

High-resolution upper crustal S-wave velocity structure and seismicity distribution around the junction of the Zemuhe and Xiaojiang Fault Zones, Southwest China

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Key Points:

- Dense array ambient noise tomography reveals high-resolution upper crustal structures around the junction of the Zemuhe–Xiaojiang Fault Zone.
- Strong velocity anomalies in the Ningnan and Qiaojia Basins highlight crustal heterogeneities along major fault zones.
- Reservoir-triggered seismicity and fault-aligned microseismic event clusters indicate deep fluid migration and its impact on tectonic stress.

Citation: Liu, X., Yao, H. J., Zhao, C. P., Liu, Y., and Luo, S. (2025). High-resolution upper crustal S-wave velocity structure and seismicity distribution around the junction of the Zemuhe and Xiaojiang Fault Zones, Southwest China. *Earth Planet. Phys.*, 9(2), 225–238. <http://doi.org/10.26464/epp2025011>

Abstract: The Anninghe–Zemuhe Fault and the Xiaojiang Fault are critical active faults along the middle-eastern boundary of the South Chuan–Dian Block. Many researchers have identified these faults as potential strong-earthquake risk zones. In this study, we leveraged a dense seismic array to investigate the high-resolution shallow crust shear wave velocity (V_s) structure beneath the junction of the Zemuhe Fault Zone and the Xiaojiang Fault Zone, one of the most complex parts of the eastern boundary of the South Chuan–Dian Block. We analyzed the distribution of microseismic events detected between November 2022 and February 2023 based on the fine-scale V_s model obtained. The microseismicity in the study region was clustered into three groups, all spatially related to major faults in this region. These microseismic events indicate near-vertical fault planes, consistent with the fault geometry revealed by other researchers. Moreover, these microseismic events are influenced by the impoundment of the downstream Baihetan Reservoir and the complex tectonic stress near the junction of the Zemuhe Fault Zone and the Xiaojiang Fault Zone. The depths of these microseismic events are shallower in the junction zone, whereas moving south along the Xiaojiang Fault Zone, the microseismic events become deeper. Additionally, we compared our fine-scale local V_s model with velocity models obtained by other researchers and found that our model offers greater detail in characterizing subsurface heterogeneity while demonstrating improved reliability in delineating fault systems.

Keywords: Zemuhe–Xiaojiang Fault Zone; shallow crust; S-wave velocity; ambient noise tomography; microseismicity

1. Introduction

The eastward extrusion of crustal materials from the Tibetan Plateau has led to the clockwise movement of crustal material along the southeastern margin of the Tibetan Plateau in China (e.g., [Tapponnier et al., 1982](#); [King et al., 1997](#); [Chen Z et al., 2000](#);

[Schoenbohm et al., 2006](#); [Xu LL et al., 2007](#)), resulting in the formation of a complex fault system characterized by strong seismic activities (e.g., [Royden et al., 1997, 2008](#); [Wang Q et al., 2001](#); [Wen XZ et al., 2008](#); [Yi GX et al., 2008](#); [Wang QX et al., 2020](#)). The approximately 1100-km-long eastern boundary of the South Chuan–Dian Block, comprising the Xianshuihe Fault Zone (XSHF), the Anninghe–Zemuhe Fault Zone (AZF), and the Xiaojiang Fault Zone (XJF), represents one of the most seismically active sinistral strike-slip fault systems in mainland China ([Xu XW et al., 2003, 2005](#); [Zhang PZ, 2008, 2013](#)). In 2014 and 2017, the county of Ludian experienced two substantial earthquakes measuring M_s

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Received 23 JUL 2024; Accepted 22 NOV 2024.

First Published online 03 JAN 2025.

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6.5 and M_L 5.3, respectively, followed by the 2020 Qiaojia County M_S 5.0 earthquake, located approximately 20 km northwest of Ludian. These events resulted in substantial casualties, as documented in previous studies (Xu XW et al., 2015; Li DH et al., 2019; Fu Z et al., 2021; Song Q et al., 2022). Additionally, modern global positioning system (GPS) data and interferometric synthetic aperture radar (InSAR) data revealed a strong shear strain rate along the eastern boundary of the South Chuan–Dian Block, indicating considerable tectonic activity along the fault system (Zhang PZ et al., 2003; Wang M and Shen ZK, 2020). As shown in Figure 1a, the study region of this work, situated at the junction of the Zemuhe Fault Zone (ZMHF) and the XJF, experiences a high shear strain rate. Using GPS data and the InSAR data, Shan XJ et al. (2023) and Li YC et al. (2024) analyzed the coseismic deformation of the eastern

boundary of the South Chuan–Dian Block and pointed out that the 2022 M_S 6.8 Luding County earthquake caused Coulomb stress loading on the ZMHF and the XJF, which may lead to potential major earthquakes with magnitudes larger than 7 in those areas.

The Qiaojia Basin, centrally situated within the study area, represents a tectonically rifted Quaternary sedimentary basin characterized by distinctive terrain slicing. It is traversed by the Jinsha River, as depicted in Figure 1b. This basin takes on a northwest-trending triangular shape, broader in the north and tapering toward the south. Its eastern boundary aligns with the Xiaojiang East Fault Zone (XJEF), whereas the western boundary coincides with the ZMHF. The Xiaojiang West Fault Zone (XJWF), lying

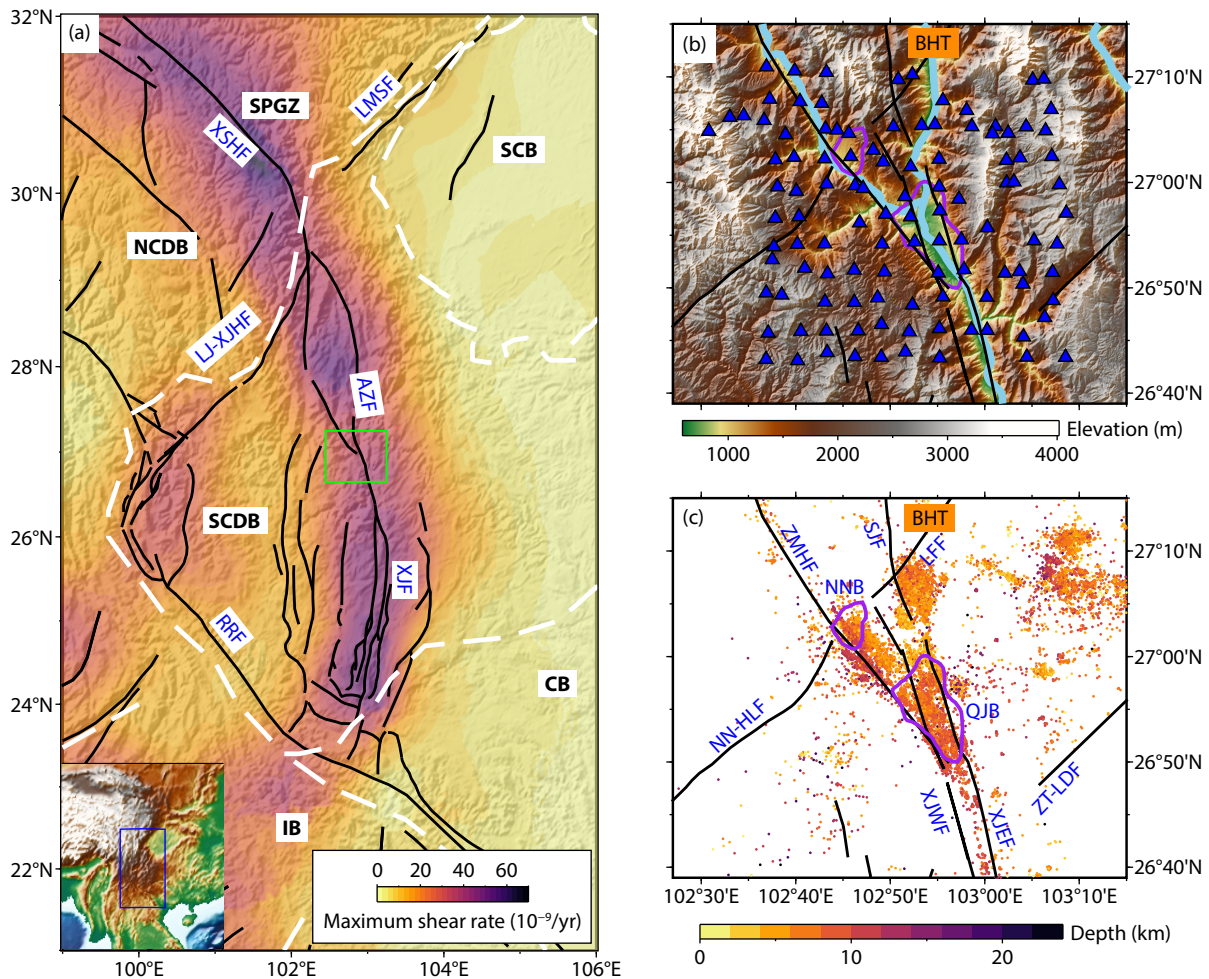


Figure 1. (a) Geological setting of the southeastern margin of the Tibetan Plateau. The green rectangle in the inset map in the bottom left corner indicates the location of the southeastern margin of the Tibetan Plateau. The background color represents the maximum shear rate (modified from Wang M and Shen ZK, 2020, and Zhang ZQ et al., 2023). The dashed white lines depict the major block boundaries, whereas the black lines represent the main faults. SPGZ, Songpan–Garzê Terrane; SCB, Sichuan Basin; NCDB, North Chuan–Dian Block; SCDB, South Chuan–Dian Block; CB, Cathaysia Block; IB, Indochina Block; LJ-XJHF, Lijiang–Xiaojinhe Fault; RRF, Red River Fault; AZF, Anninghe–Zemuhe Fault; XJF, Xiaojiang Fault. The green box denotes the study area. (b) Station map and topography of the study area. The blue triangles outlined in black mark the station distribution. The black lines indicate a more detailed fault distribution in the study area. The thick sky blue lines are the Jinsha River and the Heishui River. The purple lines depict the Qiaojia Basin (QJB) as well as the smaller Ningnan Basin (NNB). The dark orange rectangle represents the Baihetan Reservoir Dam (BHT). (c) Detailed fault information and earthquake distribution in the study area. The scattered dots represent local earthquakes detected from 2020 to 2022, with their colors indicating depth. ZMHF, Zemuhe Fault; NN-HLF, Ningnan–Huili Fault; XJWF, Xiaojiang West Fault; XJEF, Xiaojiang East Fault; ZT-LDF, Zhaotong–Ludian Fault; SJF, Sikai–Jiaojiehe Fault; LFF, Lianfeng Fault.

approximately 8 km parallel to the XJEF, intersects with the ZMHF at the southern end of the basin. Furthermore, in the study region, several other active faults are notable. Situated to the northwest of the Qiaojia Basin, the ZMHF intersects with the Ningnan–Huili Fault (NN–HLF). Moving northward from the Qiaojia Basin, the Sikai–Jiaojiehe Fault (SJF) intersects with the Lianfeng Fault (LFF). Figure 1c presents the distribution of earthquakes within this region. As a preliminary observation, the majority of earthquakes near the Qiaojia Basin exhibit spatial relationships with these faults and can be categorized into three main groups. One group clusters around the intersection of the SJF and the LFF, another group is situated around the intersection of the ZMHF and NN–HLF, and the third group is closely associated with the Qiaojia Basin, primarily located between the XJWF and the XJEF. Recent studies, such as those by Yang JQ et al. (2021) and Shan XJ et al. (2023), have highlighted the dynamic triggering effect of teleseismic events on small earthquakes around the eastern boundary of the South Chuan–Dian Block, suggesting a tendency for fault rupture and the possibility of large earthquakes. Therefore, the substantial earthquake risk posed by active fault zones in the junction of the ZMHF and XJF warrants continuous attention, underscoring the importance of further studying the seismogenic environment in this area. Moreover, many researchers have investigated the seismic activity and stress field changes in upstream areas before and after the Baihetan Reservoir impoundment (Duan MQ and Zhao CP, 2019; Zhang N et al., 2019; Guo W et al., 2022; Liu H et al., 2023). These studies have pointed out reservoir-triggered seismic activity and stress field changes, which can provide an important reference for further risk assessment of reservoir-triggered earthquakes. Accordingly, this study focuses on investigating the seismogenic environment at the junction of the ZMHF and XJF, which is located upstream of the Baihetan Reservoir.

Subsurface velocity structures provide crucial information on the deep geometry, evolution processes, and movement pattern of active faults and are important factors in determining earthquake ruptures (Lewis et al., 2005; Yang HF et al., 2020; Jiang XH et al., 2021; Luo S et al., 2021). The distribution of moderate and strong earthquakes frequently aligns with velocity anomalies, commonly referred to as earthquake asperities (Huang JL and Zhao D, 2004; Tian Y et al., 2007; Tian Y, 2008; Qu ZD et al., 2018). Hence, reliable velocity structures are critical for accurately delineating the seismogenic environment and evaluating earthquake hazards. However, various studies have proposed substantially divergent upper crustal velocity models of the study region (e.g., Yao HJ et al., 2006, 2008; Wu JP et al., 2013; Bao XW et al., 2015; Fu YY et al., 2017; Zhang ZQ et al., 2020; Liu Y et al., 2021, 2023; Deng F et al., 2022; Feng T et al., 2022; Duan MQ et al., 2023, 2024). The primary factor contributing to these discrepancies is the relatively low resolution of the models, which typically ranges from 10 to 50 km in lateral resolution and from 4 to 10 km in depth resolution. These discrepancies underscore the complexity of the geological structures and highlight the challenges researchers face in accurately characterizing seismic velocities in this area. Therefore, the development of reliable high-resolution shear wave velocity models is of paramount importance for comprehensively understanding the seismogenic environment and mechanisms, as well

as accurately predicting the risk of strong earthquakes at the junction of the ZMHF and XJF.

In recent decades, ambient noise tomography has emerged as an effective approach for investigating the three-dimensional (3-D) fine structure of fault zones (e.g., Ben-Zion et al., 2019; Li C et al., 2020; Yang HF et al., 2020, 2021; Castellanos and Clayton, 2021; Luo S et al., 2021, 2023). In this study, a dense seismic array of short-period seismometers (Figure 1b) was deployed for the first time at the junction of the ZMHF and XJF to investigate the fine-scale velocity structure of the upper crust. Nevertheless, as evidenced by previous studies, seismic waveforms recorded in valleys within the Sichuan–Yunnan region are significantly affected by teleseismic body-wave noise in the period bands of 4–8 s and 8–12 s (e.g., Wang WT et al., 2018; Luo S et al., 2023). This noise often leads to near zero-time-lag body-wave noise in the ambient noise cross-correlation functions (CCFs), which can significantly contaminate the desired surface wave signals, thus severely compromising the quality of ambient noise tomography. A mode separation method based on the high-resolution linear Radon transform (HLRT) was proposed by Luo S et al. (2023) to mitigate the interference of near zero-time-lag body-wave noise in ambient noise CCFs. Additionally, to ensure the quality of extracted dispersion data crucial for ambient noise tomography, Zhang YY et al. (2018) proposed a cluster analysis method to identify and discard dispersion curves that deviate significantly from those extracted from neighboring paths. This method has been used effectively in dense array ambient noise tomography (e.g., Jin JQ et al., 2023; Luo S et al., 2023).

In this study, we began by detailing the preprocessing procedures applied to the continuous waveform data acquired at the junction of the ZMHF and the XJF. The HLRT was used to suppress near zero-time-lag body-wave noise in CCFs, and Rayleigh wave phase velocity dispersion curves were measured by path cluster analysis to remove outliers. Subsequently, we utilized the direct surface wave tomography method, as outlined by Fang HJ et al. (2015), to derive a high-resolution 3-D upper crustal shear wave velocity structure beneath the survey region. Utilizing this high-resolution 3-D V_s structure, we analyzed the characteristics of medium structures surrounding the fault zones. Furthermore, we investigated the seismogenic environment and mechanisms of small earthquakes by examining the relationship between the velocity model and the local microseismic event distribution. Moreover, we compared our fine-scale local V_s model with the one obtained by Feng et al. (2022), highlighting its enhanced ability to detail subsurface heterogeneity.

2. Data and Method

2.1 Data Collection

In early June 2022, we deployed a dense array of seismometers in the vicinity of the Qiaojia and Ningnan Basins, specifically at the junction of the ZMHF and XJF zones. These seismometers were arranged in a quasi-regular pattern, covering an approximately square area of 70×70 km, with an average station interval of approximately 6 km. The EPS digital seismometers deployed in this array have a flat frequency response bandwidth of up to 5 s and a sampling rate of 100 Hz. The array was deployed from early

June and retrieved in mid-August 2022. As a result, we collected 109 continuous three-component seismographs with an average continuous recording duration of approximately 2 months. The distribution of the seismic stations is indicated by the blue triangles outlined in black in Figure 1b.

2.2 Data Processing

In this study, we utilized vertical-component seismic records to extract Rayleigh wave phase velocity dispersion curves. First, the raw SEED (Standard for the Exchange of Earthquake Data)-format vertical-component seismic data were reorganized into daily segments, converted to SAC (Seismic Analysis Code) format, and down-sampled to 10 Hz to efficiently reduce computational costs for subsequent procedures. We then preprocessed the down-sampled daily vertical-component data following the protocols outlined by Yao HJ et al. (2011), Zhang YY et al. (2018), and Luo S et al. (2023). This step involved traditional signal processing, such as removal of the trend, mean, and instrument response to the raw data (Bensen et al., 2007). We next performed spectral whitening for each 2-h-long segment waveform. Specifically, the data were then filtered into three frequency bands of 1–2 s, 2–5 s, and 5–10 s, and time-domain running-absolute-mean normalization was performed individually on each frequency band. The multiple-period normalization scheme effectively suppressed the influence of dominant ambient noise periods and transient earthquake waves, achieving an even spectrum to enhance weak signals (e.g., Yao HJ et al., 2011; Zhang YY et al., 2018; Li C et al., 2020). Subsequently, we cross-correlated the data in the same frequency band for each day between all possible station pairs. Finally, we linearly stacked the different daily CCFs for the same station pair, ultimately obtaining high signal-to-noise ratio (SNR) CCFs in the frequency band of 1–10 s. Figure 2a demonstrates the ambient noise CCFs between an example station and all other stations, with the example station treated as the virtual source and the CCFs plotted according to the interstation distances. However, the resulting CCFs were contaminated by near zero-time-lag signals, similar to findings reported by Wang WT et al. (2018) and Luo S et al. (2023) in nearby regions, which were interpreted as teleseismic body waves originating from deep oceans. To eliminate the detrimental effects of these body waves on the extraction of surface wave

dispersion curves from ambient noise CCFs, Luo S et al. (2023) introduced the HLRT method. This method involves selecting each station as a virtual source and forming virtual shot gathers by using all CCFs related to that station. Subsequently, all virtual gathers are transformed into the Radon domain (frequency–slowness domain) to remove interfering high-frequency, low-slowness body-wave signals. They are then inverse-transformed back to the time–distance domain to obtain the surface wave CCFs. Because each station serves as a virtual source, the CCF between one station pair will be involved in two virtual shot gathers. After HLRT mode separation, each station pair has two CCFs. Ideally, these two CCFs should show perfect equivalence, but achieving this in practical applications is challenging owing to factors such as heterogeneous subsurface structures, nonuniform noise source distribution, and low SNRs. To address potential discrepancies, we averaged the two CCFs for further processing when their correlation coefficient exceeded 0.5; otherwise, we discarded them during our quality control process. Figure 2b illustrates the CCFs from Figure 2a after removal of the near zero-time-lag body-wave signals.

The observed asymmetry in the CCFs between the causal and anti-causal branches suggests uneven distribution of the noise sources. To address this issue, we followed recommendations from previous studies and averaged both branches (Yang YJ et al., 2007; Fang LH et al., 2010). Using these averaged CCFs, we semi-manually extracted Rayleigh wave phase velocity dispersion data with image analysis techniques (Yao HJ et al., 2006). To ensure the reliability of our dispersion curves, we applied stringent quality control criteria. We selected dispersion curves with an SNR greater than 5 and an interstation distance exceeding twice the wavelength. These criteria are crucial for minimizing the influence of the uneven distribution of noise sources and maximizing the accuracy of the extracted surface wave velocities (Yao HJ et al., 2006, 2009; Yang YJ and Ritzwoller, 2008; Luo YH et al., 2015). Additionally, given the substantial topographic variation in our study region, ranging from 0.8 to 4 km, we considered the potential impact on our velocity model (Jin RZ et al., 2022; Luo S et al., 2023). Figure 3 presents a histogram of station elevation contrasts relative to the interstation distances, which follows an approximately normal distribution, with the majority of the data falling

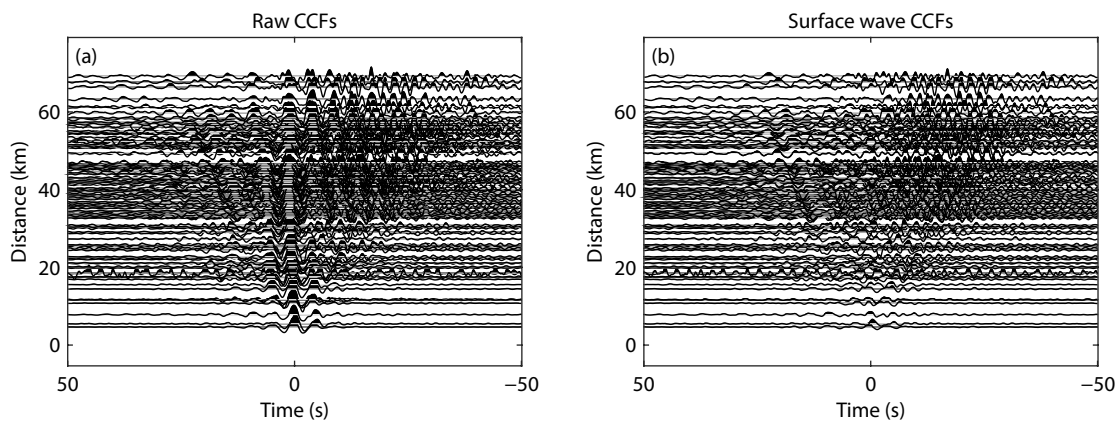


Figure 2. (a) Virtual shot gather before removing the body-wave signals; (b) virtual shot gather mainly containing surface waves after removing the body-wave signals.

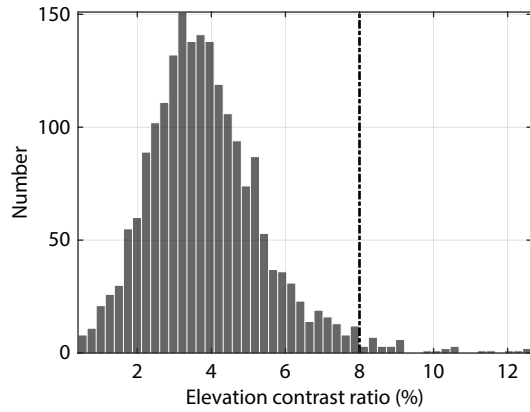


Figure 3. Histogram of elevation contrast ratios relative to station distances. The vertical dashed line indicates the 8% threshold for elevation contrast, beyond which cross-correlation functions (CCFs) were excluded to mitigate topographic effects.

below 8%. To minimize the impact of topographic effects, we excluded CCFs from station pairs with elevation contrasts exceeding 8% of the interstation distance. This approach ensured that our velocity model accurately reflected the subsurface structure with minimal impact from substantial topographical variations.

We further ensured the quality of the selected Rayleigh wave dispersion curves through path cluster analysis (Zhang YY et al., 2018; Jin JQ et al., 2023; Luo S et al., 2023). This method assumes that station pairs with similar ray paths should yield similar dispersion curves. We excluded dispersion measurements deviating by more than 1.6 times the standard deviation of the average clus-

tered dispersion data. As a result, we obtained 2352 high-quality dispersion curves (Figure 4a) for subsequent tomographic inversion. Figure 4b presents the one-dimensional (1-D) structural model resulting from inverting the average Rayleigh wave dispersion curve (red line in Figure 4a). Sensitivity analysis (Figure 4c) of this 1-D structural model revealed high sensitivity of the Rayleigh wave dispersion data in the period band of 1–10 s within the depth range of 0 to 10 km. Figure 5 illustrates the distribution of ray paths for Rayleigh wave phase velocity measurements at periods of 1–2 s, 3–4 s, 5–6 s, and 9–10 s. The density of ray paths peaks at intermediate periods (3–4 s) and decreases at longer periods, likely because of the far-field requirement in dispersion analysis and the influence of the SNR. Moreover, because of the moderate velocity heterogeneity in this region, ray paths exhibit noticeable curvature, particularly at shorter periods.

2.3 Direct Tomography of the 3-D V_s Structure

In this study, we applied the one-step direct surface wave tomography method (Fang HJ et al., 2015) to invert the picked mixed-path Rayleigh wave dispersion data for the 3-D V_s structure of the shallow crust in the study region. Compared with traditional two-step surface wave inversion methods, the one-step direct surface wave tomography method offers three major advantages. First, it eliminates the need for an intermediate step of constructing a two-dimensional group or phase velocity map, allowing for the direct inversion of the 3-D V_s structure from a large dataset, thereby increasing efficiency and reducing the potential for interpolation errors associated with two-step methods. Second, the 3-D initial velocity model can be directly utilized by partially considering the sensitivity kernels of compressional wave velocity

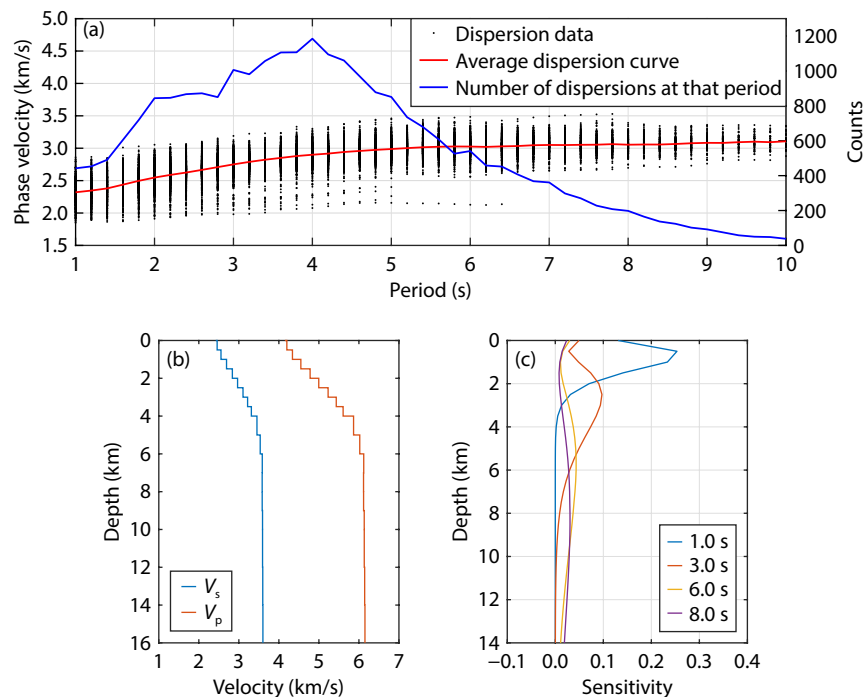


Figure 4. (a) Dispersion curves for tomographic inversion. The black lines are the picked dispersion curves. The solid red line is the average dispersion curve. The blue line is the number of phase velocity dispersion measurements picked at each period. (b) The one-dimensional (1-D) velocity model inverted from the average dispersion curve plotted in (a). This 1-D model is then used as the initial model for tomographic inversion. (c) Rayleigh wave phase velocity sensitivity kernels using the 1-D velocity model in (b) at different periods.

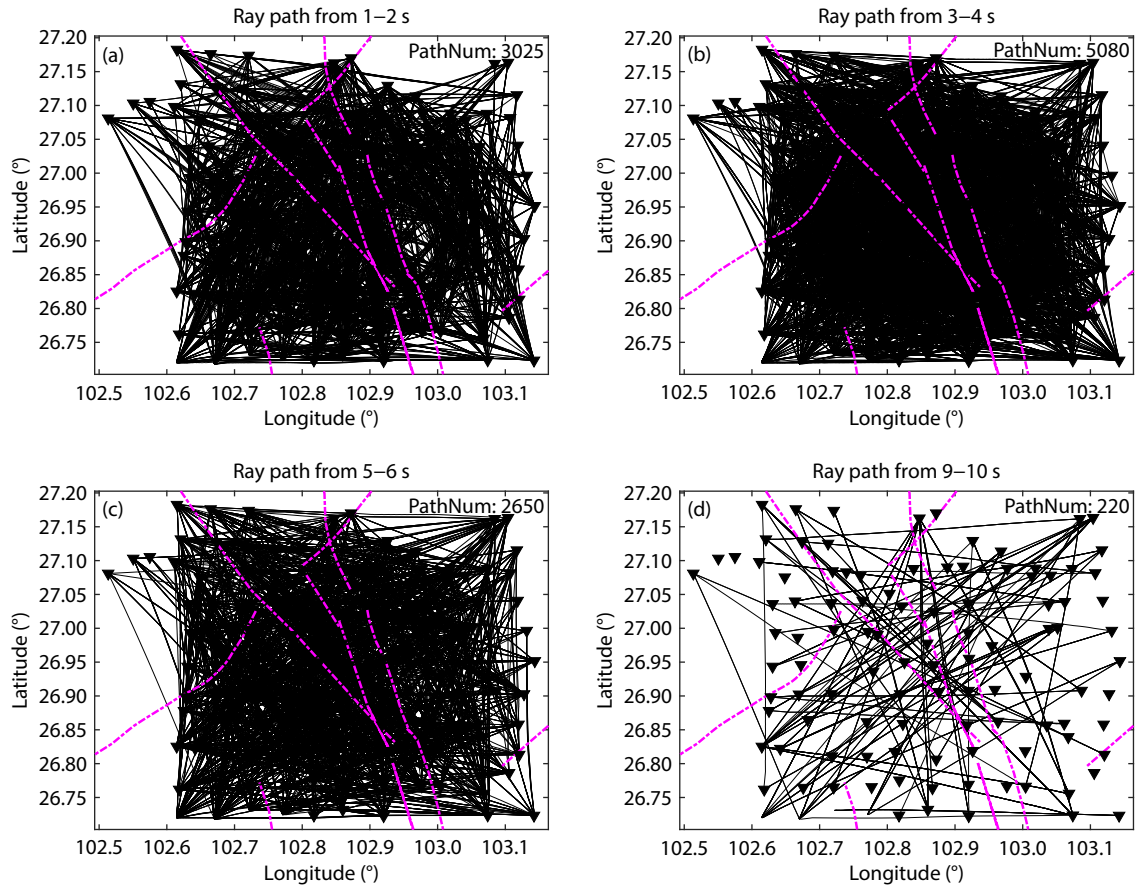


Figure 5. Ray path distribution for Rayleigh wave phase velocities at four different period bands: (a) 1–2 s, (b) 3–4 s, (c) 5–6 s, and (d) 9–10 s. The black lines represent ray paths after ray tracing; the black inverted triangles represent stations. The dashed purple lines represent faults. “PathNum” is the path number at the corresponding period band.

(V_p) and density through empirical relationships (Brocher, 2005). Third, the method better controls the lateral variation of the structure by utilizing the frequency-dependent fast-marching ray tracing method (Rawlinson and Sambridge, 2004) to address the off-great circle propagation effect caused by heterogeneous velocity structures. This approach significantly enhances the inversion accuracy of short-period surface wave dispersion data, making it a more efficient and precise method for surface wave tomography. For our study area, the initial model was constructed based on the 1-D structural model (Figure 4b) inverted from the average dispersion curve (solid red line in Figure 4a). The sensitivity analysis (Figure 4c) revealed that the depth range of sensitivity widens with longer periods, which guided the empirical setting of depth grids to be set to 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, 9, 10, 12, and 14 km, with finer spacing at shallow depths and coarser spacing at deeper depths. The horizontal grid spacing was set as $0.02^\circ \times 0.02^\circ$. The weight factor between the travel time residual and model normalization was determined as 10 based on many attempts and the checkerboard tests (Figure 6).

3. Results

3.1 Checkerboard Tests

To test the model resolution and recoverability under the current surface wave dispersion data distribution and model grid spacing,

we conducted a checkerboard test on a 3-D V_s model with a horizontal anomaly size of $0.06^\circ \times 0.06^\circ$ (three horizontal model grid points). The checkerboard model is depth dependent, and the pattern reverses at 3 and 7 km. The amplitude of the V_s anomaly is $\pm 3\%$ compared with the 1-D structural model in Figure 3b. With this 3-D V_s checkerboard model and the current surface wave dispersion data distribution, we first calculated the Rayleigh wave synthetic travel times. To simulate realistic conditions, we then introduced 0.5% Gaussian noise to the synthetic travel times and treated them as the “observed” data for surface wave tomography. Figure 6 presents the recovered checkerboard model of four horizontal slices at different depths and two cross-sections. The results of the checkerboard test demonstrate that within the ray path coverage (indicated by the solid black polygon in Figure 6), our dispersion data can effectively constrain $0.06^\circ \times 0.06^\circ$ anomalies at shallow depths (approximately 0–10 km). Nevertheless, it is important to note that although checkerboard analysis provides valuable insights, it should be regarded as a reference rather than an absolute indicator of true recoverability, as numerous other factors also influence the resolution of the model (Rawlinson and Spakman, 2016).

3.2 3-D Shear Wave Velocity Structure

Figure 7 displays nine horizontal slices of the V_s structure at depths ranging from 1 to 10 km beneath the junction area of the

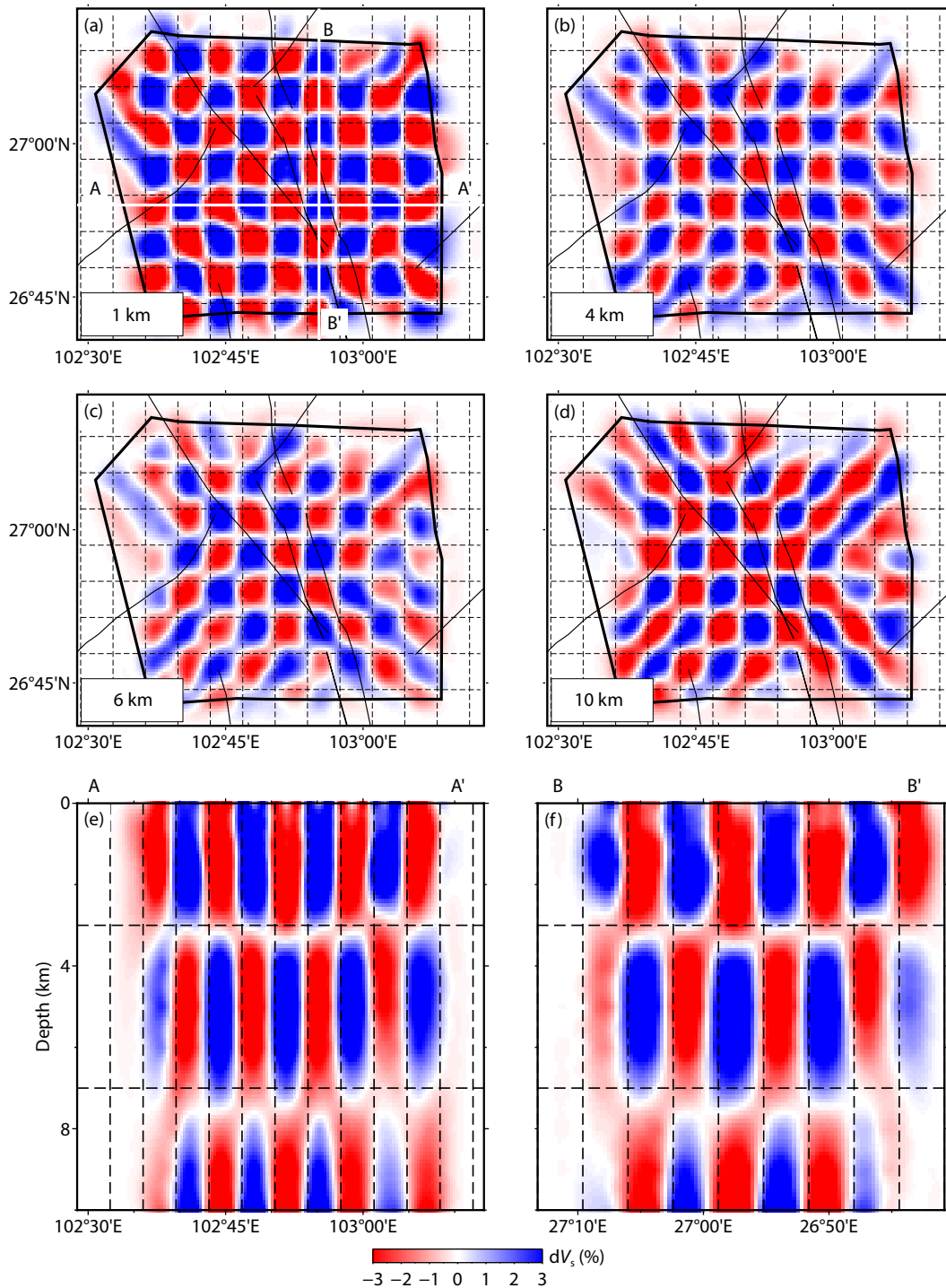


Figure 6. Results of the checkerboard tests. (a–d) The recovered horizontal slices at different depths, respectively. The dashed black lines mark the boundaries of true checkerboard patterns. The thin solid black lines represent the faults. The thick solid black polygon indicates the ray path coverage. Profiles A–A' (e) and B–B' (f) show the recovered vertical cross-sections, and their locations are marked as white lines in (a).

ZMHF and XJF zones. The tomographic results reveal a close correlation with the geological and geomorphological context of the study region. At shallower depths, the Qiaojia and Ningnan Basins exhibit distinct low-velocity anomalies, primarily attributed to the presence of highly fragmented surface sediments (Zhang N et al., 2019; Deng F et al., 2022; Duan MQ et al., 2024). In contrast, the surrounding western and eastern mountainous regions display predominantly high-velocity characteristics.

To the southwest of the Qiaojia Basin, a transition to higher V_s values is evident from a depth of 4 km extending down to 10 km. Conversely, to the east of the Qiaojia Basin and along the XJEF, the low V_s feature remains consistent from the surface down to a depth of 10 km. Furthermore, a notable high V_s anomaly is detected south of the Ningnan Basin at depths exceeding 6 km. Significant high V_s anomalies are also identified near the intersection of faults SJF and LFF, spanning from the surface through all

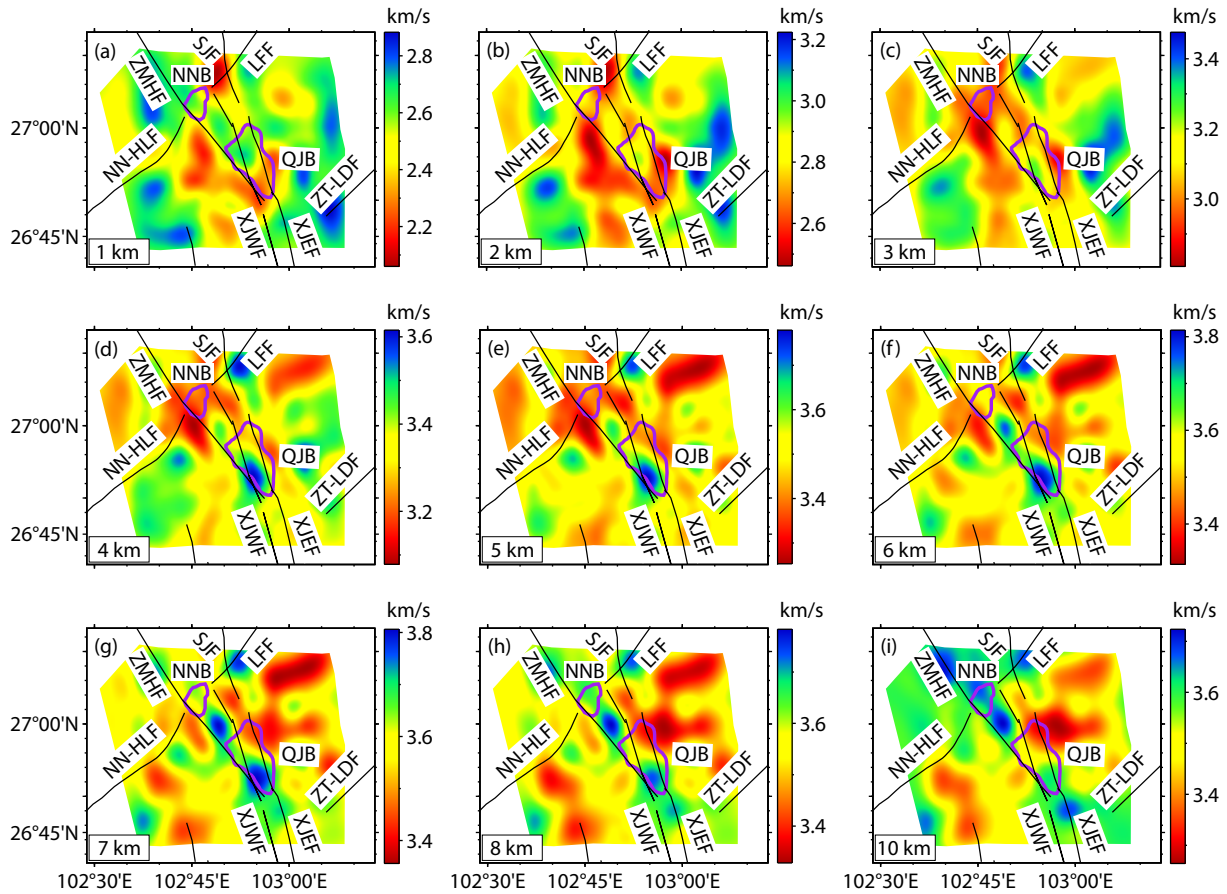


Figure 7. Map views of the 3-D shear wave velocity structure at different depths (a–i). The black lines are the faults (the abbreviations of faults are the same as in Figure 1c).

depths inverted.

3.3 Comparison with Previous Results

Leveraging the high-precision earthquake catalog obtained through a machine learning-based earthquake location workflow, Feng T et al. (2022) applied the double-difference tomography method (tomoDD) to derive a high-resolution 3-D velocity model. However, despite its advanced approach, the model's relatively sparse station distribution — compared with the local dense array used in our study — results in a grid spacing of 0.1° horizontally and 5 km vertically. As a result, it lacks the finer velocity details necessary for our study area, and its horizontal resolution in the upper crust is insufficient for capturing the local-scale variations required for this analysis.

Figure 8 presents horizontal V_s slices at depths of 5 and 10 km, comparing the model of Feng T et al. (2022, hereafter referred to as Feng's model) with our fine-scale local model. Feng's model has been cropped to match the extent of our study area, focusing on the junction of the ZMHF and XJF. The green polygon outlines the study region for this work, whereas the purple polygons highlight the Qiaojia and Ningnan Basins. Figure 9 displays V_s profiles from both Feng's model and our local model, along the locations indicated by the red lines in Figure 8a. These locations were carefully chosen to coincide with grid points, thereby avoiding interpolation. For consistency, the vertical profiles from both models in

Figure 9 are plotted with the same color scale to facilitate direct comparison.

For these velocity slices and profiles, although both models demonstrate a first-order similarity by highlighting low V_s around the sedimentary basins, our fine-scale model exhibits superior horizontal resolution, as anticipated. The most notable differences between our model and Feng's appear in the shallow crust, likely because of the sparser grid spacing, especially vertically, in Feng's model. This comparison shows that our fine-scale model better aligns with the distribution of microseismic events, offering a more accurate understanding of the seismotectonic environment at the junction of the ZMHF and XJF. Therefore, our model is more suitable for locating shallow earthquake epicenters, inverting earthquake focal mechanisms, and delineating fault geometries with greater precision.

4. Discussion

As parts of the eastern boundary of the South Chuan–Dian Block, the ZMHF and XJF exhibit substantial crustal deformation and fracturing in the shallow subsurface resulting from the material extrusion around the eastern Himalayan syntaxis in the southeast Tibetan Plateau (Chen Z et al., 2000; Zhang PZ et al., 2003). Consequently, the upper crust at the junction of the ZMHF and XJF is characterized by complex fault systems and shear strain rates (Wang M and Shen ZK, 2020; Shan XJ et al., 2023). Moreover, the

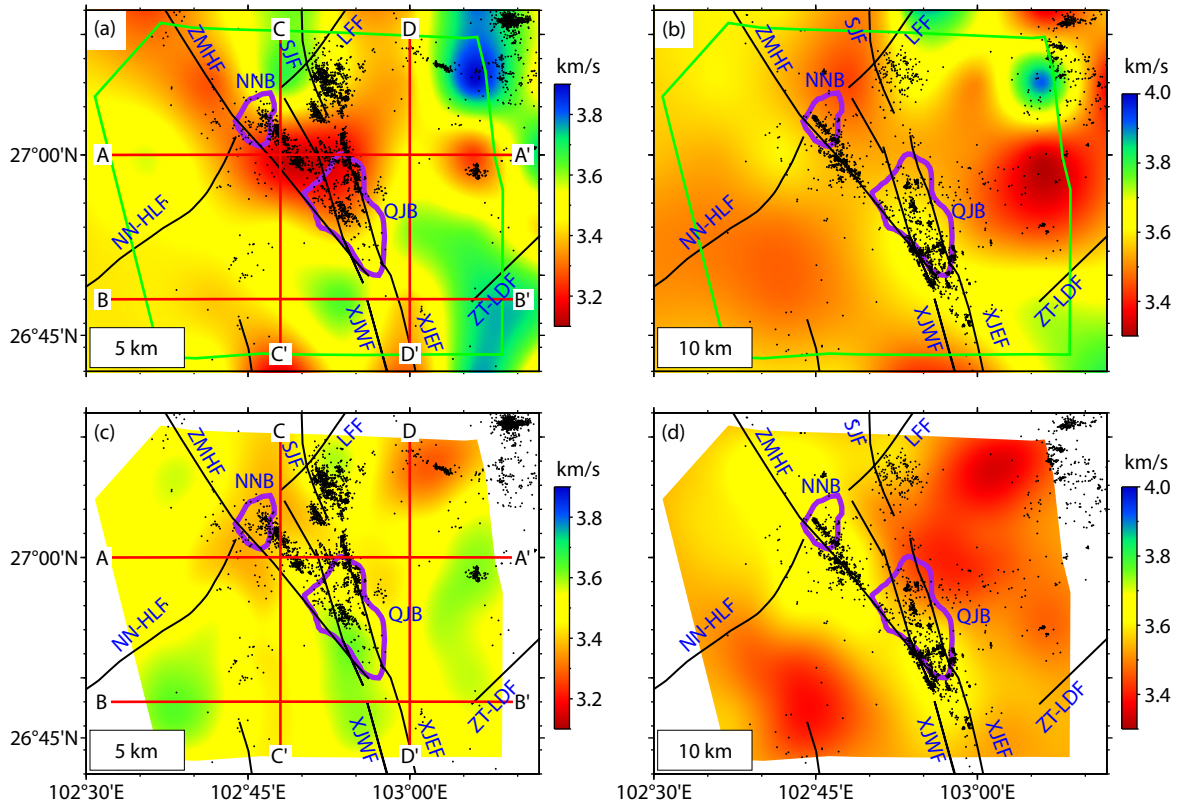


Figure 8. Horizontal V_s model slices from Feng's model (a, b), and our fine-scale local model (c, d). The solid red lines denote the profile locations, whereas the black lines indicate faults. The purple lines outline the Qiaojia and Ningnan Basins, and the green polygon represents the study area for this paper. The black dots mark microseismic events occurring within 1 km on either side of the slice.

impoundment of the Baihetan Reservoir has notably altered seismic activities and the stress regime in the upstream area (Duan MQ and Zhao CP, 2019; Zhang N et al., 2019; Guo W et al., 2022; Liu H et al., 2023). Using a newly deployed dense seismic array, we constructed a high-resolution 3-D upper crustal V_s model around the junction of the ZMHF and XJF. Our imaging results revealed similar but more detailed structural features compared with previous studies. This enhanced resolution provides new insights into the geometry of the fault planes and substantially improves our understanding of local seismotectonics in this region.

On the basis of the seismic array deployed around the reservoir area, Guo W et al. (2022) obtained a high-precision earthquake catalog and analyzed the influence of the impoundment of the BHT Reservoir. In this study, we used the same method to obtain a high-precision earthquake catalog in the junction area of the ZMHF and XJF from January 2022 to December 2023. To detail the depth changes and local microseismic event distribution of our velocity model, we included six vertical profiles with earthquake events within 2 km horizontally, as shown in Figure 10. The vertical velocity profiles revealed lower seismic velocity anomalies in the Quaternary sedimentary Ningnan and Qiaojia Basins. However, these anomalies are not strictly confined within the basin boundaries, which may be due to substantial rock fragmentation at fault junctions, sharp elevation changes, and the complex geological structure of the area. Notably, according to the earthquake locations plotted in Figure 1c and the slices in Figure 8, local microseismic events in this area form three distinct clusters, each of

which correlates with different fault systems. The first cluster is near the southern edge of the Ningnan Basin, occurring at depths of 3 to 15 km, and closely aligned with the strike of the ZMHF. Profile EE–EE' intersects the ZMHF perpendicularly, showing microseismic events beneath it at a dip angle of approximately 80°. Wang MM et al. (2024) utilized multi-data and implicit modeling to detail a precise 3-D structure of the Anninghe–Zemuhe–Xiaojiang Fault Zone, indicating a dip angle of approximately 80° for the Zemuhe Fault Plane. Our observation of the microseismic event distribution along the ZMHF aligns with this finding (Wang MM et al., 2024). Profile G–G' intersects the ZMHF at an azimuthal angle of approximately 45°, revealing a smaller apparent dip angle for microseismic events along this profile. Additionally, microseismic events along profile G–G' coincide with the boundary between high and low V_s zones on the high V_s side. This behavior is linked to fragmented rocks dominated by dolomite and sandstone-shale (Deng F et al., 2022; Guo W, 2022; Duan MQ et al., 2024), featuring high porosity and permeability (Zhou LQ et al., 2018). The association of the ZMHF with hot springs and karst features suggests geothermal water flow along the fault. Low-velocity anomalies indicate deep fluid migration into the upper crust. Microseismic events along the high and low V_s boundary suggest that deep fluids are intruding into fractures, elevating pore pressure in deeper high-velocity asperities, and triggering earthquakes in deeper seismic zones.

The second microseismic event cluster is spatially related to the XJF, with most earthquakes occurring at depths ranging from 4 to

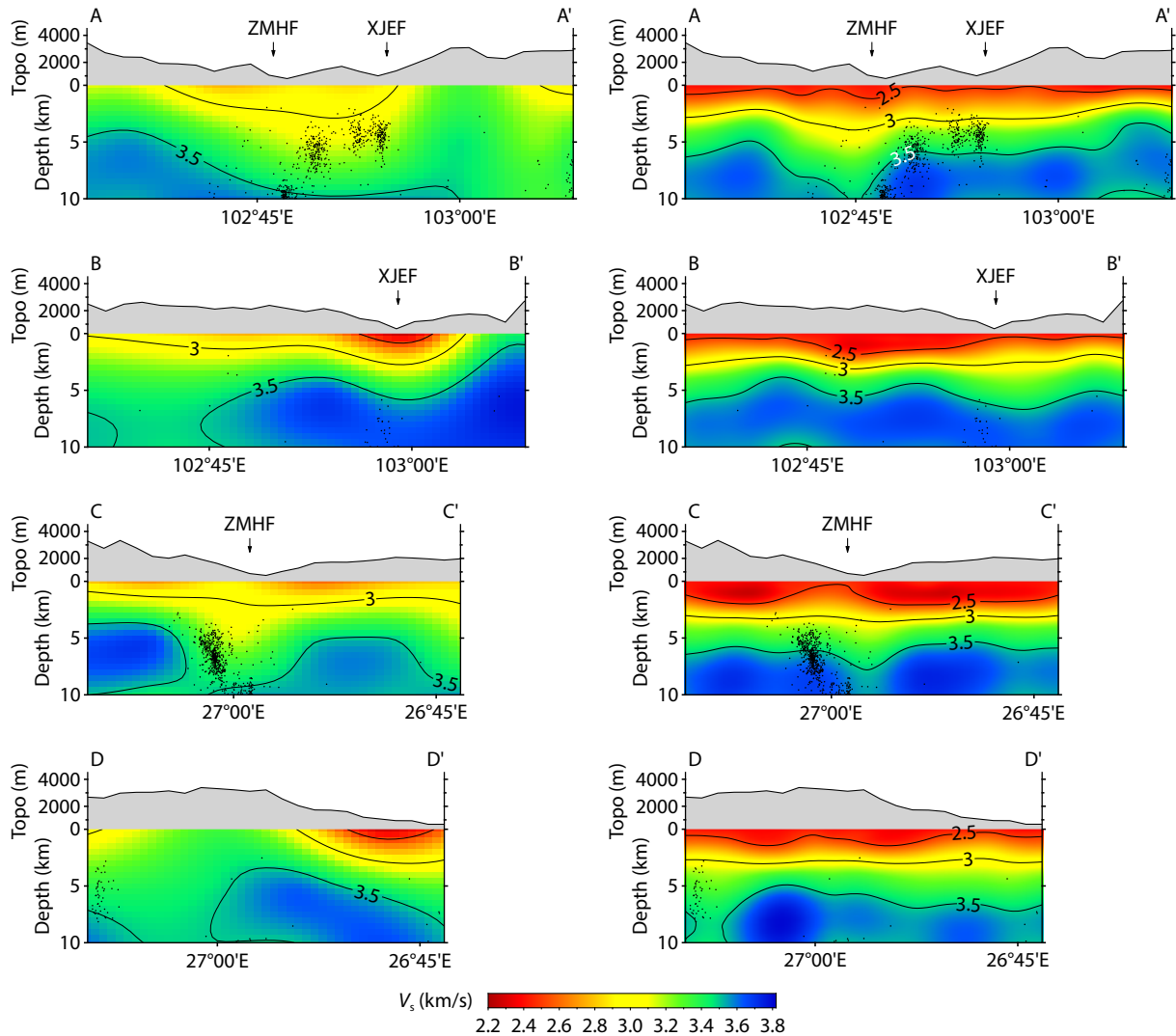


Figure 9. Vertical profiles of the shear wave velocity structure and earthquake distribution from Feng's V_s model (left column) and our model (right column). The profile locations are indicated by the red lines in Figure 8. The top section of each profile illustrates the topography along the profile, whereas the lower section presents the shear wave velocity structure. The black dots represent earthquake events occurring within 1 km on either side of the profile.

14 km, primarily within the Qiaojia Basin. Profiles F–F' and H–H' intersect the XJF at azimuthal angles close to 90° and 45°, respectively. The microseismic events in these profiles show a nearly vertical distribution beneath the XJF, indicating that the dip angle is nearly vertical. This vertical clustering of the XJF microseismic events was also observed by Duan MQ et al. (2024). The microseismic events along profile H–H' are confined between the XJWF and the XJEF, occurring on the high V_s side of the high–low V_s boundary below 7 km. Profile G–G' intersects the northern end of the XJWF, where the microseismic events also exhibit a vertical angle but are confined to a depth range of 3 to 5 km. Wang MM et al. (2024) noted that the XJF has a nearly vertical fault plane, which aligns with our observations of the microseismic event distribution. Profiles I–I' and J–J' coincide with the XJWF and the XJEF, respectively, revealing a clear trend of increasing microseismic event depth as the XJF extends southward. This seismicity depth change phenomenon was also reported by Guo W et al. (2022), who noted that the impoundment of the BHT Reservoir increased seis-

mic activity, with event depths being shallower near the reservoir and deepening to the south.

The third cluster is located within the high V_s anomaly around the intersection of the SJF and the LFF. Profile E–E' intersects the SJF, revealing a nearly vertical distribution of microseismic events beneath the fault, suggestive of a steep fault dip angle. Profile J–J', running parallel to the SJF, traverses this cluster of microseismic events, most of which occur in the high V_s region associated with both faults. Furthermore, the majority of microseismic events in this cluster are concentrated at depths ranging from 3 to 9 km. Guo W et al. (2022) and Liu H et al. (2023) have interpreted these events as reservoir-triggered earthquakes, characterized by relatively low magnitudes and shallow depths.

5. Conclusions

In this study, we utilize dense seismic station data to derive surface wave phase velocity dispersion curves, which are inverted to construct a high-resolution 3-D shear wave V_s model of the

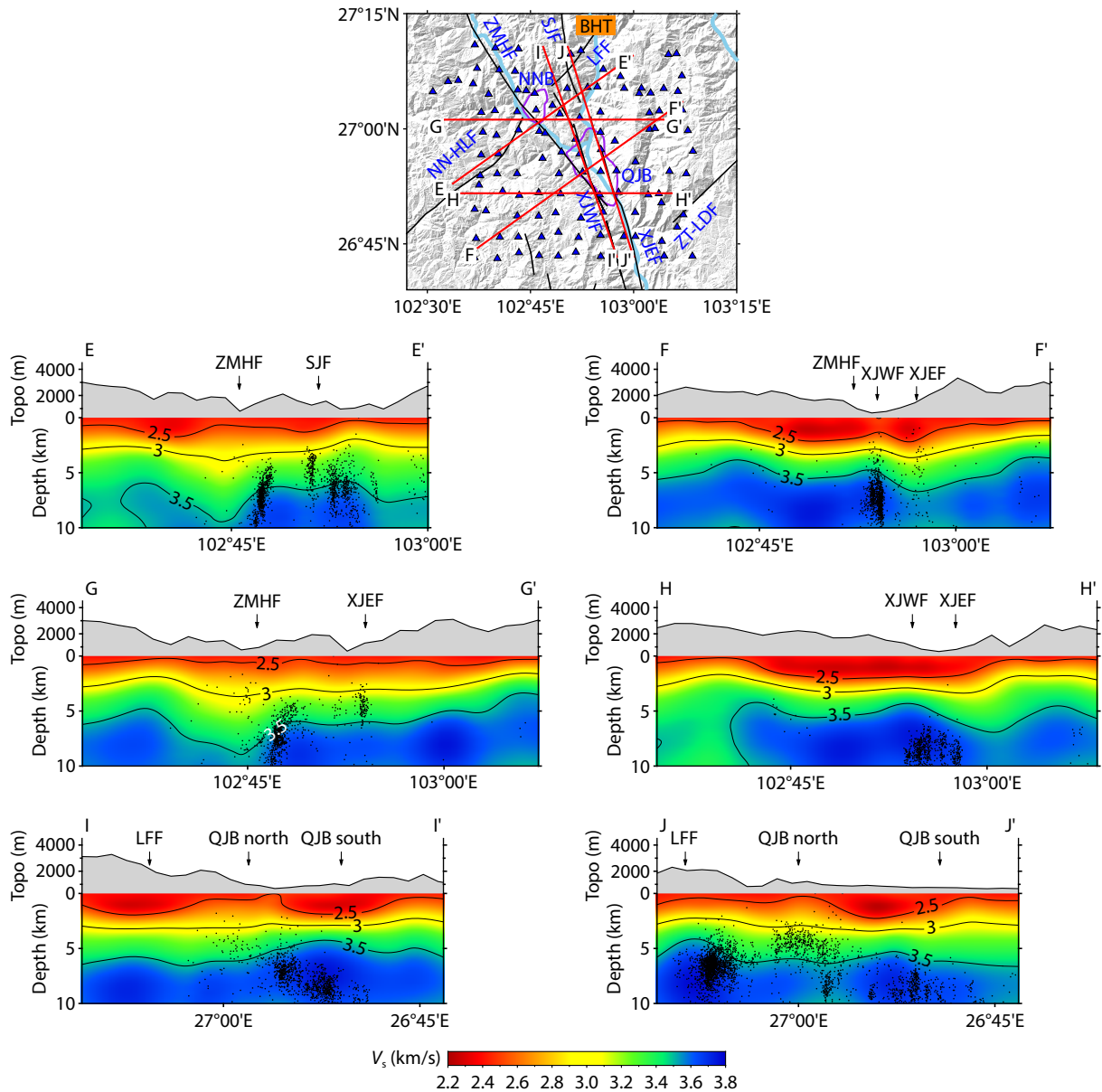


Figure 10. Vertical profiles of the shear wave velocity structure and earthquake distribution in the study area. The locations of the profiles are marked by the red lines in the first subplot. In each profile, the top part shows the topography along the profile, and the bottom parts show the shear wave velocity structure. The black dots represent earthquake events within 1 km on both sides of the profile. The red lines in profiles I–I' and J–J' indicate a deepening of seismicity toward the southeast along the XJF.

upper crust at the junction of the ZMHF and XJF. Utilizing a direct inversion method based on high-frequency surface wave dispersion data, we achieved a significant improvement in model resolution compared with previous studies. The resulting V_s model achieves a horizontal resolution of approximately 5 km and a vertical resolution of 2 km, revealing detailed subsurface structures and segmentation characteristics. The region under study is known for its high risk of potential large-magnitude earthquakes, highlighting the critical importance of our fine-scale velocity model for accurately predicting strong earthquake motion in this area. Spatial correlation analysis between the V_s model and microseismic event distributions around active fault zones reveals a strong alignment with fault planes. Furthermore, the presence of multiple buried water-filled fault zones parallel to the XJF within

the Qiaojia Basin correlates with relatively low V_s values in shallow sedimentary areas. Moreover, the spatial distribution of microseismic events suggests a hydraulic connection between these faults and deep subsurface karst aquifers. We propose that this connection reflects a seismogenic mechanism whereby deep fluids intrude into fractures, increase pore pressure, and trigger earthquakes in deeper seismic zones. This phenomenon contributes to the formation of a seismogenic zone characterized by heightened microseismic activity.

Acknowledgments

The study was funded by the National Key R&D Program of China (Grant No. 2021YFC3000704), the National Natural Science Foundation of China (Grant No. 42125401) and the Central Public-inter-

est Scientific Institution Basal Research Fund (Grant No. CEAIEF20240401). Some figures in this paper were generated by Generic Mapping Tools (GMT) software (Wessel et al., 2019).

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