Ambient noise surface wave tomography of marginal seas in east Asia

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Abstract: We conducted ambient noise tomography in east Asia, including the Chinese coastal provinces, Korea Peninsular, Japan, Taiwan Island, and marginal seas in between. We retrieved Rayleigh Green’s functions from inter-station correlations of 12 months of continuous waveform data at 573 broadband stations in the region. We obtained group and phase velocity dispersion curves and dispersion maps for periods from 10 to 70 s and inverted for 3D Vs model of the crust and uppermost mantle. Moho and lithosphere thickness were derived from the 3D model. We observed three prominent low velocity zones in the upper mantle, two in the accretionary wedges above the Pacific and Philippine subduction slabs and one beneath the Changbai Mountain region. The crust and lithosphere are generally thin in the region. The velocity anomalies, crustal thickness, and lithosphere thickness all show a similar trend in NNE-SSW direction. The lithosphere shows a striking “sausage”-type structure with alternating thickness. The crust thickness and lithosphere thickness both decrease progressively from NW to SE direction, which coincides with the distribution of episodic magmatism in SE China. We propose that the subduction of paleo-Pacific slab and its rollback were mainly responsible for the crustal and lithosphere extension and the mantle lithosphere removal in east Asia.

Keywords: ambient noise tomography; east Asia; Moho; lithosphere; extension

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1. Introduction

East Asia is located in the junction of the Eurasian plate, the Pacific plate and the Philippine Sea plate (Figure 1). It has undergone complicated tectonic evolution since the Mesozoic. The interactions of the above three plates as well as the Indian plate formed the largest marginal sea area in the world, including the Japan (East) Sea, the Bohai Sea, the Yellow Sea, the East China Sea, the Taiwan Strait, and the South China Sea. In the Cretaceous, the Pacific plate subducted beneath the Eurasian plate in the NNW direction (Hilde et al., 1977). Beneath eastern China, tectonic extension and upper mantle upwelling resulted in the thinning of the lithosphere, which is particularly evident in the North China Craton and South China (Molnar and Tapponnier, 1977; Northrup et al., 1995; Zhou XM and Li WX, 2000; Liu M et al., 2004). The subduction of the Pacific plate also triggered large-scale volcanic eruptions and strong tectonic activities in eastern China, which produced extensive NE-NNE-distributed magmatic rock belts (Northrup et al., 1995; Zhou XM and Li WX, 2000; Liu L et al., 2014) and large fault zones, such as the Tan-Lu fault zone (Zhu G et al., 2005, 2010; Chen L et al., 2006). In the Cenozoic, intense compression from the Indian-Eurasian collision led to the eastward extrusion of the Eurasian plate (Tamaki and Honza, 1991; Liu M et al., 2004). While the direction of the Pacific plate subduction shifted from NNW to NWW (Uyeda and Miyashiro, 1974; Hilde et al., 1977), the Philippine Sea plate also began its oblique subduction under the Eurasian plate. Under the interaction of these plates, back-arc extension and back-arc basin began to appear on the East Asian margin. The East China Sea, the Japan (East) Sea and the Okinawa Trough were all formed during this period (Uyeda and Miyashiro, 1974; Tamaki, 1995).

Our study region (Figure 1) includes the Western Pacific subduction zones, the Japan island arc, the Ryukyu island arc, and the Taiwan Island in the east and the northeastern provinces and the eastern coastal provinces of China in the west. In between, there are several major marginal seas, including the Japan (East) Sea, the Bohai Sea, the Yellow Sea, the East China Sea, the Taiwan Strait, and the South China Sea. The subduction of the Pacific plate and the Philippine Sea plate led to a series of typical trench-arc-basin systems, including the Japanese island arc, the Japan (East) Sea, the Ryukyu island arc and the Okinawa Trough. Within the study, the Bohai Sea, the Yellow Sea, the East China Sea, and the Taiwan Strait, and the South China Sea constitute the vast Chinese continental shelf. The geological structure of the land region is complex too with the Songliao basin in the northeast, the
Sino-Korea Craton in the central part and the South China block in the south. The study area covers the eastern part of the Sino-Korea Craton – the North China Basin, the Bohai Bay, the Korean Peninsula and several mountain ranges. The Sino-Korea Craton and South China blocks are separated by the Qinling-Dabie orogenic belt. South China block is composed of Yangtze Craton and Huaxia block, between which is the Jiangnan orogenic belt as the suture.

Although relatively new, the ambient noise tomography (ANT) method has been applied in seismology rapidly and extensively in the recent decade. The method is based on the idea that the Green's function between the two receivers can be directly obtained from the cross-correlation of the diffuse field at the receivers (Lobkis and Weaver, 2001; Weaver and Lobkis, 2002). In seismology, researchers use seismic ambient noise for the cross-correlation calculation to derive the empirical Green's functions (EGFs) of the surface waves between stations for tomography (Shapiro et al., 2005; Shapiro and Campillo, 2004; Weaver, 2005; Sabra et al., 2005; Yao HJ et al., 2006; Yao HJ et al., 2008; Bensen et al., 2007; Yang Y et al., 2007; Zheng SH et al., 2008; Lin FC et al., 2008).

Compared with traditional methods based on seismic waves from teleseismic earthquakes or other energetic sources, the ANT method is not affected by the distribution of sources and short-period surface waves can be more easily obtained. Thus, the method has been effective in improving the resolution of the shallow strata and the lithosphere.

Previous studies of the ANT of east Asia have focused mostly on land. The studies that cover the study area or part of it include the whole China and neighboring regions (Zheng SH et al., 2008; Sun XL et al., 2010; Xu ZJ et al., 2013; Bao XW et al., 2015; Shen WS et al., 2016) and northeast Asia (Zheng Y et al., 2011; Witek et al., 2014), the Korean Peninsula (Kang TS and Shin JS, 2006; Cho et al., 2007), North China (Fang LH et al., 2009), South China (Zhou LQ et al., 2012), and the Taiwan Island (Huang TY et al., 2015).

In this study, we conducted surface wave ANT of the east Asia marginal seas. We used continuous waveform data of a large number of broadband stations (total of 573), located in the eastern coastal areas of China, the Korean Peninsula, Japan and Ryukyu arcs, and the Taiwan Island (Figure 1, inset). The combination of the stations from different regions along the two sides of the marginal seas provides a good coverage of the study area for our tomographic imaging. Previous ANT studies have focused mostly on land. In this study, we focus on the deep structures of the coastal regions as well as the marginal seas, island arcs, and subduction zones and discuss the implications for the complex tectonics of the region.

2. Data and method
We used the continuous waveform data of 573 broadband seismic stations in east Asia (Figure 1, inset) for the whole year of...
2011. The data were obtained respectively from 491 stations of the China Regional Seismic Networks in 15 eastern provinces, 74 stations of the F-NET in Japan, and 8 stations in South Korea and the Taiwan Islands from the International Research Institution of Seismology Data Management Center. We used only the vertical component at the sampling rate of 1 Hz. These stations are mainly located in the eastern part of Chinese mainland, the Japan island and the Ryukyu island arcs, and the Taiwan Island. Thus, although there is no station in the marginal seas in the middle, a great advantage of the ANT method is that the station correlations provide a dense coverage of the ray paths of the region between stations.

We followed similar data processing procedures for the ANT as in previous studies for the whole China (Zheng SH et al., 2008; Sun XL et al., 2010; Xu ZJ et al., 2013). The steps include extraction of Rayleigh-wave EGFs from ambient noise correlation, extraction of group velocity and phase velocity dispersion curves from a frequency-time analysis method, construction of dispersion maps from the inter-station dispersion measurements, and inversion of 3D S-velocity structure from the dispersion maps. We used the procedures by Bensen et al. (2007) to retrieve EGFs. The continuous data are bandpass-filtered from 5 to 150 s. We selected only the EGFs with the signal-to-noise ratio greater than 10. Group and phase velocity dispersion curves from 8 to 70 s were measured using frequency-time analysis (Levshin and Ritzwoller, 2001). Figure 2 displays the numbers of reliable group and phase velocity dispersion measurements we obtained for periods from 8 to 70 s. The distributions of the numbers of group and phase velocity measurements are very similar with the maximum numbers of 65,000 and 68,000 both at 15 s for group and phase velocity measurements, respectively.

Figure 2. Numbers of dispersion measurements for different periods obtained in this study. Blue dots are group velocity measurements, green dots are phase velocity measurements.

We performed the inversion of dispersion maps in an iterative process to filter out poor measurements. The grid size of the dispersion maps is $0.5\degree \times 0.5\degree$. We first used a large smoothing factor to generate a relatively smooth image, and dispersion measurements with large residuals were rejected. We excluded measurements with the interstation distance less than three wavelengths and travel time residuals greater than twice the standard deviation of all the residuals. We then used the dispersion models from Bao XW et al. (2015) as the background reference models and applied regular smoothing and damping parameters in the inversions.

Finally, we inverted for 3D S-velocity structure from the dispersion maps. For each grid, we used the group and phase dispersion curves to invert for the 1D S-velocity profile using the inversion program by Herrmann and Ammon (2002). The initial model was the 3D Vs model by Bao XW et al. (2015) or the AK135 model (Kennett et al., 1995) where the model by Bao XW et al. (2015) does not cover in the eastern part of the study region. The inversion model is parameterized as layers: the layer thickness is set to 5 km in 0-50 km depth, 10 km in 50-125 km depth, and 25 km layer below 125 km depth, respectively. Finally, we obtained the shear wave velocity at different depths of 0-120 km in the study area.

Based on the 3D shear wave velocity model, we derived the Moho depth map and the lithosphere thickness map. The Moho is defined as the interface with shear-wave velocity of 4.0 km/s, which is found to be a good approximation (Xu ZJ et al., 2013; Bao XW et al., 2015). The lithosphere thickness is more difficult to define using a seismic velocity model. We experimented three different criteria for the lithosphere/asthenosphere interface, i.e., the velocity gradient is zero, the gradient of the velocity decrease with depth is maximum, and the velocity is set at constant $V_s$ = 4.25 km/s, respectively (Figure 3). We found that the constant $V_s$ method produces most stable and coherent lithosphere depth map, thus we used the method to define the lithosphere thickness. This empirical definition is useful in examining the general trend of lithosphere thickness variation, but it may have large errors relative to the true lithosphere thickness, particularly in the subduction zones and accretionary wedges (see below).

We performed checker-board resolution tests of our ray coverage (Figure 4). The initial model velocity is set at 3.0 km/s as the original velocity with a $1\degree \times 1\degree$ pattern of $\pm 5\%$ perturbations. We performed the test for different periods (Figure 4). Results show that the resolution for the continental area and island arcs is higher than that for the ocean area, which is consistent with the distribution of the stations. In addition, rays passing through the ocean are mostly in NW direction, while rays in the NE direction are lacking, leading to higher resolution in the NE direction and lower resolution in the NW direction.

3. Results

In this section, we present velocity maps and profiles from the surface wave inversions and discuss their main features, including dispersion maps of Rayleigh wave group velocities between 8 and 70 s, maps of the 3D Vs in different depths, Vs depth profiles along different latitudes and longitudes, Moho depth map and lithosphere thickness map. The Rayleigh-wave phase velocity dispersion maps were also obtained independently from the inter-station dispersion curves and were used in the inversion for the 3D Vs model. However, they are not shown here as the main features are reflected in the other maps.

3.1 Rayleigh Wave Dispersion Maps

Figure 5 shows the Rayleigh wave group velocity maps of different periods (10-70s). Rayleigh wave is sensitive mainly to shear-
Figure 3. Velocity structures (right) of representative example sites (A to F) (left). The calculated Moho depth and lithosphere depth with different criterions are also marked. The Moho depth (black dashed line) is defined at the depth with $V_s = 4.0$ km/s. The lithosphere depth is calculated in three ways — green dash line ($V_s$ gradient = 0), blue dash line (max $V_s$ gradient) and red dash line ($V_s = 4.25$ km/s).

Figure 4. Results of checker board resolution tests of surface wave inversion. Input model has 1° by 1° checker pattern, with ±5% velocity perturbation. Retrieved models at different periods are shown.

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wave velocity and in general, the depth of the sensitivity of the Rayleigh wave increases with periods. Therefore, Rayleigh wave group velocity maps at different periods can indicate Vs features at different depths.

Maps at short periods (10-20 s) are mainly sensitive to the upper crustal structure, and the velocity variations in these maps have good correspondence with the regional geology. The distribution of sedimentary basins and orogenic belts in study area can be clearly distinguished from the maps. Areas with thick sedimentary layers always display low velocity anomalies, including several large basins (Songliao Basin, North China Basin) on the continent and most part of marginal seas (Bohai Sea, Yellow Sea and East China Sea). In contrast, high velocity anomalies are distributed over the mountain fold belts and stable cratons with little sediments, such as the stable ancient craton (e.g., Yangtze Craton) and large fold belts (e.g., Changbai Mountains, South China Orogenic Belt).

Maps at intermediate periods (20-40 s) are primarily sensitive to lower crust and uppermost mantle. In this period range, boundaries of relatively small tectonic blocks are less clear or even disappear, replaced by the gradually enhanced velocity contrast between continent, ocean, and island arcs. In the 30-s map, the mainland of China, the continental shelf and the Japan island arc display low velocity, and the Japan (East) Sea shows high velocity. In the 40-s map, the low-velocity zone beneath the Japan island arc expands, while the marginal seas on the continental shelf and the southeastern China turn into relatively high-velocity, displaying a high-velocity belt in NE-SW direction along with the Japan (East) Sea.

Maps at long periods (40-70 s) are mainly affected by the upper mantle and mantle lithosphere structure. In this period range, most regions show high-velocity anomaly, but there are three stable and broad low velocity bands located in Japan island arc, Ryukyu island arc and Korean Peninsula. These low velocity bands can be recognized easily in 50-s and 70-s period velocity maps, and their formation mechanisms will be discussed below.

### 3.2 3-D Shear Wave Velocity Maps

Several horizontal slices of shear velocity maps at different depths are plotted in Figure 6. Representative velocity profiles down to 160 km are also plotted in Figures 7 and 8. The 3-D shear velocity model shows good correlation with surface geology and regional tectonics.

#### 3.2.1 3-D shear wave velocity maps

Figure 6 shows the shear wave velocity maps at a range of depths:
the upper crust, the middle, the lower crust, uppermost mantle, and below 80-km depth. At 9-km depth, the distribution of shear-wave velocity anomalies is affected by the thickness of sedimentary layers. The low-velocity anomalies are mainly distributed in large basins (Songliao Basin, North China Basin) and marine areas (Bohai Sea, Yellow Sea, East China Sea, and Japan/East Sea), consistent with thick sedimentary layers. The high-velocity anomalies are mainly distributed in the stable craton (Yangtzi Craton), orogenic fold belts (Hinggan Ling, Changbai Mountain, Korean Peninsula and South China fold belt) and the large Tan-Lu fault zone.

At depths of 21 to 33 km, large-scale low velocity anomalies in study area are mainly distributed in continent and subduction zone, and high velocity anomalies are mainly distributed in the Japan (East) Sea and the East China Sea. The Japan (East) Sea is in the mantle, which well delineated by high velocities.

At the depths of 51 and 75 km, most of the study area displays high shear velocities, while there are three significant low-velocity zones beneath the Japan island arc, the Ryukyu island arc and the Korean Peninsula. This is consistent with the three low-velocity bands shown in the long-period Rayleigh wave dispersion maps. At depths greater than 80 km, the low-velocity band beneath the Korean peninsula remains unchanged, while the low-velocity bands beneath the Japanese island arc and the Ryukyu arc expand in NW direction and reach the center of the Japan (East) Sea and the East China Sea.

### 3.2.2 Profiles of shear wave velocities

Figure 7 shows 6 profiles at different latitudes. The Moho beneath continent is relatively flat with depth slightly larger than 30 km, while the Moho below the ocean is sharply thinned. The Moho depth beneath the Japan (East) Sea is about 15 km (profiles 1 and 2), and it thins from west to east from China coastal region to the East China Sea, especially under the Okinawa Trough (profiles 4, 5 and 6). In addition to the Moho, three low velocity zones can also be clearly observed in profiles. Profiles 1, 2 and 3 pass through the Japan (East) Sea. It is observed that the low velocity zone on the west side of Japan (East) Sea is inclined to the west and the belt extends up to the central part of the Japan (East) Sea with increasing depth. Profiles 4, 5 and 6 pass through the Ryukyu island arc, and the low-velocity zone beneath this area also dips westward. Subduction slabs also show clearly in profiles. The Pacific subduction plate, which
appears as high-velocity slab, is clearly visible at the right side of profiles 1 and 2. The subduction Philippine Sea Plate is on the right side of profiles 4, 5 and 6. Compared with the Pacific plate, the subduction angle of Philippine Sea plate is significantly smaller. In addition, profile 6 passes through the Taiwan Strait and Taiwan island and beneath Taiwan island and the Philippine slab shows up clearly as a high velocity anomaly.

Figure 8 shows 6 profiles at different longitudes. The depth of Moho on land or near the China coast (profiles 1, 2) is relatively flat (about 30 km or slightly larger). Profiles 3 and 4 pass through the Yellow Sea and the East China Sea and reveal that the Moho is gradually reduced to about 20 km with decreasing latitude. Profiles 5 and 6 pass through the Japan (East) Sea, the Moho thickness of which is only 10-15 km. Profiles 4, 5, and 6 pass through the Ryukyu Island arc, the Korean peninsula and the Japanese island arc respectively, and images show the distribution of low-velocity zones beneath these areas.

### 3.3 Crustal Thickness Map

The distribution of crustal thickness displays good correlation with surface geology (Figure 9). On the continent, the depth of Moho mainly ranges from 23 km to 40 km. Tectonic fold belts (Changbaishan, Hinggan Ling and Dabie-Sulu orogenic belts) usually have thicker crustal thickness (> 30 km), crust of other regions (Songliao Basin, North China craton, South China fold belt) is relatively thin (23-30 km). In sea area, the Moho depth ranges from 10 km to 30 km. The crustal thickness beneath the Yellow Sea is 30 km, beneath the East China Sea is reduced to 25 km, and beneath the Japan Sea and Okinawa Trough is the thinnest, less than 20 km. The depth of the Moho in study area shows a thinning trend from NW to SE, and the crustal thinning region displays as stripes in the NE direction.
3.4 Lithosphere Thickness Map

We derived lithosphere thickness from the interface with constant $V_s=4.25$ km/s (see Method section above) (Figure 10 and Figures 7 and 8). There are limitations in this definition, resulting obvious artifacts near the subduction zones and the accretionary wedges (Figures 7 and 8). However, in other locations, the interface generally indicates the location of rapid velocity decrease with depth (Figures 7 and 8). From lithosphere thickness map (Figure 10) and 3D-shear wave velocity profiles (Figures 7 and 8), we can summarize several characteristics of lithosphere distribution in the study area.

1. Lithosphere thickness in east Asia is around 100 km, mostly in the range of 90 to 120 km.

2. The lithosphere thickness variation shows as stripes in NNE direction in map view (Figure 10) and a striking “sausage” shape in the cross-section views (Figures 7 and 8) with alternating thicker and thinner lithosphere.

3. The lithosphere thins generally from west to east. The lithosphere thickness in the west is about 110-120 km, and about 90 km in the marine area in the east.

4. The lithosphere under Changbai Mountain-Korean Peninsula and subduction zones is rather thin, reflecting the low velocity anomalies beneath these regions. Much of the high velocity mantle lithosphere has been removed in the accretionary wedges above the subducting slabs (Figures 7 and 8).

4. Discussion

We presented the main features of the 3D $V_s$ model above. In this
4.1 3-D Shear Velocity Model

Shear wave velocity patterns reflect the diverse crust and upper mantle structures of the complex region. In shallow layers above 20 km, the distribution of velocity anomalies correlates well with the surface geology, which mainly reflects the contrast of sedimentary cover and crystalline rock. Major sedimentary basins appear as low velocity zones, and mountains and fold belts formed by magmatic activity appear as high velocity zones. At the depth of 20-30 km, the velocity distribution shows distinct difference between the east and the west, which is consistent with the distribution of Moho depth in this region. The continent and the continental shelf have thicker (continental) crust, so the west part is still in lower crust at this depth and shows as low velocities. The crust beneath the Japan (East) Sea and that beneath the Okinawa Trough are relatively thin. The east part of the study region has entered into the upper mantle at this depth and shows as high velocity anomalies. The highest velocity region is distributed under the western part of the Japan (East) Sea, due to its extremely thin oceanic crust. The velocity contrast between the east and the west is also evident in previous ANT studies (Zheng SH et al., 2008; Zheng Y et al., 2011; Sun XL et al., 2010; Xu ZJ et al., 2013; Shen WS et al., 2016) as well earthquake-based studies that cover the region (e.g., Ritzwoller and Levshin, 1998; He ZQ et al., 2001; Li HY et al., 2001; Huang ZX et al., 2003; Zhu J et al., 2007; Li YH et al., 2013). At depths > 30 km, as the whole study area enters the upper mantle, the velocity anomalies reflect the heterogeneity of the upper mantle structure. Surrounded by relatively high velocities are three obvious low-velocity zones, located in Japan Island arc, Ryukyu Island arc and the Korean Peninsula. The low velocity zones are also evident in previous ANT studies (Zheng Y et al., 2011; Shen WS et al., 2016). We discuss the implications of the low velocity anomalies next.

4.2 Low Velocity Zones Beneath Japan, Ryukyu and Korean Peninsula

In the upper mantle, the low-velocity zones in study region mainly concentrate on three zones — the Japan Island, the Ryukyu Islands and the Korean Peninsula. Based on the shear velocity maps, the low velocity zones under Japanese island arc and Ryukyu Island arc are quite similar. Both of them are located close to the subduction zones and move in NW direction as the depth increases. Compared to the 50-km depth map, these two low velocity zones at 80-km depth expand in NW direction, and below 100 km, these low velocity zones have moved to the middle of the Japan (East) Sea and the East China Sea respectively. Profiles (profiles 1, 2 and 4 in Figure 7) show that these two low-velocity zones appear as low-velocity anomalies in the accretionary wedges overlying the subduction plates and have similar inclination to the plugging subduction slabs. Thus, the formation of these low-velocity zones is likely related to the dehydration of the subduction of the Pacific plate and the Philippine Sea plate (Zhao DP et al., 2007; Yoshizawa et al., 2010).

In contrast, the low-velocity band beneath the Korean Peninsula is much more stable. The low-velocity zone is located far from the subduction zone and exists beneath the Korean Peninsula and the Changbai Mountain Range. The location of the low-velocity zone remains unchanged with increasing depth. In profile 1 of Figure 7 and profile 4 of Figure 8, it is easy to recognize the low velocity region beneath the Korean Peninsula and the Changbai Mountains, which is quite different from low velocity bands of the subduction zones. This suggests a different forming mechanism. The distribution of this low-velocity zone coincides with the volcanic activity and heat flux anomalies in Changbai Mountain area. The
continuous low velocity zone is likely related to mantle upwelling. Tang YC et al. (2014) proposed that the anomaly represents subduction-induced upwelling process — the hot sub-lithospheric mantle beneath the subducting the Pacific Plate escapes through a gap in the subducting slab.

4.3 Mechanisms for Extension in East China and Western Pacific and Thinning of Lithosphere
Since the Paleozoic, the lithosphere in the eastern part of the North China Craton has undergone strong deformation and destruction (Griffin et al., 1998; Menzies et al., 2007; Zhu RX et al., 2011). Studies show that the lithosphere in the Paleozoic craton of North China was 200 km thick, but thinned to less than 90 km in Cenozoic (Menzies and Xu, 1998; Xue YG, 2001; Gao S et al., 2004; Menzies et al., 2007). In South China, strong folds and overthrusting occurred during the Mesozoic (Charvet et al., 1996; Gilder et al., 1996). The post-orogenic tectonics caused the upwelling of the asthenosphere, the thinning of lithosphere and the large-scale intrusion and eruption of magma in South China (Jahn, 1974; John et al., 1990; Zhou XM and Li WX, 2000; Wang FY et al., 2011). Several NE-NNE-oriented magmatic belts also have been developed in this area (Zhou XM and Li WX, 2000; Liu L et al., 2012).

Our seismic observations support the crustal and lithosphere thinning in east Asia. In North China Craton or the South China, the Moho depth is 25-30 km, and the lithosphere thickness is 80-110 km. They thin towards the east into the marginal seas. The striking observation of the “sausage”-type structure of alternating thicker and thinner lithosphere (Figures 7 and 8) is a strong indication that the whole lithosphere is extended. Among the whole study region, the Japan (East) Sea has the thinnest crust (<20 km) and the thinnest lithosphere (<70 km). Thin ocean crust lies in western and northern part of the Japan (East) Sea (Uyeda and Miyashiro, 1974). Beneath the Yamato Rise in center of Japan Sea is retained continent crust and has relatively thick crust and lithosphere (Jolivet et al., 1994; Tamaki, 1995). The Okinawa Trough on the eastern side is a typical back-arc basin in early stage of expansion. It is formed due to the back-arc basin activity of the Philippine Sea plate subduction in the Pliocene (Letouzey and Kimura, 1986; Sibuet et al., 1998). The Moho depth is less than 20 km.

By examining the variation of lithosphere thickness, we can get some insights on the mechanisms for the extension and the lithosphere thinning and the formation of the marginal seas in east Asia/western Pacific.

(1) The lithosphere thickness across east Asia is consistently thinned. The consistency indicates that the thinning of lithosphere is not limited to the North China craton but also includes South China and marginal seas. Eastern China is a combination of several continental blocks. In early Neoproterozoic, the collision of the Yangtze block and the Huaxia block formed a unified ancient land of South China (Charvet et al., 1996). In early Mesozoic, the collision of the South China continent and the North China continent formed a unified ancient Asian continent (Li SG et al., 1993; Hacker et al., 1998). However, the inversion results show that the lithosphere thickness in eastern China is relatively homogeneous (in range of 90-120 km). The lithospheric thickness of each block is quite similar with each other. It indicates that after Cretaceous, eastern China has experienced complex but common tectonic processes as a whole. The activation of craton occurred in North China and South China and marginal seas. Widespread extension and lithosphere destruction led to the present-day continental lithosphere structure.

(2) The lithosphere thinning in eastern China has a dominant orientation. The lithosphere stripes (Figure 10) show NNE trend, which is consistent with the distribution of magmatic rocks in the region (Zhou XM and Li WX, 2000). We argue that the formations of both the magmatic pattern and the lithosphere stripes are related to the change of the slab dipping angle and the rollback of the Pacific subduction plate.

In the Early Cretaceous, the Pacific Plate dived rapidly below the Eurasian plate at low angle (Coney and Reynolds, 1977; Hilde et al., 1977; Engebretson et al., 1984; Zhou XM and Li WX, 2000). As such, the oceanic plate dips into the interior of the continent plate and creates a broad igneous rock belts in eastern China (Zhou XM et al., 2006; He ZY and Xu X, 2012). In the Late Cretaceous, with the increasing dipping angle and the rollback of the Pacific plate (Engebretson et al., 1984; Zhou XM and Li WX, 2000), the igneous rock belts in eastern China migrated to the east (Zhou XM et al., 2006; He ZY and Xu X, 2012; Liu L et al., 2016). The distribution of Mesozoic igneous rocks in South China provides strong evidence. The distribution of igneous rocks in South China is along NE-NNE direction, and the ages of igneous rocks becomes progressively younger from the continent to the ocean direction (Zhou XM and Li WX, 2000; Liu L et al., 2012, 2016). The lithosphere thickness we obtained also shows the same NNE trend. It is reasonable to infer that the retreat of the Pacific plate resulted in the extension and the thinning of lithosphere from the continent to ocean and led to the formation of magmatic belts at surface and lithosphere stripes and “sausage”-type structure at depth.

(3) The thickness of the lithosphere in the study area thins progressively from west to east. In the Mesozoic, east Asia was subject to a large-scale thermodynamic activation process due to the subduction of the Pacific Plate (Northrup et al., 1995; Menzies and Xu Y-G, 1998; Zhou XM and Li WX, 2000; Wu FY et al., 2003). It was the most intense period of magmatism and mineralization in eastern China, and also the main period of crustal and lithospheric thinning (Charvet et al., 1996; Gilder et al., 1996; Zhu RX et al., 2011; Wu FY et al., 2003). In the Cenozoic, the subduction of the Pacific plate became steep and the active magmatism gradually migrated to east (Zhou XM and Li WX, 2000; Liu L et al., 2016). The lithosphere thinning also migrated to the east. At the same time, the newly formed Philippine Sea plate began to subduct towards west. The long-range effect of the collision between the Indian plate and the Eurasian plate also caused the Eurasian mantle to move gradually eastwards (Molnar and Tappinon, 1977; Tamaki and Honza, 1991; Menzies and Xu Y-G, 1998; Liu M et al., 2004). With the interaction of these plates, the back-arc area in the subduction zones had intense extension and a series of large marginal seas and back-arc basins rapidly formed in eastern Asia (Hilde et al., 1977; Letouzey and Kimura, 1986; Jolivet et al., 1994; Maruyama et al., 1997). The crust and lithosphere in east Asia are further stretched and thinned gradually to form the present con-
5. Conclusion

In this study, we obtained a 3D high-resolution shear velocity model of crustal and upper-mantle structure of the east Asia using ambient noise seismic tomography. Main conclusions are as follows.

(1) The velocity pattern at shallow depths correlates well with surface geological structures. In study region, basins with thick sedimentation layer show low velocities and mountain ranges in surrounding show high velocities. This kind of velocity distribution exists mainly above 20 km.

(2) Shear velocity model shows large low velocity zones in the upper mantle beneath Japan island, Ryukyu island and Korean peninsula. The low velocity zones beneath Japan island and Ryukyu island at depth of 40-100 km are parallel to the subducting slabs and are likely caused by the dehydration of the subduction plates. The low velocity zone underneath Korean peninsula at the depth of 40-80 km coincides with the active volcanism and magmatism in Changbai Mountain region.

(3) The crust in east Asia is generally thin, ranging from 23-40 km on continent to 10-30 km in the sea area. The Moho thins from NW to SE and the crustal thickness displays as stripes in the NE direction.

(4) Lithosphere in east Asia is very thin, mostly around 100 km and thinning from west to east and much of the high velocity mantle lithosphere disappears in the accretionary wedges above the subducting Pacific and Philippine Sea plates. The lithosphere under Changbai Mountain region is also very thin, likely related to the mantle upwelling. The lithosphere displays a striking "sausage"-type structure of alternating thickness in the cross-section view and the thickness variation shows as stripes in NNE direction in the map view.

(5) The progressive thinning of crust and lithosphere from NW to SE direction correlates well with age progression of the NE-NNE banded magmatic rock belts at surface (older to younger from west to east) in Eastern and Southern China. We propose that the mechanism of the correlation is related to the change of dipping angle and the retreat of the Pacific subduction plate since Mesozoic.

(6) The extension of east Asia is widespread from eastern China to the marginal seas, occurring at the lithosphere scale. The extension and the crustal and lithosphere thinning were most likely driven by the subduction of the Pacific plate and the retreat of the subduction slab since Mesozoic and aided by the subduction of the Philippine Sea plate and the long-range effects of the collision between Indian plate and Eurasian plate since Cenozoic.

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