3-D shear wave velocity structure in the shallow crust of the Tan-Lu fault zone in Lujiang, Anhui, and adjacent areas, and its tectonic implications

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Key Points:
- Ambient noise tomography reveals high-resolution shallow crustal structures of the Tan-Lu fault zone in Lujiang
- Strong velocity anomalies exist in the Hefei basin, the Tan-Lu fault zone, and the Dabie orogenic belt
- The high-speed intrusive rocks may come from the Luzong volcanic rock basin through the fractured fault zone

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Abstract: The Tan-Lu fault zone is a large NNE-trending fault zone in eastern China. Investigations of the structures of the fault zone and its surrounding areas have attracted much attention. In this study, we used dense-array ambient noise tomography to construct a three-dimensional shear wave velocity model of shallow crust in an area about 80 km × 70 km in Lujiang, Anhui Province, eastern China. For approximately one month we collected continuous ambient noise signals recorded by 90 short-period seismographs in the region, and obtained the short-period Rayleigh wave empirical Green’s functions between stations by the cross-correlation method; we also extracted 0.5–8 s fundamental mode Rayleigh wave group velocity and phase velocity dispersion curves. Based on the direct surface wave tomography method, we jointly inverted the group velocity and phase velocity dispersion data of all paths and obtained the 3-D shear wave velocity structure in the depth range of 0–5 km. The results revealed important geological structural features of the study area. In the north region, the sedimentary center of the Hefei Basin — the southwestern part of the Chaohu Lake — shows a significant low-velocity anomaly to a depth of at least 5 km. The southwestern and southeastern regions of the array are the eastern margin of the Dabie orogenic belt and the intrusion area of Luzong volcanic rocks, respectively, and both show obvious high-speed anomalies; the sedimentary area within the Tan-Lu fault zone (about 10 km wide) shows low-velocity anomalies. However, the volcanic rock intrusion area in the fault zone is shown as high velocity. Our shallow crustal imaging results reflect the characteristics of different structures in the study area, especially the high-speed intrusive rocks in the Tan-Lu fault zone, which were probably partially derived from the magmatic activity of Luzong volcanic basin. From the Late Cretaceous to Early Tertiary, the Tan-Lu fault zone was in a period of extensional activity; the special stress environment and the fractured fault zone morphology provided conditions for magma in the Luzong volcanic basin to intrude into the Tan-Lu fault zone in the west. Our 3-D model can also provide important information for deep resource exploration and earthquake strong ground motion simulation.

Keywords: Tan-Lu fault zone; Lujiang of Anhui; ambient noise tomography; shallow crust structure; intrusive rocks

1. Introduction

The Tan-Lu fault zone has experienced multiple tectonic movements and is the greatest large-scale fault zone in east China; its length within Chinese territory exceeds 2400 km and its width varies from tens to more than 200 km, traversing the North China Block, the Yangtze Block, and the Qinling–Qilian–Kunlun Fold Belt (Xu JW et al., 1985; Zhu G et al., 2004). The fault zone is composed of several nearly parallel faults, which are mainly of strike-slip and reverse types. At present the fault zone maintains a steady overall slip rate of about 2 mm/a (Hou MJ et al., 2006). In many of its regions earthquakes are still active. In the history of China the great Tancheng earthquake occurred in this fault zone in 1668, with a magnitude as high as 8.5, resulting in severe human casualty and economic loss. Based on seismicity, regional geology, and tectonic evolution, the fault zone can be divided into three distinct segments: northern, central, and southern (Wang XF et al., 2000). The present study region is located near Lujiang County, Anhui Province, at the south end of the near-NS-trending Tan-Lu fault and to the south of Hefei Basin. To its southwest is the Dabie oro-
The Dabie orogenic belt is a near east-west-oriented collisional orogen that separates the North China craton and the Yangtze craton; it was formed under NS compression in the Indosinian-Early Yanshanian. In the 1980s, after the discovery of coesite-bearing eclogite and widespread high pressure and ultra-high pressure metamorphic rocks, the Dabie orogenic belt became the world’s largest experimental field for studying continent-continent collision and plate exhumation (Zheng YF et al., 2003; Wang YS et al., 2004). The Luzong volcanic rock basin is located in the middle-lower Yangtze River depression belt at the northern border of the Yangtze craton. In this basin, volcanic rocks generally derived from the magmatic activities in the Early Cretaceous are widely distributed. These magmas are responsible for the region’s rich metal mineral resources and geothermal resources (Tang JF et al., 2010). The Hefei Basin is an area about 20,000 km² located in the middle of Anhui Province; it belongs to the southern North China craton. The formation and evolution of Hefei Basin have been controlled primarily by the Dabie orogenic belt and the Tan-Lu fault zone (Lu GM et al., 2002). Our chosen study region is situated at the junction of these extensively studied areas.

Previous surface geological investigations and studies have focused mainly on the following subjects: Dabie orogen (Wang YS et al., 2004, 2018), Hefei Basin (Liu GS et al., 2006), the tectonic characteristics and evolution history of different segments of the Tan-Lu fault zone on a relatively large scale (Chen et al., 2007; Hou MJ et al., 2006; Huang Y et al., 2011; Gu QP et al., 2016; Zhang JD et al., 2010; Zhao T et al., 2016), surface wave phase velocity and shear wave velocity models beneath the Dabie orogen (Luo YH et al., 2012), short-period array ambient noise tomography for the shallow crustal structure of the Feidong segment of the Tan-Lu fault zone (Gu N et al., 2019), the controlling effect of fault belt on the Hefei Basin (Liu GS et al., 2002, 2006; Lu GM et al., 2002; Song CZ et al., 2003), the evolution and geologic features of the Luzong volcanic rock basin (Yuan F et al., 2008; Dong SW et al., 2009; Tang JF et al., 2010), and velocity structure tomography of the shallow and deep structures in the middle-lower Yangtze River metallogenic belt (Ouyang LB et al., 2015; She YY et al., 2018; Tian XF et al., 2018; Luo S et al., 2019). These previous studies have concentrated primarily on geochemical topics or characteristics of the resources in some mining areas, and on fine structure exploration and interpretation of the top few hundred meters in a very small area (e.g., Tao SZ and Liu DL, 2000). Generally speaking, there is a lack of fine regional upper crust geophysical modeling, which hampers in-depth study of structural details inside the tectonic block and its evolution. Because our chosen study region is at the junction of areas that have received considerable previous research attention, results of this study can provide new details useful in improving understanding of the shallow crustal structure of the region and the juncture configuration and relationship of neighboring tectonic blocks, and may be of use in exploration of deep resources.

Since development of a method for recovering the empirical Green’s functions of surface waves between two stations from the cross-correlation of ambient noise (Shapiro and Campillo, 2004; Shapiro et al., 2005; Yao HJ et al., 2006; Fang LH et al., 2010), some studies have also discussed the generation mechanisms of surface waves of relatively low frequency (e.g., Stehly et al., 2006; Shapiro et al., 2007; Stehly et al., 2012).

Figure 1. The main geological units and station distribution in the study area. The black triangles represent station locations, the blue asterisk represents a borehole location of Shaxi Copper Mine, and the red solid line represents six profiles of AA’, BB’, CC’, DD’, EE’, and FF’, respectively. The main geological units and geographic sites include: HFB for Hefei basin, TLF for Tan-Lu fault zone, DBO for Dabie orogenic belt, LZB for Luzong volcanic basin, ZBL for Zhangbaling uplift, HF for Hefei, LJ for Luijiang, CH for Chaohu Lake, CJ for Yangtze River, NCC for North China craton, YZC for Yangtze Craton.
Because of the dispersion characteristics of surface waves, relatively long-period surface waves are more sensitive to deep structures, and thus can be used to recover the shear wave velocity structures of the crust and the uppermost mantle in different regions (e.g., Yao HJ et al., 2008; Luo YH et al., 2012; Qiao L et al., 2018). High frequency surface waves decay very fast, but they are sensitive to shallow velocity structures and, therefore, can be used to recover the shallow crust and near surface velocity structure in small areas, such as of a city, or gas storage, or a location of ore concentration (Fang HJ et al., 2015; Li C et al., 2016; Liu Y et al., 2018). The ambient noise tomography method has the advantages of convenience, safety, low cost, and high resolution, so it is widely used to explore the interior structure of the earth.

The present study utilizes continuous waveform data of a short period dense array deployed in 2015 in the Lujiang region of Anhui Province. We apply the ambient noise cross-correlation method to get the cross-correlation functions of station pairs, then retrieve the short period Rayleigh wave dispersion curves from the stacked cross-correlation functions, and invert for the fine 3-D shear wave velocity structure of the shallow crust. Finally, we discuss the characteristics of shallow crust structure in each part of the study region, particularly the characteristics and generation mechanisms of volcanic intrusive rocks in the Tan-Lu fault zone and their tectonic implications.

2. Data and Method

2.1 The Collection of Data

In order to detect the multi-scale structure of crust and the deeper part of the middle-lower Yangtze River metallogenic belt, the China Earthquake Administration and other institutions carried out the “Yangtze River experiment” with a new type of large volume air gun in the Anhui section of the Yangtze River in October of 2015 (Chen Y et al., 2017). To complement this experiment, we deployed a fan-shaped array consisting of 90 three-component short-period seismographs in an area about 80km x 70km in the southern segment of the Tan-Lu fault zone near Lujiang County. The observation instruments included 50 REFTEK130-L22E and 40 CMG-40T-1 short period seismographs. The inter-station distance was 2–8 km (Figure 1). We collected the continuous ambient noise signals about one month, from October to November of 2015, with a sampling frequency of 200 Hz.

2.2 Data Processing

We first pre-processed the data (Bensen et al., 2007). The vertical component data were cut into one-day long pieces, re-sampled to 25 Hz, and corrected for instrument response; after de-meaning, de-trending, and spectral whitening, the data were filtered into three frequency bands of 0.5–2 s, 2–5 s, and 5–10 s, and were normalized in the time domain and superimposed to obtain a normalized waveform in a wider frequency band (Zhang YY et al., 2018). Then we cross-correlated the data in the same frequency band of each day for all station pairs, and added together the cross-correlation functions of different days of the same station pair, finally obtaining the cross-correlation functions (CCFs) of that station pair in the frequency band of 0.5–10 s. Figure 2a shows the cross-correlation functions with signal-to-noise ratio (SNR) greater than 5 by taking one station as the virtual source. The slope between the red line and blue line indicates that the group velocity of surface waves is about 2–3 km/s. The amplitudes of the left and right branches of the cross-correlation functions have little difference, indicating that the distribution of noise sources is basically uniform with azimuth. We calculated the ratios of the maximum amplitudes of the positive and negative branches of the superimposed cross-correlation functions and got the relative amplitude distribution of noise sources of that station pair with azimuth. After taking all the stations as the virtual source in the calculation, the resulted noise source distribution of most station
pairs is relatively uniform (Figure 2b).

Then we adopted the method of Yao HJ et al. (2006, 2011) to extract from these cross-correlation functions the Rayleigh wave group and phase velocity dispersion curves in the period range 0.5–8 s, under the conditions that the SNR is greater than 5 and the interstation distance is greater than 2 times the wavelength. Figure 3 shows the path number of dispersion curves at different periods. The number of dispersion data reaches maximum at 3–4 s and becomes fewer when the period is greater than 5 s and less than 2 s.

2.3 Inversion Method

We used the direct inversion method of surface wave travel times based on ray tracing (Fang HJ et al., 2015, Fang HJ and Zhang HJ, 2014) to invert for the 3-D shear wave velocity structure of shallow crust in the Luijiang array area. This method bypasses the inversion of 2-D group and phase velocity distributions of various periods and is able to consider the effect on the surface wave tomography of ray bending in a complex medium. For the forward calculation, this method adopts the fast marching technique to calculate travel times and ray paths of the surface waves of various periods (Rawlinson and Sambridge, 2004).

In the iterative inversion, we jointly used all the observed group and phase travel times of the surface waves of different paths and frequencies and obtained the 3D shear wave velocity structure of the study region; in the inversion the density and P-wave velocity are derived from the shear velocity by empirical formulas (Brocher, 2005); for the detailed inversion method and procedure see Fang HJ et al. (2015) and Li C et al. (2016).

Because the Rayleigh wave phase velocity is mostly sensitive to the shear wave structure at the depth about 1/3 of the wavelength, we calculated the average shear wave velocity at the approximate depth corresponding to each period based on the phase velocity dispersion curve, and by interpolation we obtained a 1-D initial model for inversion (Fang HJ et al., 2015). In the initial model there are 18 grid nodes in the NS and EW directions, respectively, and the grid interval is 0.05°; in the depth direction there are 29 nodes, the interval is 0.2 km from 0 to 4 km below the surface, and 0.5 km from 4 to 8 km depth.

3. Inversion Result

3.1 Data Residual Distribution and Ray Path Distribution

After inversion the standard deviation of the surface wave travel time residuals decreases from 2 s to 1.2 s (Figure 4a), and the average value of the residuals is also reduced from the initial 0.81 s to 0.009 s; the more concentrated distribution of the residuals (Figure 4b) indicates that the model is quite well constrained by the data. We calculated the depth sensitive kernels below the central grid for the group (Figure 5a) and phase (Figure 5b) velocities of three different periods of 1 s, 3 s, and 5 s. The number of dispersion curves reaches its maximum between 3 s and 4 s, and the most sensitive depth corresponding to 3 s is approximately 3 km. Therefore, we can roughly infer that the resolution is best at a depth of about 3 km. Figure 6 shows the ray path distribution of Rayleigh wave phase velocity measurements at the periods of 1 s, 3 s, 5 s, and 8 s. In the inversion of this study we used both group and phase velocity data. For extracting the phase velocities in the high-frequency band, the group velocities were taken as reference. Therefore, the group and phase velocity data basically overlap in the period band, so their ray path distributions are also similar. Because the structure in the study region is quite complex, the velocity varies rapidly, so the ray paths are obviously bent (Figure 6). Furthermore, it can be seen that in the northern part of the array, which is close to the Hefei Basin with tremendously thick sediments, the seismic waves are strongly attenuated; short period surface wave signals (e.g., 1 s) of relatively high SNR cannot be retrieved at many stations, therefore the dispersion data in this area are fewer. Near the Dabie orogeny in the southwest, however, the bedrock is outcropped, the medium is of high strength and low attenuation, and the short period surface wave signals are relatively strong, resulting in a large number of dispersion data.

3.2 3-D Shear Wave Velocity Structure

We carried out the joint inversion of all group and phase velocity dispersion data and obtained the 3-D shear wave velocity structure of the shallow crust from surface to 8 km depth. Figure 7 shows the shear wave velocity structures at four depths: 1 km, 2 km, 3 km, and 5 km; Figure 8 shows the shear wave velocity structures along 6 vertical profiles marked in Figure 1. The tomo-
The structure in entire region is quite complex; the lateral variation of shear wave velocity exceeds 50%, leading to obvious bending of short period surface wave ray paths (Figure 6). The profiles in Figure 8b coincide basically with the profiles derived from the first arrival travel time tomographic study by Liu ZD et al. (2012). The two results also confirm each other: from west to east the velocity varies as high−low−high−low, and the high velocity anomaly displays an upwelling shape, indicative of the volcanic intrusive rock body.

### 3.3 Model Recovery Test and Travel Time Error Estimation

In order to test the capability of the data to recover the model, we used the result model to generate theoretical travel time data. Because the phase velocity dispersion error caused by the non-uniform distribution of noise sources is generally about 1% (Yao HJ and van der Hilst, 2009), we added 2% random errors to the theoretical travel time data. After inversion we obtained the results shown in Figure 7(e, f) and Figure 8(g, h). Comparing with Figure 7(a, b) and Figure 8(a, b), we observe that the major structural bodies in the original models are basically recovered, indicating that the 3-D velocity model obtained in this study is reliable.

Because unevenness of noise source distribution may cause errors in travel time measurements, we adopted the method of Fro-
The travel time error caused by an uneven source distribution can be expressed by Fourier expansion as \( \delta t = B_0 + B_1 \cos \theta + B_2 \cos 2\theta + B_3 \cos 3\theta + \ldots \)

The travel time error caused by an uneven source distribution can be written as \( \delta t = \frac{\theta^* (0)}{2t_\omega^2 B(0)} \) for the positive correlation time part and \( \delta t = \frac{\theta^* (180)}{2t_\omega^2 B(180)} \) for the negative correlation time part, where \( \delta t \) is travel time error, \( t \) is reference time, and \( \omega \) is angular frequency.

According to the above formula, the higher the frequency or the longer the travel time, the smaller the travel time error. We calculated the average value and the standard deviation of the relative travel time errors along all the paths at period 4 s. The result indicates that both are within 1.5%, which is far smaller than the velocity anomalies (above 30%), suggesting that the travel time error caused by uneven noise source distribution can be neglected in the inversion.

4. Discussion

Remarkable lateral variation is found in the shallow crustal velocity structure of the study region (Figures 7 and 8), which is characterized by a variety of distinct structural features such as orogen, fault belt, sedimentary basin, and intrusive rocks. In the following we discuss the structural and tectonic characteristics of the shallow crust in the west of the Tan-Lu fault zone, within the fault zone, and in the eastern part, respectively.

4.1 Shallow Crustal Structure in the East Margin of Dabie Orogen and Hefei Basin

The Dabie orogen in the southwestern part of the array has been a favored location for investigations of high pressure and ultrahigh pressure metamorphic rocks (Xu SF et al., 1992; Wang YS et al., 2004) since the discovery of coesite-bearing eclogite in the 1980 s (Okay et al., 1989). The lithology in this area is dominated mainly by metamorphic, some magmatic (e.g., Mesozoic granite), and ultra-high-pressure rocks (Wang YS et al., 2004). The imaging result of Huang Y et al. (2011) for the depth range 2–25 km in this area using earthquake multi-phase body wave travel time tomography, and that of Hu J et al. (2016) using air-gun source body wave travel time data, detected a high P-wave velocity structure in this area. The result of ambient noise tomography of Luo YH et al. (2012) also showed that the phase velocity and shear wave velocity in this region are high. Our result indicates that the shallow crust of this region is possessed of relatively high shear wave velocities, which increase from about 3 km/s at 1 km depth to about 4.5 km/s at 4 km depth. Our result reveals finer structural characteristics of the orogen in the shallow crust; i.e., with the increase of depth, the margin of the high velocity body extends northward, to the sedimentary basin in the north, from south of Shucheng and Lujiang in the south (Figures 7 and 8).
Figure 7. Shear wave velocity slices at the depth of (a) 1 km, (b) 2 km, (c) 3 km, and (d) 5 km after inversion; black triangles represent stations and the black lines show the main faults. In (a), CH represents Chaohu Lake, the black circles represent the location of cities (LJ for Lujiang, TC for Tongcheng, SC for Shucheng), the red triangle represents the Yefushan area, and the red pentagon represents the Shaxi area. The O, P, Q, and R in (c) represent four different regions: O for the Hefei basin, P for the Dabie orogenic belt, Q for the Yefushan area, R for the sedimentary area of Huangpi Lake and other smaller local drainage systems, and the black arrow represents the direction of the Luzong volcanic basin. (e) and (f) show the results of the model recovery test in Section 3.2 for horizontal slices at depths of 1 km and 3 km, respectively.
The Hefei Basin in the northwestern part of the study region is controlled primarily by the uplifting of the Dabie Orogen, but its eastern part is also controlled by tectonic activity of the foreland basin of the Tan-Lu fault zone. A set of continental strata with a maximum thickness of 7 km were deposited in the basin (Lu GM et al., 2002; Liu GS et al., 2006). In the profile, the closer to Chaohu Lake the thicker the sediment layer becomes. In the study area it may be thicker than 5 km (Figure 7 and Figure 8c, d). The basin has been filled by continental clastic sediments since the Jurassic. Alluvial fan facies deposits exist widely in the margin of the basin. In the Chaohu Lake direction, the basin successively received deposits of river facies, shore-shallow lake facies, and shallow-semideep lake facies. After later multiple stages of basin development and shrinkage, the sedimentary area reached its present area and shape (Liu GS et al., 2006; Li Z et al., 2001). Our result clearly exhibits the impact range of the sediments at different depths in the study area. In the shallow layer (1 km) the impact may reach to the south of Sucheng County and the north of Lujiang County. With increasing depth the sedimentary area shrinks rapidly towards the Chaohu Lake direction (e.g., Figure 7 and Figure 8a, c, d), indicating that the migration direction of sedimentation is centered in the eastern part of Hefei Basin. At the same time, this variation pattern in the low velocity area is coupled with the extension direction of a high velocity anomaly in the Dabie orogenic area in the south, indicating the area of impact of the Dabie orogen at deeper depths.

4.2 The Characteristics of Intrusive Rocks in the Tan-Lu Fault Zone

In this region the lithology of the Tan-Lu fault zone varies, leading to different velocity characteristics in different areas. There are both sedimentary clastic rocks left by fault slipping and extension, and intrusive rocks formed by magmatic activities. The intrusive rock body in the Tan-Lu fault zone is distributed mainly in the area

Figure 8. The shear wave velocity structures along six vertical cross-sections shown as the red lines in Figure 1: (a) AA’, (b) BB’, (c) CC’, (d) DD’, (e) EE’, and (f) FF’. The black upward triangle represents the orogenic belt area, the black inverted triangle represents the area of volcanic intrusive rocks, and the black dotted line represents the location of the two main faults in the Tan-Lu fault zone. (g) and (h) show the results of a model recovery test in Section 3.2 for the AA’ and BB’ cross-sections, respectively.

Li C and Yao HJ et al.: Shallow crustal structure of the Tan-Lu fault zone in Lujiang
from Yefushan in the northeast to Shaxi in the southeast of Lujiang County. In our result it is shown as a high velocity anomaly marked as region Q, and extends further southeastward and connects with the Luzong volcanic rock basin (Figures 7 and 8), indicating that the two velocity structures are continuous. There is a deep seismic reflection sounding profile near and parallel to profile AA′, and the result indicates that in the Tan-Lu fault of that area the reflection signal from Moho is weak, while to its east, beneath the northern part of Luzong Basin, the magmatic channels can be clearly seen (Gao R et al., 2010), probably indicating the source of magma and accompanying metal ores in the study region. Various mineral resources related to intrusive rock bodies in the shallowest crust of depth less than 500 m have long been exploited; the Shaxi copper mine is an example. With the development of deep geophysical prospecting, molybdenum, tungsten, and other metal ores have been found within the last several years at the depth of about 1 km near Yefushan. Without a single exception, these metal mineral resources have all been found within the high velocity anomaly bodies of intrusive magmatic rocks and extension areas identified in our result. In recent years the mining and petroleum industry departments have been very active in the Hefei Basin and its periphery, and have found that in the areas off the intrusive rock body and its extension it is almost impossible to find related mineral resources. Therefore, our imaging result may provide some guiding references for geophysical prospecting even in the deeper part.

In terms of lithology the intrusive rocks in the study area show continuity with that in the northern Luzong volcanic basin more than ten kilometers to the southeast. We collected data of a borehole in the Shaxi copper mine (red star in Figure 7a) and compared its lithological characteristics to those of the northern part of the Luzong volcanic basin. Both show that a large quantity of tuff, trachyte andesite, and basalt are mixed in breccia, sandstone, and shale (Yuan F et al., 2008; Yang SX et al., 2017). In addition, geological dating studies indicate that the strong Early Mesozoic magmatic activities in the Luzong volcanic rock basin occurred between 136–124 Ma (Zhou TF et al., 2008; Yuan F et al., 2008; Tang JF et al., 2010), while according to Xie CL et al. (2008a, b) the age of the magmatic rock at the borehole of the Shaxi copper mine is between 125–93 Ma, closely related to the time of magma activity in the Luzong basin. There are also outcropped rock bodies in the southern segment of the Zhangbaling uplift to the north, in the same fault zone separated only by a lake, where the shear wave velocity is also relatively high (Gu N et al., 2019); but its lithology and age are very different from that of the intrusive rock in our study area. The southern segment of the Zhangbaling uplift is composed mainly of about 680Ma-old Neoeprotorozoic Feidong metamorphic complex rock (Zhao T et al., 2014; Zhang DB et al., 1995). The Dabie orogeny, only about ten kilometers to the southwest of this area and also with high shear wave velocity, is composed primarily of Precambrian metamorphic rocks, mixed with high pressure and ultrahigh pressure metapelitic rocks formed by the orogeny and some Yanshanian and Mesozoic magmatic rocks (Wang YS et al., 2018).

Here the intrusive magmatic rocks are outcropped in a rather special segment of the Tan-Lu fault. The Tan-Lu fault zone has experienced multi-stage tectonic activities; different areas in the fault zone exhibit different seismic activities. The Anhui segment of the Tan-Lu fault zone exhibits two main types of active fault: broken type and fault gouge type, and the activity of the former is remarkably higher than that of the latter. This segment from Tongcheng to Chaohu Lake is mainly of the broken type, containing many loose broken zones. The active fault zone is composed of multiple faults (Liu B et al., 2015). We collected data from earthquakes of magnitude 1.5 and greater that have occurred in this and neighboring areas since the 1990 s (Figure 9). The result shows that small earthquakes occurred densely around Lujiang County, indicating the characteristics of broken strata in this area. These broken faults with large pore space may provide the condition for intrusive rocks outcropping onto the surface. In addition, the near-NS compressional stress in the Mesozoic Luzong volcanic rock basin (Dong SW et al., 2009) may also have provided the possibility for the magma intruding westward into the Tan-Lu fault zone. Therefore, we infer that a part of the magmas originated in the northern part of Luzong volcanic rock basin migrated upward along the broken faults and intruded into the Tan-Lu fault zone, and outcropped on the broken strata. After multi-stage compression and extension of the fault zone, these processes have created the present intrusive rock distribution in this region.

The Luzong volcanic rock basin is generally considered to be controlled by the rift-depression in the middle-lower Yangtze River. Therefore, we infer that the intrusive rock bodies in the Tan-Lu fault zone are closely related, in terms of stress and source material, to the Luzong volcanic rock basin to its southeast in the middle-lower Yangtze River fault zone. These intrusive rocks came or partly came from the Luzong volcanic rock basin, and are connected with the Luzong volcanic rock basin at depths. These relations are the specific manifestation of large area plate motion in a small-scale region. From Late Cretaceous to Early Tertiary the Tan-Lu fault zone was in a period of extensional activity (Xu JW and Zhu G, 1994; Zhu G et al., 1995; Xu JW et al., 1995; Zhu G et al., 2004), which was also the time of volcanic intrusive rock development in our study area. The extension of the Tan-Lu fault zone in this time period was mainly controlled by the rapid high-angle subduction of the paleo-Pacific plate in the east beneath the East Asia continent (Engebretson et al., 1985). Such subduction and plate retreat facilitated asthenosphere upwelling beneath the Tan-Lu fault and surrounding areas, further leading to the extensional activities in the fault zone (Zhu G et al., 2001). Many extensional basins appeared in the fault zone, and the faults in the zone became more broken. This time was the late stage of development of the Luzong volcanic rock basin, the magma intruded through the broken faults into the Tan-Lu fault zone, and outcropped on the surface. Finally, since the Late Tertiary the westward compression caused by the back-arc spreading of the west Pacific plate turned the Tan-Lu fault zone to the reverse type, and the large-scale magmatic activity in the fault zone basically disappeared (Zhu G et al., 2001).

5. Conclusions
Based on the continuous waveform data of the Lujiang array in Anhui Province, we used the direct surface wave tomography...
method to determine a 3-D shear wave velocity model of the shallow crust in the depth range of 0–5 km for the Lujiang segment of the Tan-Lu fault zone and its neighboring areas. The result reveals the spatial distribution of some anomalous structures, including the low-velocity Hefei Basin and nearby sedimentary areas, and the junction of the high-velocity eastern margin of the Dabie orogen with the intrusive rocks in the Tan-Lu fault zone, which correlates with the geology and landform of the area. The result shows that the sedimentation center of Hefei Basin is toward Chaohu Lake. The high velocity rock distribution in the shallow crust is in the eastern margin of the Dabie orogen. We also reveal the structural characteristics of the deep connection of the intrusive rocks in the Tan-Lu fault zone with the Luzong volcanic rock basin to its southeast. These intrusive rocks have come partly from the magma in the Luzong volcanic rock basin, which upwelled along broken faults due to the extension of the Tan-Lu fault zone and by the aid of stress inside the Luzong basin, and finally cooled and outcropped on the surface, providing a possible explanation of the rich mineral resources in the south area of the Tan-Lu fault zone, and thus a possible guide for deep resources prospecting. This may also imply that the Tan-Lu fault zone and the middle-lower Yangtze River fault-depression zone are closely related in terms of stress and source material. In the meantime, this model also provides a relatively precise 3-D velocity model for the calculation of earthquake strong motion in this area.

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