Shallow crustal velocity structures revealed by active source tomography and fault activities of the Mianning-Xichang segment of the Anninghe fault zone, SW China

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Abstract The Anninghe fault is a large left-lateral strike-slip fault in southwestern China. It has controlled the deposition and magmatic activities since the Proterozoic, and has frequent seismic activities. The Mianning-Xichang segment of the Anninghe fault is a seismic gap and has been locked with high stress. Many studies suggest that this segment has a great potential for large earthquakes (magnitude>7). We obtained three vertical profiles of the Anninghe fault (between Mianning and Xichang) based on inversion of P-wave first arrival times. The travel time data were picked from seismograms generated by Methane Gaseous Source and recorded by three linearly distributed across-fault dense arrays. The inversion results show that the P-wave velocity structures at depths of 0-2 km corresponds well with the local lithology. The Quaternary sediments have low seismic velocities, while the igneous rocks, metamorphic rocks and bedrocks have high seismic velocities. Then we further discuss the fault activities of the two fault branches of Anninghe fault in the study region based on the small earthquakes (magnitude between $M_L$ 0.5 and $M_L$ 2.5) detected by the Xichang array. The eastern fault branch is more active than the western branch, and the fault activities in the eastern branch are different on the northern and southern segments at the border of 28°21'N. The obtained high-resolution models are essential for future earthquake rupture simulation and hazard assessment of the Anninghe fault zone. Future studies of velocity models at deeper depths may further explain the complex fault activities in the study region.

Keywords
Anninghe fault zone; shallow crust; P-wave velocity; Methane Gaseous Source; fault activity
1 Introduction

Southwestern China has a complex fault system and is an active region with strong seismic activities (Figure 1a). The crustal movement in southwestern China shows a clockwise pattern due to the eastward extrusion of crustal materials from the Tibetan plateau (King et al., 1997; Chen et al., 2000; Zhang et al., 2004). The Xianshuihe-Anninghe-Zemuhe-Xiaojiang fault system forms the eastern boundary of the clockwise rotation (Xu et al., 2007), and behaves as a huge left-lateral strike-slip active fault system (Wang et al., 1998a; Wen et al., 2008b; Zhu et al., 2016). It is not only a seismic belt with lots of devastating earthquakes, but also a gradient belt of gravity variation and crustal thickness (Zhang, 2008).

The fault zone structure may reflect the localization of strain, the triggering of earthquakes, and the mechanics of earthquake rupture (Cochran et al., 2009; Weng et al., 2016). Many studies have been carried out in this region to investigate the fault system, including surface wave tomography (e.g., Yao et al., 2008; Fu et al., 2017; Zhang et al., 2020), body wave travel-time tomography (e.g., Huang et al., 2002; Wang et al., 2003; Li et al., 2006), receiver functions (e.g., Xu et al., 2007; Peng et al., 2017; Hu et al., 2018), and joint inversions (e.g., Liu et al., 2014; Bao et al., 2015; Liu et al., 2021). The velocity structures can not only reveal the complicated characteristics of the fault system, but also provide information of the block motion distributions, rock differences, and tectonic features. However, due to the limited resolution, it is difficult to distinguish the local characteristics and the small-scale sharp velocity variations across the major faults from regional studies.

Tomography using spatially dense arrays can significantly improve the resolution of fault zones. Bleibinhaus et al. (2007) obtained highly resolved images of the upper 5 km of the crust across the San Andreas Fault which constrained the top of the Salinian granite with great detail using the explosive shots data from a dense array. Cochran et
al. (2009) found seismic velocities reduced by 40%–50% and shear moduli reduced by 65% compared to wall rock in a 1.5-km-wide zone along the Calico fault using the data from a dense array adjacent to fault. Li et al. (2020) revealed the high-speed intrusive rocks at shallow crust in the Tan-Lu fault zone in Lujiang, Anhui Province using dense array ambient noise tomography. Yang et al. (2020, 2021) found that there was a low-velocity zone within the southern array of the Chenghai fault, Yunnan, but no such signature in the northern array using the data of the two dense linear arrays across the fault. These high-resolution fault zone images provide an important basis for earthquake rupture simulation and hazard assessment (e.g., Weng et al., 2016; Yang et al., 2021).

Our study area is located on the active segment of the Anninghe fault zone, between Mianning and Xichang (Figure 1a). Since the Late Pleistocene, the fault became strongly active to the north of Xichang (Wang et al., 1998a, 1998b; Ren et al., 2018). The slip rate of the Mianning-Xichang segment is approximately 6.5 mm/yr (Papadimitriou et al., 2004). It is a transition area for Moho where sharp dip tends to be gently (Chen et al., 1984). The local maximums of the Bouguer gravity and aeromagnetic anomalies are located to the west side of the fault (Pei et al., 1985; Wen, 2000). The fault consists of two nearly parallel branches in this segment (Figure 1b.: F1 and F2 represent the western and eastern branch, respectively). Between the two branches lies a hill. The Anninghe valley is located to the west of the western branch (Figure 1b).

The Mianning-Xichang segment used to be an area with strong earthquake hazard. There were five earthquakes with magnitude larger than 6.0 occurred in the Anninghe fault region since the 6th century AD, and four of them nucleated in the Mianning-Xichang segment (Qian et al., 1990). This segment is also thought to be a risky area with great potential seismic hazards (Chen et al., 1984; Wen, 2000; Yi et al., 2004; Wen et al., 2008a; Cheng et al., 2010). It is located in the middle of the Anninghe seismic gap (Wen et al., 2008a) and has been locked with high stress (Yi et al., 2004). It is
speculated that the segment would have reached pre-rupture stress levels of their preceding ruptures (Luo et al., 2018). The probable maximum magnitude of the potential earthquakes is estimated to be 7.0-7.5 (Yi et al., 2004; Wen et al., 2008a). Such a risk should be taken seriously. Local structure of fault zone holds information for rupture dynamics and earthquake physics, and is also critical for better seismic hazard preparation (Yang et al., 2021). Therefore, high-resolution imaging of this fault segment is demanded.

We deployed three 8 km long linear arrays across the Mianning-Xichang segment of Anninghe fault with station spacing of 50-100 m (Figure 1b). Then we obtained three P-wave velocity profiles at depth of 0-2 km using the P-wave first arrivals picked from waveforms generated by the Methane Gaseous Source (MGS). The velocity structures have great correlation with the local lithology. Then we further discuss the fault activities of the two branches based on the small earthquakes with magnitude between 0.5 and 2.5 detected by the Xichang array in the study region.

2 Dense Arrays and Active Source Data

The dense seismographs (Figure 1b, black triangles) and the MGSs (Figure 1b, red stars) are distributed along three nearly east-west orientated lines across the two fault branches. From north to south, Line 1 contains 129 short-period seismographs and 10 shots, Line 2 contains 88 seismographs and 10 shots, and Line 3 contains 88 seismographs and 9 shots. The station spacing is about 50-100 m, and the shot spacing is about 0.5-1 km.

The MGSs used in this study were excited in January 2020. The MGS is an environmentally protective active source. Active source tomography has great advantages compared with passive source tomography methods (i.e., using the seismic waveforms generated by earthquakes or ambient noise). It does not depend on the occurrence and distribution of earthquakes and the location and excitation time of the active sources are accurate. Therefore, active sources such as explosions (e.g., Teves-
Costa et al., 1996; Catchings et al., 2002; Cochran et al., 2009) and airguns (e.g., She et al., 2018; Shao et al., 2021; Yang et al., 2021) have been widely used in shallow velocity structure studies in recent years. The MGS experiments in the Tibetan Plateau (Ji et al., 2021) show that the frequency range of the seismic energy is 1–50 Hz, with the dominant range in 5–30 Hz. The generated seismic wave can propagate up to 6.5 km from the source (Ji et al., 2021).

We collected the seismic waveforms from all the 305 seismographs generated by the 29 shots. All records were band-pass filtered to 5–30 Hz. And the bad records were removed. Then we picked the first arrivals manually (Figure 2a, red dots). The excitation time of each shot was calibrated with the first arrivals of the closest seismographs on its western and eastern sides. Then the travel times were calculated by subtracting the excitation times from the first arrivals (Figure 2b). Finally, we obtained 453 travel times for Line 1, 557 travel times for Line 2, and 479 travel times for Line 3. The travel time curves are shown in Figure 3.

When the epicentral distance is less than 1 km, the seismic waves almost propagate along the surface. We obtained the P-wave velocities in the near surface in Line 1 and Line 2 through the linear fit of the travel times on both sides of each shot (Figure 2b and Figure 4). On one hand, the results can better reveal the velocity structures on the surface. On the other hand, they can be used to mutually verify the inversion results. We did not calculate the surface P-wave velocities in Line 3, because the seismographs installed there were not distributed in a straight line, which would lead to relatively large errors in the linear fit of travel times.

3 Tomographic Method

We performed independent inversions for the three lines in 3-D rectangular coordinate systems with travel times using the double-difference tomography method (Zhang and Thurber, 2003, 2006). The method combines the differential and absolute arrival times to determine the hypocenters and velocity structures simultaneously. Since
the locations of the shots in each line are not close enough, the requirement of the
differential time (i.e., the ray paths of the event pairs to a common station need to be
almost identical) is not satisfied, we only used absolute arrival times in the inversions.
The initial models for inversions of each line are layered 1-D P-wave velocity models
(Tables 1-3). They were derived from the shallow crustal S-wave velocity obtained
from the surface wave ambient noise tomography of Line 1.

For each line, we designed a cubic model. The horizontal grid size is 1 km. There are
11 grid nodes on the $X$-axis, distributed from $X = -5$ km to $X = 5$ km, and 3 grid nodes
on the $Y$-axis at -1, 0, and 1 km. The vertical grid size for all the 3 lines are 0.5 km (Line
1), 0.4 km (Line 2), and 0.5 km (Line 3), respectively. The grid nodes on the $X$- and $Z$-
axes are shown in Figure 5. The negative values on the $Z$-axis mean that they are above
the sea level. In Line 1 and Line 2, the stations are almost distributed in straight lines.
The $X$-axes in these two lines are parallel to the distributions of stations, and $Y = 0$ km
coincide with the station locations. In Line 3, the $X$-axis is set parallel to the linear fit
of the station locations, and $Y = 0$ km also coincides with this line. The coordinate
system of Line 1 rotates clockwise 2.22° with its center located at
$(28.476°N,102.206°E)$. The coordinate system of Line 2 rotates anticlockwise 4.35°
with its center located at $(28.376°N,102.189°E)$. The coordinate system of Line 3
rotates anticlockwise 0.64° with its center located at $(28.156°N,102.195°E)$.

Since the shots and stations are almost distributed along straight lines, most seismic
rays propagate within the profiles. However, seismic rays tend to travel along the
shortest paths and avoid the low-velocity area. If the P-wave velocity becomes lower at
$Y = 0$ km compared with $Y = 1$ km and $Y = -1$ km, the ray paths may deviate from the
profile. Therefore, we copy the velocity value in each node of $Y = 0$ km to $Y = 1$ km
and $Y = -1$ km after each iteration.

4 Inversion Results

We first conducted checkerboard resolution tests for each line to test the model
resolution with the current data distribution and inversion grid. The checkerboard models were built by adding perturbations to the initial 1-D velocity model (Table 1-3). The perturbation at each node has the same absolute value (5%) and is distributed in the sequence of positive and negative change. We calculated the theoretical travel times with the real distributions of stations and shots with the true checkerboard models first. Then we performed inversions over the same 3-D coordinate system as in the inversions of the real data. The recovered models of different lines are shown in Figure 5. The checkerboard models are relatively well-recovered in the middle region (outlined by red lines and red dots). The horizontal resolution of all the three lines is 1 km. The vertical resolution of Line 1 and Line 3 is 0.5 km and that of the Line 2 is 0.4 km.

The changes in the root-mean-square (RMS) residual of the travel times in the inversion of each line are shown in Figure 6. The inverted results are shown in Figures 7-9. The highest altitude of stations in each line are set to zero value on the Z-axis to translate topography to depth. For Line 1 (Figures 7b and 7c), the highest altitude is 2.4235 km. For Line 2 (Figures 8b and 8c), it is 1.9970 km. For Line 3 (Figures 9b and 9c), it is 1.9670 km. Regions that are not well recovered are cut-off based on the checkerboard resolution test. The perturbations (Figures 7c, 8c, and 9c) are obtained by subtracting the initial 1-D velocities (Tables 1-3) from inversion results (Figures 7b, 8b, and 9b) and can better reflect the distributions of high- and low-velocity anomalies.

In all three lines, remarkable low-velocity anomalies are observed to the west of F1, which is caused by the sediments in the Anninghe valley. The vertical profile of Line 1 has a layered P-wave velocity structure (Figures 7b and 7c). The interface of the low- and high-velocity anomalies becomes shallower from left (west) to right (east). There are two high-velocity anomalies. One is located to the west of $X = -3.5$ km and the other is located between the $X = -0.5$ km and $X = 0.5$ km near the surface. In Line 2, high-velocity anomalies are distributed to the west of $X = -1$ km and to the east of $X = 2$ km (Figure 8b and 8c). The P-wave velocity can reach 6 km/s in the high-velocity anomaly to the west of $X = -1$ km. In Line 3, low-velocity anomalies are located to the west of
F1 and to the east of F2 (Figures 9b and 9c). The P-wave velocity is relatively low at depths of 0-1 km and relatively high at depths of 1-2 km beneath F1. Between the two fault branches, there is a high-velocity anomaly at depths of 0-1 km and a low-velocity anomaly at depths of 1-2 km. There are two high-velocity anomalies located to the west of $X = -3$ km and to the east of $X = 3$ km.

To further validate the reliability of the inversion results, we compare the inversion results with the P-wave velocities on the surface obtained from the linear fit of first arrival times at shorter propagation distances (Figure 4). In Line 1, the P-wave velocity near the surface does not show large variations except for the region between the two branches. The velocity between $X = -1.5$ km and $X = -0.5$ km is relatively low and it is relatively high between $X = -0.5$ km and $X = 0.5$ km (Figures 7b and 7c). Shots B05 and B06 are located very close to F1 and F2, respectively. The velocity obtained from linear fit to the east of the B05 is lower, and that to the west of the B06 is higher (Figure 4), which coincides well with the inversion results. In other regions, the velocity obtained from the linear fit does not vary greatly either. In Line 2, the inversion results (Figures 8b and 8c) show that the P-wave velocity does not change much to the west of B23 except for the velocity is slightly lower to the east of B22. The lowest velocity locates between B24 and B26, then it increases to the east of B26. The velocity becomes lower again to the west of B27 and increases gradually to the east of B27. This pattern also coincides well with the velocities obtained from the linear fit (Figure 4). The consistency of the results obtained from these two different methods indicates that our inversion results are reliable.

5 Discussion

5.1 Velocity Structure and its Correlation with Local Lithology

The three profiles are only approximately 8 km at length and 2 km at depth, while the inversion results show great vertical and lateral P-wave velocity variations, from approximately 2 km/s to 6.5 km/s. The variations have close relationships with the
complex lithology in the fault fracture zones.

The Anninghe fault zone has a long geological evolution history. It has controlled the deposition and magmatic activities since the Proterozoic (Wang et al., 1998b; He et al., 2007). Therefore, magmatic rocks, metamorphic rocks and sedimentary rocks at different periods can be found (Figure 7d). The Anninghe fault was a rift and grew wider in the Proterozoic, which provided pathways for magma intrusions. Proterozoic metamorphic rocks are distributed on both sides of the Anninghe River (Chang and Huang, 2014). In the Late Paleozoic, the fault became more active and mafic-ultramafic rocks intruded along the fault. Metamorphism occurred together with the magma intrusion. In the Mesozoic, many faulted basins were formed. Mesozoic and Cenozoic strata were deposited in some large basins. The fault activities are strong in the Cenozoic and the Anninghe fault system is completely formed (Chang and Huang, 2014).

The velocity models of the Mianning-Xichang segment in our results show good correlation with the geological structures (Figures 7-9). The noticeable low-velocity anomalies in the profiles are distributed to the west of F1, beneath the Anninghe valley, where a thick layer of the Quaternary sediments is covered. The large-scale high-velocity anomalies are caused by igneous rocks, metamorphic rocks, and bedrocks. Other velocity anomalies also correlate well with the lithologic variations.

In Line 1 (Figure 7), the seismic line is almost all covered with the Quaternary sediments, except for the region to the west of F2, which are mostly composed of bedrocks. The depth of the interface of the low- and high-velocity anomalies may reflect the thickness of the sediments. It becomes shallower to the east of $X = -1$ km, which may indicate that the sediment layer becomes thinner from west to east.

In Line 2 (Figures 8), the seismic line crosses the Indosinian igneous rocks, Quaternary sediments, Neogene rocks, and Quaternary sediments from west to east (left to right in the profile). The high-velocity anomaly to the west of $X = -1$ km is caused by the Indosinian igneous rocks. The low-velocity anomaly between $X = -1$ km and $X$
= 1 km is caused by the Quaternary sediments. To the east of F2, there is a narrow area covered with the Neogene rocks, which is mainly composed of siltstone and claystone (Luo, 2019). Their physical and mechanical properties are between sediments and rocks. Therefore, the P-wave velocity becomes a little higher between $X = 1$ km and $X = 2$ km. To the east of $X = 2$ km, the low-velocity anomaly near the surface is caused by the Quaternary sediments, and the high-velocity anomaly beneath it may reflect the bedrocks.

In Line 3 (Figures 9), the seismic line crosses gneiss, Quaternary sediments, Triassic rocks, Sinian rocks, Triassic rocks, Quaternary sediments, and Sinian rocks from west to east (left to right in the profile). The seismic velocity of the gneiss is higher than sedimentary rocks, which is reflected by the high-velocity anomaly to the west of $X = -3$ km. The Sinian rocks are mainly composed of ignimbrite (Luo, 2019). Their seismic velocities are relatively higher, which is reflected by the high-velocity anomalies between $X = 1$ km and $X = 2$ km, and to the east of $X = 3$ km. The Triassic rocks are mainly composed of sandstone, siltstone, and mudstone (Luo, 2019). Their seismic velocities are lower than the Sinian rocks.

The shallow crust is characterized by very slow P-wave velocity around the Anninghe fault zone due to existence of Quaternary sediments. Weng et al. (2016) found the fault damage zone, which is characterized by strong low velocity anomalies, can promote rupture extent and increase earthquake hazards. Therefore, our high-resolution images can provide an important basis for future simulation of earthquake rupture and assessment of earthquake hazards of the Anninghe fault zone and surrounding areas.

5.2 Fault activities

The Anninghe fault consists of two left-lateral strike-slip fault branches (F1 and F2) in the study region (He et al., 2007; Hu et al., 2021). However, there are no obvious velocity changes beneath the two branches (Figures 7-9), which indicates that the velocity structure at shallow depths is mainly determined by the lithology in the study
In fact, the two branches have large differences. The western branch (F1) has a thrust component and the eastern branch (F2) has a normal component (He et al., 2007; Hu et al., 2021). And the eastern branch is more active than the western branch since the Late Pleistocene (Xu et al., 1987; Qian et al., 1992; He et al., 2007). The scanning electron microscope (SEM) images of the micro-surface textures on quartz fragments shows that recent fault activities of the western branch mostly concentrate in the early and middle Pleistocene while the eastern branch is still active in the Late Pleistocene and Holocene (Xu et al., 1987).

The distribution of earthquakes reflects the fault activities. The distributions of small earthquakes with magnitude between 0.5 and 2.5 detected by the Xichang seismic array (Figures 1b and 1c) show that most earthquakes occurred to the east of the eastern branch. There are only a few earthquakes between the two branches, and almost no earthquakes to the west of the western branch (Figure 1b). It indicates that the eastern branch is still more active than the western branch at present. In the vertical section (Figure 1c), the depths of the hypocenters are mostly less than 10 km to the north of 28°21′N, while it is greater than 10 km to the south of 28°21′N. It indicates that the fault activities along the active branch (the eastern branch) vary greatly in the north-south direction.

For the different fault activities in the two branches, it is speculated that the eastern branch became part of the eastern border of the Sichuan-Yunnan block together with the Xianshuihe, Zemuhe, and Xiaojiang faults since the late Pleistocene, while the western branch was no longer a boundary fault and the fault activity declined (Qian et al., 1992; Wang et al., 1998b). The eastern branch consists of a series of secondary fractures in the study region. Two of them connect near 28°21′N (Figure 1b), which may be the reason for the different focal depths on the northern and southern segments at the border of 28°21′N. Geological and geophysical studies also reveal that the central Anninghe fault zone near Mianning is an important border for earthquake
rupture (Wen, 2000).

Since our active source tomography only reveals the shallow crustal velocity structures of the Anninghe fault zone while the local earthquakes most occur at depths greater than 5km, further tomographic studies are needed to reveal high-resolution velocity structures at deeper depths in this region, which may reveal the deep fault structures and their correlation with fault activities and distribution of earthquakes.

6 Conclusions

We obtained three high-resolution P-wave velocity profiles of the Anninghe fault zone between Mianning and Xichang in this paper from Methane Gaseous Sources. The inversion results show that the velocity structures at depths of 0-2 km in the study region are mainly determined by the local lithology. The Quaternary sediments have low seismic velocities, while the igneous rocks, metamorphic rocks and bedrocks have high seismic velocities. The fault activities are complex in the study region. The eastern branch is more active than the western branch. Moreover, the eastern branch itself has different activities on the northern and southern segments at the border of 28°21′N. Our high-resolution tomographic images provide an important basis for future simulation of earthquake rupture and assessment of earthquake hazards of the Anninghe fault zone. Further study of our project is aiming to obtain the velocity structures at deeper depths, which may reveal the fault structures and explain the different strengths of fault activities.

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References


Hu, M., Wu, Z., Li, J., Zhang, K., Reichert, K., Bi, W., 2021. Late Quaternary left-lateral strike slip rate along the Anninghe–Zemuhe Section of the Xianshuihe–Xiaojiang Fault System and its implication to the clockwise block rotation of the SE margin of the Tibetan Plateau. Geochemistry, Geophysics, Geosystems. doi: 10.1002/essoar.10505860.2


segment of the Anninghe fault and their significance to seismological research (in
Chinese with English abstract). Earthquake Research in China, 6, 43-49.
Qian, H., Tang, R., Wen, D., Huang, Z., 1992. Research on the recent surficial faulting
on the northern segment of the Anninghe fault zone and earthquake potential (in
Ren, Y., Lu, J., Li, G., Ji, P., 2018. Analysis of the extension direction of Anning River
isotropic and anisotropic shallow crustal structure on Pingtan Island, Fujian,
southeastern coast of China. Physics of the Earth and Planetary Interiors, 310. doi:
10.1016/j.pepi.2020.106620
She, Y., Yao, H., Zhai, Q., Wang, F., Tian, X., 2018. Shallow crustal structure of the
middle-lower Yangtze River region in eastern China from surface-wave
tomography of a large volume airgun-shot experiment. Seismological Research
Letters 89, 1003–1013. DOI: 10.1785/0220170232
activity on the north segment of the Anninghe fracture zone since Late Pleistocene
models in the Lisbon area from explosion data using body and surface wave
analysis. Tectonophysics, 258, 171–193. https://doi.org/10.1016/0040-
1951(95)00194-8.
Wang, C., Chan, W. W., Monney, W. D., 2003. Three-dimensional velocity structure of
crust and upper mantle in southwestern China and its tectonic implications. Journal
Wang, X., Zhang, C., Pei, X., 1998b. Structural activity and evolution since the Late


Figures

Figure 1

Figure 1 Regional map of the southwestern China. (a) Map of topography, major faults, and seismicity in southwestern China. Gray dots show earthquakes from 1970 to 2012 with magnitude larger than 3.0. Dashed blue lines represent the major block boundaries from Zhang et al. (2020). SPGZ, Songpan-Ganzi Block; LB, Lhasa Block; SCB, Sichuan Basin; YZC, Yangtze Craton. Black lines show the main faults in southwestern China (Zhang et al., 2020). LTF, Litang fault; ZDF, Zhongdian fault; LJ-XJHF, Lijiang-Xiaojinhe fault; CHF, Chenghai fault; RRF, Red River fault; ANHF, Anninghe fault; ZMHF, Zemuhe fault; LZJF, Luzhijiang fault; LMSF, Longmenshan fault; DLSF,
Daliangshan fault; XJF, Xiaojiang fault. The red box indicates the study region in this paper. The two black dots near the red box are locations of Mianning and Xichang. (b) Map of the study region with topography. Red stars represent shots and black dots represent stations. Black lines show the two branches of the Anninghe fault. F1 and F2 represent the western and eastern branch, respectively. Black circles represent earthquakes with magnitude between $M_L$ 0.5 and $M_L$ 2.5 (from January 13, 2013 to January 28, 2019) detected by the Xichang seismic array. (c) Map of the depths of the earthquakes in (b). The legend for seismicity in (b) and (c) is presented on the right side.
Figure 2

An example from one shot (ID: B06). (a) Waveforms band-pass filtered to 5-30 Hz. Red dots show the picked first arrivals. (b) Travel times of P-wave first arrivals. The two black lines show the linear fit between the epicentral distance and travel times in both the forward (positive distance) and backward (negative distance) directions, with the P-wave velocities obtained from the linear fit indicated above (forward) and below (backward), respectively.
Figure 3 Travel time curves of Line 1 (a), Line 2 (b), and Line 3 (c), respectively.
Figure 4

Figure 4 P-wave velocities obtained from the linear fit of Lines 1 and 2. Red stars represent shots and black dots represent stations. Shots ID are above the red stars. The direction of the arrow shows the propagation directions of seismic wave, and its length shows the distance of the linear fit. The values above and below the arrows indicate the P-wave velocities (km/s) obtained from the linear fit as shown in Figure 2b.
Figure 5 Recovered velocity checkerboard patterns of Line 1 (a), Line 2 (b), and Line 3 (c), respectively, with locations of the shots (yellow stars) and stations (red dots). Red lines and red dots depict the regions with reasonably good recovery, which are further used as the clipping areas for Figure 7-9.
Figure 6

Figure 6 The root-mean-square (RMS) values of the output models after each inversion iteration for Line 1 (a), Line 2 (b), and Line 3 (c), respectively.
Figure 7

Figure 7 (a) Geological map near Line 1 (rotate 2.22° anticlockwise from (d)). Red stars represent active shots and black dots represent stations. Black lines show the two branches of the Anninghe fault. (b) P-wave velocity model of Line 1. (c) P-wave velocity perturbation model of Line 1. The reference model of the perturbation model is shown in Table 1. Black stars in (b) and (c) show the location of shots. The ID of the shots are above the box in (b) and (c). (d) Geological map of the study region with lithology. Red stars represent active shots and black dots represent stations. Black lines show the two branches of the Anninghe fault. F1 and F2 in (a) and (d) represent the western and eastern branch, respectively. The legends for lithology are presented on the right side. The lithology is modified after Tang et al. (1992) (north of 28°26′N) and Luo (2019) (south of 28°26′N), respectively.
Figure 8

Figure 8 (a) Geological map near Line 2 (rotate 4.35° clockwise from 7(d)). The legends for lithology are presented on the right side. (b) P-wave velocity model of Line 2. (c). P-wave velocity perturbation model of Line 2. The reference model of the perturbation model is shown in Table 2. The other labels are the same as those in Figure 7.
Figure 9 (a) Geological map near Line 3 (rotate 0.64° clockwise from 7(d)). The legends for lithology are presented on the right side. (b) P-wave velocity model of Line 3. (c) P-wave velocity perturbation model of Line 3. The reference model of the perturbation model is shown in Table 3. The other labels are the same as those in Figure 7.
Tables

Table 1

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</thead>
<tbody>
<tr>
<td>Vp (km/s)</td>
<td>3.396</td>
<td>3.636</td>
<td>4.170</td>
<td>4.723</td>
<td>5.159</td>
<td>5.479</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>-2.3</th>
<th>-1.8</th>
<th>-1.3</th>
<th>-0.8</th>
<th>-0.3</th>
<th>0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vp (km/s)</td>
<td>3.376</td>
<td>3.468</td>
<td>4.025</td>
<td>4.723</td>
<td>5.249</td>
<td>5.607</td>
</tr>
</tbody>
</table>