. The central and eastern sections of this belt are roughly within the geographical location of the Jiangnan orogenic belt defined by Shu (2012), Charvet (2013), and Guo and Gao (2018). There are mainly two possible reasons for the large decrease of crustal Poisson’s ratio in this belt. One reason is that the mafic lower crust underthrust westward so that of the uppermost mantle and became thinning (Lü et al., 2013) while the felsic upper crust became thickening due to the eastward overthrust (Dong et al., 2015; Guo and Gao, 2018). Another reason is that the subsidence of the Precambrian basement due to intracontinental rifting in the late Neoproterozoic and the coverage of sediments since the Paleozoic thickened the felsic upper crust in central and western sections of this belt (Shu, 2012; Guo and Gao, 2018). Previous seismic tomography (Zhou et al., 2012) demonstrated thin high-velocity lower crust and thick low-velocity upper crust in this belt, supporting low mafic and high felsic mineral within the crust.

5.3. Discussion on the possible suture zone between Yangtze and Cathaysia blocks

The nature of the suture zone between Yangtze and Cathaysia blocks in South China during the Neoproterozoic is crucial to our understanding of the formation and tectonic evolution of South China and even East Asia. This suture zone is commonly defined by the Shaoxing–Jiangshan–Pingxiang fault zone (Fig. 1), but its western extension remains unknown and controversial (Shu, 2012; Zhao and Cawood, 2012; Charvet, 2013; Zhang et al., 2013; and reference in). According to the regional stratigraphic data, Shu (2012) and Charvet (2013) suggested that the suture zone is roughly along the eastern margin of the Jiangnan orogenic belt, that is, the line of Shaoxing–Jiangshan–Pingxiang–Yongzhou–Guilin, but the western extension of the suture zone remains unknown. Based on the magnetotelluric data, Zhang et al. (2015) found that Cathaysia block underthrust Yangtze block along the Jiangnan orogenic belt. In terms of the deep seismic reflection profile and regional gravity and magnetic anomalies, Guo and Gao (2018) found that the Jiangnan orogenic belt presents the features of crustal structure and deformation similar to Yangtze block as a whole and thus should be part of Yangtze block rather than Cathaysia block. Guo and Gao (2018) also found that Cathaysia block underthrust Yangtze block and sutured to Yangtze block along the line of Shaoxing–Jiangshan–Pingxiang–Qidong–Guilin–Nanning in the shallow crust and along the line of Shitai–Jiujiang–Dayong–Tongren–Hechi–Baise in the deep crust.

With constraints of the stratigraphic data and the deep seismic reflection profile aforementioned, we suggest that the eastern margin of the low crustal Poisson’s ratio belt (the line of Shaoxing–Jiangshan–Pingxiang–Yongzhou–Guigang–Beihai, or white dotted line in Fig. 6) represents the leading edge of Yangtze block buried in the shallow. This eastern margin is relatively clear and coincident with the suggestions of Shu (2012), Charvet (2013) and Guo and Gao (2018) in the central and eastern parts (the line of Shaoxing–Jiangshan–Pingxiang–Yongzhou), but remains debatable in the western part (the line of Yongzhou–Guigang–Beihai). We also suggest that the western margin of the low crustal Poisson’s ratio belt (the line of Shitai–Jiujiang–Yiyang–Jishou–Baise, or white dashed line in Fig. 6) represents the possible leading edge of Cathaysia block buried in the deep. This western margin is rel-
atively clear as a whole and consistent mostly with suggestions of Shu (2012), Charvet (2013) and Guo and Gao (2018). Hence, this low crustal Poisson’s ratio belt reflects the possible suture zone between Yangtze and Cathaysia blocks. During the Neoproterozoic, Cathaysia block underthrust Yangtze block, and collided and amalgamated with Yangtze block along this suture zone to form the South China block.

6. Conclusions

We have improved the crustal thickness and Poisson’s ratios of South China by using the joint inversion of receiver function and gravity data, which reduced the uncertainty of each single-method inversion and enhanced the accuracy of the estimation. The results demonstrate that the crust is thick in Yangtze block and relatively thin in Cathaysia block. A NNE-trending gradient zone of crustal thickness is presented along the line of Yichang–Jishou–Baise in central South China. The crust seems overbalance in most of Yangtze block while underbalance in most of Cathaysia block. The crustal Poisson’s ratio is high in the northern South China, intermediate around the eastern coastal area, very low within the Jiangnan orogenic belt and around the southern coastal area, and slightly low in other places. We suggested the low-value of crustal Poisson’s ratio within the Jiangnan orogenic belt to be the possible suture zone between Yangtze and Cathaysia blocks. The northern margin of the low-value belt along the line of Shitian–Jiujiang–Yiyang–Jishou–Baise represents the possible leading edge of Cathaysia block buried in the deep, and the southern margin along the line of Shaoying–Jiangshan–Pingxiang–Yongzhou–Guigai–Beihei represents the leading edge of Yangtze block buried in the shallow.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2018.12.039.

References