

Strong earthquake hazards in sparse earthquake segments of fault zones on the western Ordos margin: Insights from relocation and *b*-value analysis

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Key Points:

- This study combines earthquake relocation, *b*-value analysis, velocity structure, the sparse earthquake segment of fault zone identification, and magnitude–rupture length scaling relations to evaluate strong earthquake hazards of active fault zones on the western Ordos margin, with a focus on their correlation with historical ($M \geq 6$) and modern ($M_L \geq 5.0$, 2009–2025) earthquakes.
- On the western Ordos margin, sparse earthquake segments of the fault zone overlapping with low *b*-value zones ($b < 0.7$) are relatively high-stress locked segments and potential asperities characterized by low V_p/V_s ratios. On other fault segments, high *b*-values ($b > 1.1$) combined with normal or low V_p/V_s ratios correspond to friction-dominated creep, commonly relating to seismic swarms and presenting a low short-term strong earthquake risk.
- Several strong earthquake high-hazard areas are identified, including the Wuzhong–Lingwu region and the Yongning–Yinchuan region in NNE–SSW faults of the Yinchuan Basin, the Tongxin region in the southeastern Tianjingshan–Yantongshan Fault Zone, the Baiyin–Jingtai region in the western Haiyuan Fault Zone, and the Guyuan region from the eastern Haiyuan Fault Zone to the Liupanshan Fault Zone. The findings offer targeted support for strong earthquake hazard mitigation.

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Abstract: To evaluate strong earthquake hazards of major active fault zones on the western margin of the Ordos Block, in this study we integrate multiple methods, including earthquake relocation, *b*-value analysis, identification of sparse earthquake segments of fault zones, and magnitude–rupture length scaling relations. With the aim of delineating the seismogenic potential of key tectonic belts and identifying potential asperities, we focus on the spatial correlation between sparse earthquake segments, low *b*-value anomalies, the crustal velocity structure, historical earthquakes ($M \geq 6$), and modern earthquakes ($M_L \geq 5.0$, 2009–2025). The results show that seismicity in the study area is spatially clustered along the strike of active faults, with focal depths mainly ranging from 0 to 30 km. Sparse earthquake segments are widely distributed in all major tectonic units, and their spatial overlap with low *b*-value zones ($b < 0.7$) reliably indicates high stress accumulation as well as locked fault segments and potential seismogenic asperities characterized by low V_p/V_s ratios. All modern $M_L \geq 5.0$ earthquakes occurred within low *b*-value zones, consistent with the contemporary stress background, and some historical $M \geq 6$ earthquakes were outside low *b*-value domains, which may be attributed to the mismatch between their occurrence times and the 2009–2025 earthquake catalog used for *b*-value calculation. Empirical magnitude–length scaling relations confirm that the geometric extent of sparse earthquake segments is consistent with the magnitude range of historical strong earthquakes in each tectonic belt. Localized high *b*-value zones ($b > 1.1$) with normal or low V_p/V_s ratios reveal friction-governed fault creep and correspond to seismic swarms, presenting a low short-term strong earthquake risk. Several core areas with elevated strong earthquake hazards are recognized, including parts of the Yinchuan Basin, the Tianjingshan–Yantongshan Fault, and the Haiyuan–Liupanshan Fault Zone. In conclusion, the integrated analysis of sparse earthquake segments and *b*-value anomalies provides a robust framework for identifying high-stress, seismogenically capable fault segments. This study improves the identification of potential asperities and their seismogenic potential in the western margin of the Ordos Block and provides critical scientific support for regional seismic hazard assessment.

Keywords: western Ordos margin; earthquake relocation; *b*-value; sparse earthquake segments of the fault zone; strong earthquake hazards

1. Introduction

The occurrence of strong earthquakes is primarily associated with the rupture of asperities, which involves relatively high rupture strength. Asperities are heterogeneous localized patches on the fault rupture surface and correspond to independent high-stress

areas. Current methods for identifying asperities are predominantly oriented toward detecting unruptured asperities, and they can be grouped into three core categories (Xu CJ et al., 2022): seismicity analysis, medium structure distribution, and active fault slip behavior. These technical frameworks integrate multiple disciplines, including seismology, geodesy, and electromagnetics. Within seismology, three relatively stable and well-established indicators are widely used: relatively high-velocity zones, small to moderate earthquake gaps or sparse zones, and regions with anomalously low b -values (Xu CJ et al., 2022; Wei B et al., 2023). It is evident that methods and techniques for identifying asperities involve many different disciplines. Among these, moderately small earthquake gaps or sparse zones and anomalously low b -value zones within seismicity studies are currently one of the relatively well-defined seismological technical approaches for identifying asperities. This approach also constitutes a key task in the field of seismicity that we aimed to undertake in this work.

Seismic gaps generally include the “earthquake gap” delineated by the traditional earthquake epicenter catalog and sparse earthquake segments of the fault zone outlined by a precisely relocated earthquake catalog (Wen XZ et al., 2008; Xu XW et al., 2017; Department of Earthquake Monitoring and Prediction of China Earthquake Administration, 2020; Shao ZG et al., 2022). The most common earthquake gap is defined by using the epicenter gap method based on raw earthquake catalogs, and it does not necessarily correspond to high-stress accumulation zones (Chen YT and Ni XX, 1990). In reality, the high-stress accumulation areas are more localized than the delineated gap. Furthermore, the delineation of earthquake gaps as seismological anomalies currently relies on the epicenter gap method, using earthquakes of relatively large magnitudes (the larger the magnitude, the larger the potential gap area, whereas lowering the magnitude threshold can yield smaller gaps). These delineated gaps often deviate slightly from the true asperity morphology. In contrast, sparse earthquake segments of the fault zone outlined by precisely relocated catalogs can intuitively indicate the approximate location of potential asperities. A seismic gap may contain an asperity or overlap with one. However, to determine the approximate location of an asperity from a seismicity perspective within seismology, b -value studies must also be integrated (Xu CJ et al., 2022). Conversely, large-scale seismic gaps (i.e., fault segment gaps or sparse zones) are roughly outlined by using traditional catalogs based on epicenter distribution (merely a planar distribution, without utilizing focal depth information). Delineating seismic gaps along fault zones requires precisely relocated catalogs. Therefore, whether it is the traditional earthquake gap (planar view) or sparse earthquake segments of the fault zone (planar and profile views, mainly profile), these seismic gaps generally may include asperities, barriers, and surrounding relatively low-stress areas (Chen YT and Ni XX, 1990; Jiang HK et al., 2003; Yi GX et al., 2004, 2005; Wen XZ et al., 2013; Zeng XW et al., 2021). Consequently, with the densification of seismic networks, improved regional small-earthquake monitoring capabilities, and advances in earthquake relocation techniques, an increasing amount of seismic observation data is being used in precise relocation work. Through precisely relocated earthquake catalogs, we can better detect fault zone asperities and investigate

strong earthquake hazards. It is an urgent undertaking for future research.

Regarding b -value and magnitude of completeness (M_c) research objects, they are mainly divided into planar regional b -values and fault zone profile b -values. The former, primarily obtained from traditional raw earthquake catalogs, have been widely applied and operationalized. Corresponding predictive index systems have been established for various tectonic regions (Department of Earthquake Monitoring and Prediction of China Earthquake Administration, 2020). Analysis of planar regional b -value maps based on traditional raw catalogs has been applied in routine seismic consultation. However, for the latter (i.e., fault zone profile b -values), primarily using relocated catalogs, operationalization and application levels have not been as advanced as the former because of limited monitoring capabilities in some early domestic networks, and they are only seen in a small number of studies (Wiemer and Wyss, 1997; Yi GX et al., 2004, 2005, 2013; Wen XZ et al., 2013; Zeng XW et al., 2021). In terms of b -value calculation methods, the most common are the least squares method and the maximum likelihood method (Department of Earthquake Monitoring and Prediction of China Earthquake Administration, 2020). Although the least squares method is simple and easy to implement, it gives greater weight to larger magnitude earthquakes. The least squares b -value is easily influenced by a few large-magnitude earthquakes. In contrast, in the maximum likelihood method, all earthquakes have equal weight. Therefore, under specific conditions, the maximum likelihood method can serve as an alternative to the least squares method (Wu G et al., 2019). The least squares method generally requires a larger sample size than the maximum likelihood method. Consequently, the maximum likelihood method for fitting b -values has gradually developed and matured in recent years (Aki, 1965; Wiemer and Wyss, 2002; Long F et al., 2009; Li ZF and Zhou BG, 2014; Xie ZJ et al., 2015; Liu JW and Lü YJ, 2016; Zhou YJ et al., 2018; Zeng XW et al., 2021). Zhu AL et al. (2005) relocated 1825 earthquakes in the capital region from 1980 to 2000 using the double-difference earthquake relocation algorithm (hypoDD) and used the relocated catalog to study the variation in maximum likelihood b -values with focal depth. They found that uncertainties in the relocated catalog focal depth and lower magnitude thresholds have little impact on the systematic variation of b -values in focal depth profiles. Yu M (2021) first obtained a new earthquake catalog by using double-difference relocation, then calculated b -values based on ZMAP. They found that the maximum likelihood method has relative advantages in temporal b -value studies and that the starting magnitude should be based on the M_c . Zhang JZ and Song LY (1981), through Monte Carlo simulation, concluded that the maximum likelihood method of b -values has smaller calculation errors, a smaller computational load, and a smaller required sample size than the linear least squares method. Li SJ et al. (2018) reached similar conclusions based on fitting synthetic and natural earthquake catalogs. They found that the difference in results between the two methods decreased as the sample size increased. Currently, the least squares b -value is rarely used internationally, whereas the maximum likelihood b -value is widely used. Regarding fault zone b -value profile research, although the literature is less abundant

than for planar regional b -values, preliminary studies have been conducted in a few regions of Chinese continent with relatively good monitoring capabilities and high seismicity, such as the Sichuan–Yunnan region and the northeastern margin of the Tibetan Plateau (Yi GX et al., 2004, 2005, 2013; Wen XZ et al., 2013; Zeng XW et al., 2021). These studies have mainly used precisely relocated catalogs to investigate fault zone profile b -values and strong earthquake hazards, although different scholars have applied different relocation methods and combined other auxiliary analysis techniques (e.g., multiple seismicity parameters, GPS fault-locking research, magnitude–rupture relationships).

The western margin of the Ordos Block, situated in the northern segment of the North–South Seismic Belt, serves as the convergence zone of the Ordos Block, the Alxa Block, and the northeastern margin of the Tibetan Plateau (Figure 1a). This region, with the Niushoushan Fault (NSSF) as the boundary, exhibits diverse fault activities. Its southern section comprises an arcuate structural belt formed by several left-lateral strike-slip faults and terminal thrust faults, belonging to the Tibetan Plateau tectonic domain—primarily including the Haiyuan Fault (HYF), the Liupanshan Fault (LPSF), the Tianjingshan Fault (TJSF), and the Yantongshan Fault (YTSF). The northern section features the Yinchuan Graben Basin and Helanshan structural belt controlled by multiple normal faults and right-lateral strike-slip faults, forming a typical basin–range

system within the North China Block region—mainly consisting of the Yinchuan Fault (YCF), Huanghe Fault (HHF), and Helanshandonglu Fault (HLSDF). Historically, $M \geq 6.0$ seismic activity on the western Ordos margin was relatively concentrated along these active fault zones, including the 1920 $M 8\frac{1}{2}$ Haiyuan earthquake and the 1739 $M 8$ Yinchuan–Pingleo earthquake. Previous studies on strong earthquake ($M \geq 6$) hazards in this area have primarily utilized geological and geodetic deformation approaches, although seismological research remains scarce, particularly regarding b -value profile analysis of relocated earthquake fault zones along the western Ordos margin. However, the recent accumulation of observational data has now established a substantial foundation for precise earthquake relocation and b -value calculations. Thus, comprehensive seismological research focusing on the identification of sparse earthquake segments of the fault zone, b -value analysis from relocated earthquakes, and an associated strong earthquake hazard assessment in this region is imperative.

In summary, considering the current state of research in the field of seismicity, studies on strong earthquake hazards via fault zone asperity identification have formed supporting seismological identification methods for seismic consultation. This approach is suitable for procedural application and delivers high efficiency and practicality. However, research on strong earthquake hazards based on fault zone seismic gaps is also paramount. For this

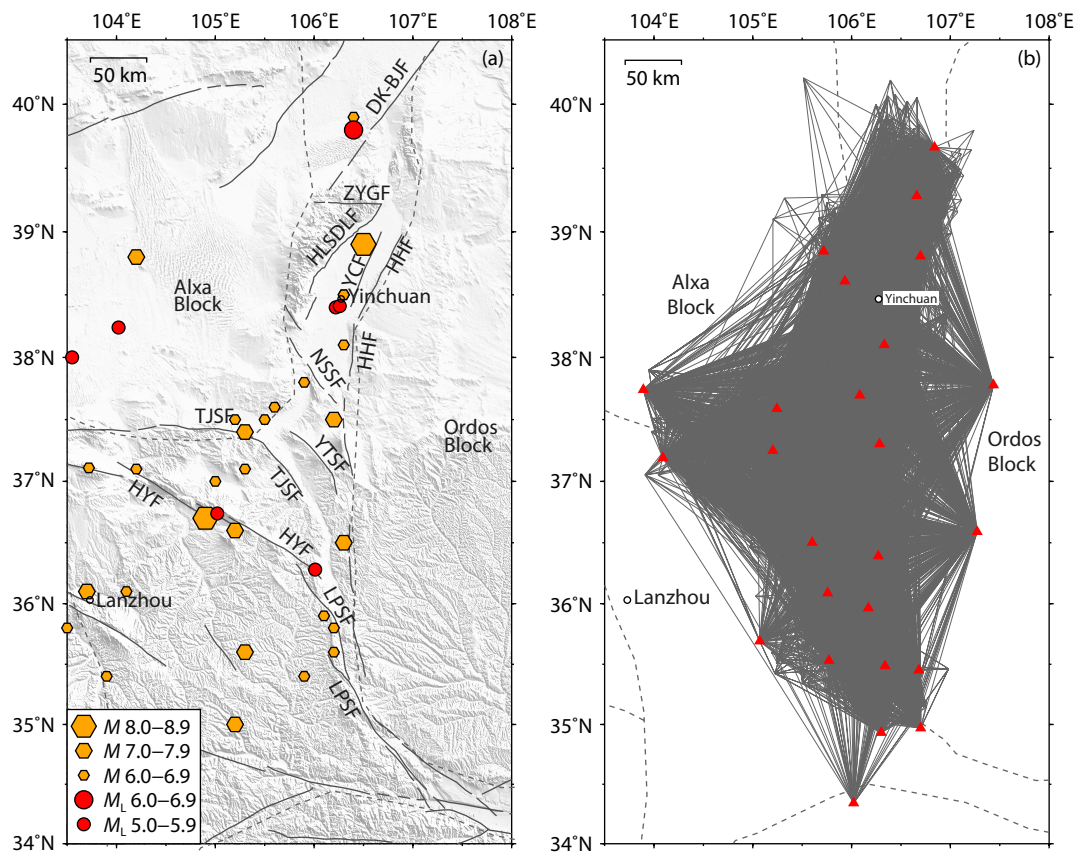


Figure 1. (a) Tectonic background, major faults, epicenters of historical earthquakes with $M \geq 6.0$, $M_L \geq 5.0$ events from 2009 to 2025, and (b) seismic rays on the western Ordos margin. DK-BJF: Dengkou–Benjing Fault; ZYGF: Zhengyiguan Fault; HLSDF: Helanshandonglu Fault; YCF: Yinchuan Fault; HHF: Huanghe Fault; NSSF: Niushoushan Fault; YTSF: Yantongshan Fault; TJSF: Tianjingshan Fault; HYF: Haiyuan Fault; LPSF: Liupanshan Fault.

purpose, the relative relocation technique chosen is the double-difference seismic tomography (TomoDD) method (Zhang HJ and Thurber, 2003, 2006). For b -value calculation, the currently stable, reliable, and procedurally operationalizable ZMAP platform (Wiemer, 2001) is adopted. Both conform to the requirements of current seismic tracking work and represent key future tasks in seismic monitoring. They offer the potential for rapid preparation of firsthand materials for real-time seismic tracking and consultation. In this study, we analyzed the sparse seismicity segments of fault zones in the western margin of the Ordos Block and their associated seismic hazard potential. By collecting seismic phase observation reports of $M_L \geq 1.0$ earthquakes from 2009 to 2025 and applying the TomoDD method (Zhang HJ and Thurber, 2003, 2006) for relocation, with missing events supplemented by results from the original earthquake catalog, we constructed a merged new earthquake catalog. This catalog served as input for ZMAP (Wiemer, 2001) to calculate the b -value. Subsequently, we utilized the maximum likelihood method to perform b -value imaging of the active fault zones. By analyzing the spatial distribution of b -values along planes and cross-sections of the faults, combined with the precisely relocated earthquake epicenter and depth distributions, we delineated the spatial extent of the sparse earthquake segments and regions with b -values below the average background. Using empirical relationships between earthquake magnitude and rupture length (Guo ZJ and Qin BY, 1979; Deng QD et al., 1992; Wells and Coppersmith, 1994; Ye WH et al., 1996; Long F et al., 2006), we evaluated the theoretical seismic potential of the identified sparse segments and low b -value zones. By integrating other available data and conducting a retrospective analysis of historical strong earthquakes ($M \geq 6$) related to b -value anomalies and the sparse earthquake segments of fault zones, we further explored the possible existence of asperities on the faults. This approach revealed the relative stress levels at different positions and asperities along the fault zones, ultimately assessing the current seismic activity characteristics and potential strong earthquake hazard of each active fault zone.

2. Data and Methods

2.1 Data Acquisition

In this study, we used data from P-wave and S-wave phase reports recorded from 2009 to 2025 by 25 permanent stations on the western margin of the Ordos Block (Figure 1a), provided by the Ningxia Regional Seismic Network. To ensure the reliability of the

inversion results, we conducted strict screening of the raw seismic data: we selected only phase data on 3936 events with $M_L \geq 1.0$ in the observation reports and removed travel-time information with significant anomalies in the raw dataset by using the time–distance curve fitting method (Figure 2). As a result, the phase dataset included 32,805 P phases and 33,342 S phases. We then performed relative relocation using TomoDD, which yielded 3540 successfully relocated events, corresponding to a relocation rate of approximately 90%. The overall location residual was reduced from 0.26 s to 0.07 s. The large volume of seismic data and dense earthquake ray coverage in the study area provided an excellent data foundation for delineating the sparse earthquake segments of fault zones and characterizing the spatial distribution of b -values (Figure 1b). First, we performed relative relocation to obtain a high-precision earthquake catalog for delineating sparse earthquake segments along fault zones and for calculating the b -value input. To ensure the completeness of the catalog for the b -value calculation, the small number of earthquakes not included in the relocation results was supplemented from the original catalog. The final merged catalog for b -value calculation thus retained the full 3936 events, consisting of 3540 precisely relocated events plus the remaining events from the original catalog.

2.2 Method of Earthquake Relocation, b -Value Calculation, and Strong Earthquake Analysis

For earthquake relocation, we applied the TomoDD method (Zhang HJ and Thurber, 2003, 2006) to refine the accuracy of earthquake locations. This method was developed from the hypoDD method (Waldhauser and Ellsworth, 2000). The TomoDD method, combined with conventional travel-time tomography, utilizes the difference in travel-time residuals between adjacent earthquakes and the absolute travel times from earthquakes to stations for joint inversion of the source locations and velocity structure. In this study, the TomoDD method was adopted instead of hypoDD because it is more suitable for large-scale regional background seismicity with a broad spatial range and long temporal span, whereas hypoDD is more typically applied to small-scale dense earthquake sequences. The TomoDD method also enables simultaneous inversion of velocity structures to constrain the mechanisms of high and low b -value anomalies. We adopted a grid spacing of 0.3° in the horizontal direction, with finer 0.5° spacing on the western margin of the Ordos Block area. The depth

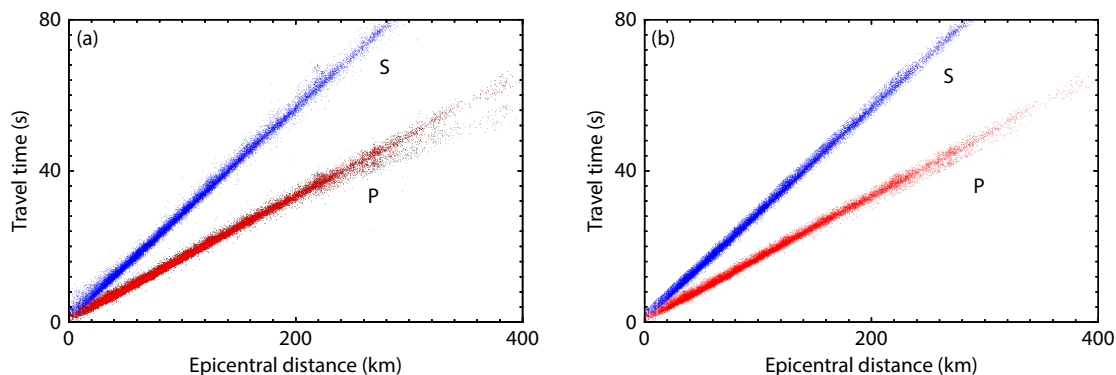


Figure 2. Travel time–epicentral distance curves for P and S waves. (a) Raw data; (b) selected data.

discretization primarily consisted of the following layers: -5, 0, 5, 10, 15, 20, 30, 40, and 60 km. To evaluate the reliability and spatial resolution capability of the tomographic inversion, we conducted checkerboard tests by setting the velocity model nodes to a spatial “alternating positive-negative checkerboard” pattern. During the calculation of theoretical travel times, we introduced random errors to assess the stability of the model under these conditions. The results indicated that at depths of 5, 15, and 20 km, the resolution was generally good across most areas, with clear grid patterns discernible (Figure 3). This finding was primarily attributed to the high density of seismic rays traversing the upper and middle crust. The initial velocity model was constructed by comprehensively referencing the USTClitho model (Xin HL et al., 2019) and the artificial seismic deep reflection models (Editorial Board of Geoscience Transect, State Seismological Bureau, 1992a, b; Yang MZ et al., 2007), as shown in Table 1. Given that the TomoDD method utilizes a damped LQSR (Least-Squares QR-factorization) algorithm, the selection of the damping factor and smoothing weight has a significant impact on the stability of the inversion results. Therefore, to enhance inversion stability, we tested various ranges of damping factors and smoothing weight factors, plotting the trade-off curves between data variance and model variance (Eberhart-Phillips, 1986; Lin GQ et al., 2010; Wang XN et al., 2015). We also tested various combinations of damping and smoothing parameters. The L-curves were constructed by varying the smoothing parameter with the damping parameter fixed, and by varying the damping parameter with the smoothing parameter fixed. The optimal combination of smoothing and

damping parameters was then determined. The optimal damping and smoothing parameters were determined to be 200 and 10, respectively (Figure 4).

For b -value calculation, we used the relocated earthquake catalog as the primary input for the ZMAP program (Wiemer, 2001) to calculate the maximum likelihood b -value. We then analyzed the magnitude–frequency curve and the standard deviations of b -values with magnitude to select an appropriate M_C for the b -value calculation. To analyze the influence of different minimum M_C values on b -value calculations, earthquakes with $M_L \geq 1.0$ on the western Ordos margin were selected. The b -value and its standard deviation were calculated using the maximum likelihood method (Utsu, 1966) and its error estimation (Woessner and Wiemer, 2005), respectively. Figure 5 shows that for the western Ordos margin, when $M_C \leq M_L 1.5$ and $M_C > M_L 2.5$, the calculated b -values exhibit larger variations and their standard deviations are significantly higher because of the smaller sample sizes. In contrast, when $M_C = M_L 1.6$ – 2.0 , the standard deviation of the b -value is relatively minimized. Furthermore, the magnitude–frequency relationship indicates a b -value of 0.75 ± 0.03 and an M_C of 1.6 ± 0.08 , estimated via the maximum likelihood estimation, where uncertainties were assessed through bootstrapping. Therefore, in this study we adopted $M_C = M_L 1.6$ as the lower magnitude cutoff for calculating the planar and cross-sectional b -values on the western Ordos margin. Only four earthquakes with $M_L \geq 5.0$ occurred during the study period. The 2025 Yinchuan $M_L 5.2$ event belongs to an earthquake swarm sequence (Xu YC, 2026). The 2012 Yongning $M_L 5.0$, the 2017 Guyuan $M_L 5.0$,

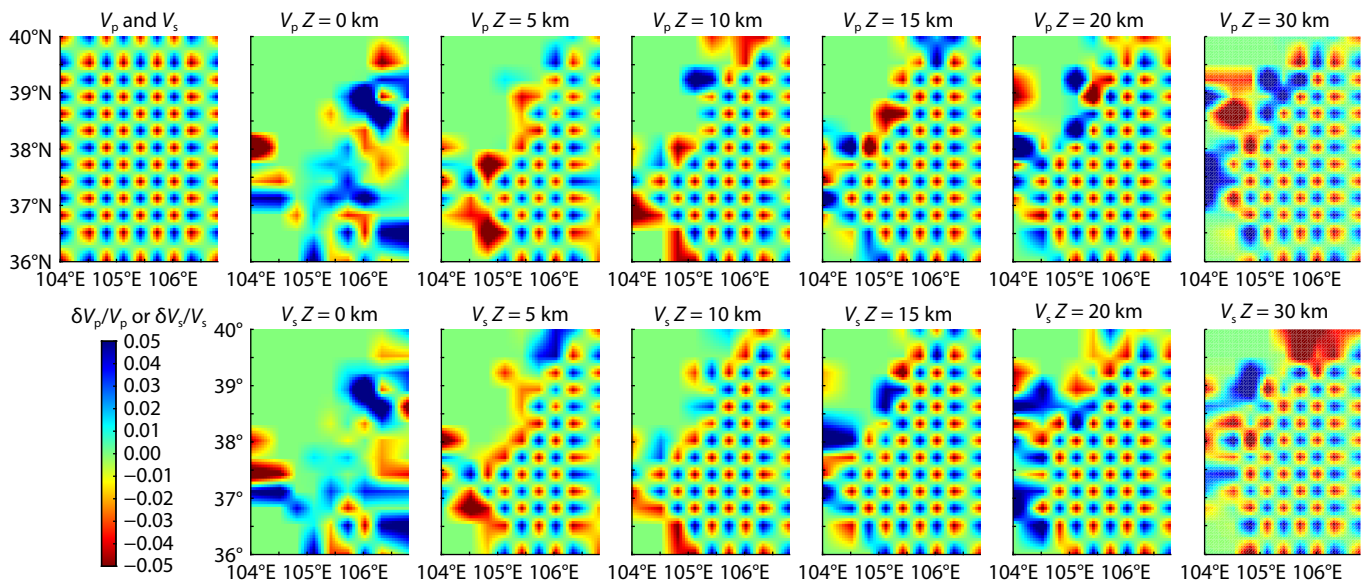


Figure 3. Checkerboard test results for different depth sections.

Table 1. Initial velocity model for the western margin of the Ordos Block.

Parameter	Top depth (km)							
	0	5	10	15	20	30	40	60
P-wave velocity (km·s ⁻¹)	4.706	5.608	5.923	6.139	6.260	6.632	6.909	7.949
V_p/V_s ratio	1.686	1.693	1.696	1.701	1.703	1.721	1.740	1.790

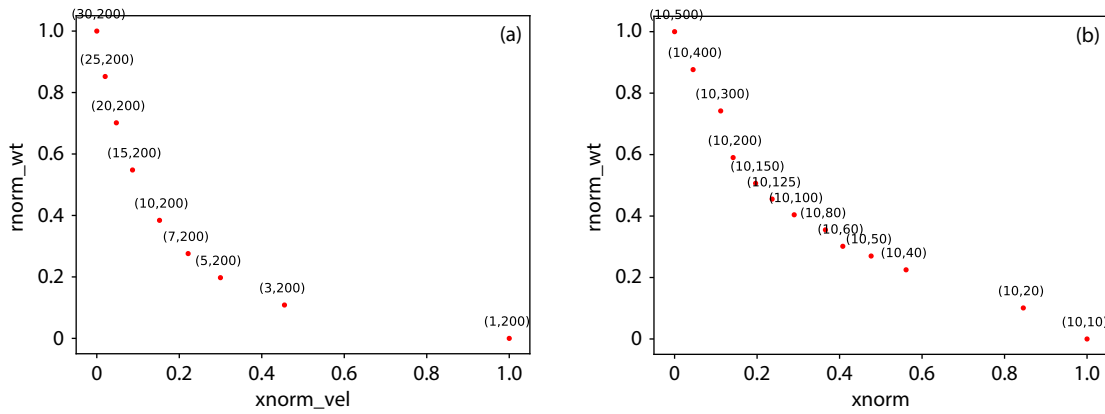


Figure 4. Optimal smoothing factor and damping parameter selected via the L-curve method. (a) L-curve for selecting the smooth regularization parameter; (b) L-curve for selecting the damp regularization parameter. The xnorm is the L2-norm of perturbations in earthquake locations and slowness, xnorm_vel denotes the L2-norm of slowness perturbations, and nrm_wt represents the weighted L2-norm of data-fitting residuals.

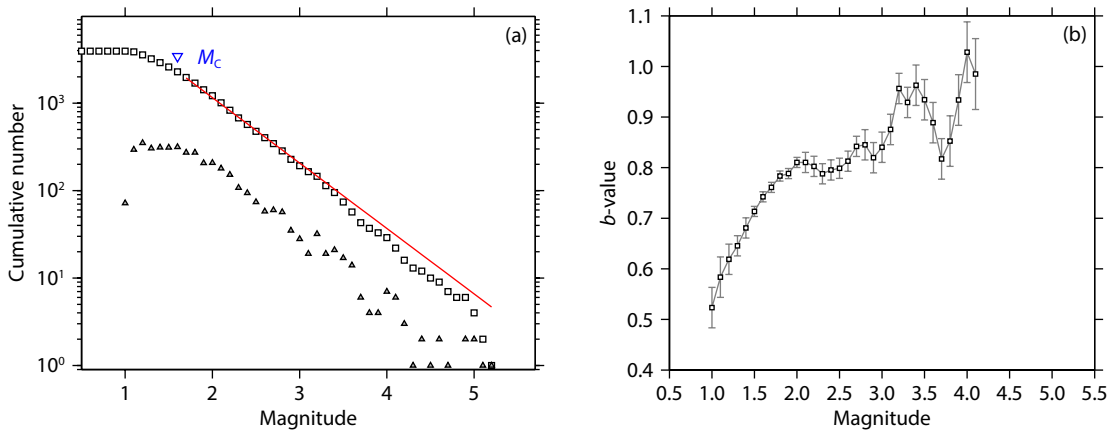


Figure 5. Earthquake magnitude–frequency curve (a) and variation in the b -value with magnitude (b).

and the 2023 Pingchuan M_L 5.3 earthquakes belong to isolated earthquake sequences with scarce aftershocks. These four $M_L \geq 5.0$ earthquake sequences are spatially restricted to discrete local areas and cannot alter the large-scale spatial pattern of b -values along the western margin of the Ordos Block. A fixed M_c of 1.6, determined from regional background seismicity, was adopted for all b -value calculations in this work. This threshold is fully consistent with the minimum detectable magnitude of M_L 1.6, which mostly applies in the local seismic network (Feng LL et al., 2019; Tang H et al., 2025), representing an inherent and stable detection capability unaffected by individual moderate earthquake events. We also examined whether M_c increased within the short period following these $M_L \geq 5.0$ mainshocks: the network detection capability depends mostly on permanent station configuration and instrumental performance, which remain stable before and after each $M_L \geq 5.0$ event and do not degrade in the post-mainshock window. The scarcity of small aftershocks for the three $M_L \geq 5.0$ isolated earthquakes reflects intrinsic tectonic behavior, rather than temporary underrecording of low-magnitude events. The maximum likelihood method was used to calculate the b -value at each node. The specific b -value calculation adopted the “Best combination” (M_c 95– M_c 90–MACX [maximum curvature]). A $0.02^\circ \times 0.02^\circ$ grid was established over the study area for b -value grid-

ding in the plane, with each grid node designed to accumulate 100 seismic events, halting the search upon reaching this threshold. To ensure the robustness of the results, two thresholds were tested (Figure S1): at least 20 and at least 50 earthquakes exceeding the M_c , respectively, for subsequent b -value estimation via the maximum likelihood method. A 1×1 km grid was established for b -value gridding in cross section along the strike of the fault zone, with each grid node fixed to search for 100 earthquakes. Correspondingly, two thresholds were adopted (Figure S1): at least 20 and at least 50 earthquakes exceeding the M_c . The width on either side of the cross-section profile mainly ranged from 40 to 60 km (determined by the specific fault zone and earthquake distribution). Low b -values were interpreted as indicators of relatively high stress and possible asperities, with a threshold of 0.7 (Yi GX et al., 2004, 2005, 2010; Zhu AL et al., 2009). Conversely, high b -values suggested relatively low stress or possible creep segments, using a threshold of 1.1 (Wiemer and Wyss, 1997).

For strong earthquake hazard analysis, the identification of small earthquake sparse segments or voids, which contain partial asperities, is a key step in delineating potential strong earthquake sources. Asperities refer to regions of high strength on active fault zones, typically characterized by high surface roughness, high fric-

tion, and low pore pressure. Consequently, the fault segments hosting asperities often exhibit high stress and a relatively locked behavior, and during earthquakes, they control the main rupture and release the primary energy (Aki, 1984; Wiemer and Wyss, 1997; Wyss et al., 2000; Yi GX et al., 2004). Therefore, asperities are the most likely potential hazardous segments for strong earthquakes on a fault zone. Because the stress level is inversely proportional to the b -value in the magnitude–frequency relationship (Scholz, 1968; Urbancic et al., 1992), it is possible to map asperities on active fault zones based on low b -value distributions (Wiemer and Wyss, 1997; Wyss et al., 2000). A comprehensive analysis can be performed by using integrated data, such as precise earthquake locations, low b -values, locked faults (or other GPS observations), and large earthquake rupture gaps or zones. Among these, precise earthquake locations provide the fundamental data for delineating small earthquake sparse segments or voids, and the b -value is one of the most basic tools for studying asperities, strong earthquake hazards, and seismic potential. By mapping the spatial extent of regions below the average background b -value and combining them with the different magnitude–source rupture length relationships $M_S = 3.3 + 2.1 \lg L$ (Guo ZJ and Qin BY, 1979), $M_S = 6.11 + 0.86 \lg L$ (Deng QD et al., 1992), $M_S = 6.0705 + 0.8205 \lg L$ (Ye WH et al., 1996), $M_S = 1.860 \lg L + 3.821$ (Long F et al., 2006), $M_W = 4.33 + 1.49 \lg L$ (Wells and Coppersmith, 1994), the theoretical seismic potential of various small earthquake sparse segments and low b -value areas can be evaluated. From the perspective of historical strong earthquakes ($M \geq 6$) related to b -value anomalies and sparse earthquake segments of the fault zone, we can further assess the potential strong earthquake hazard of these sparse earthquake segments within the fault zones.

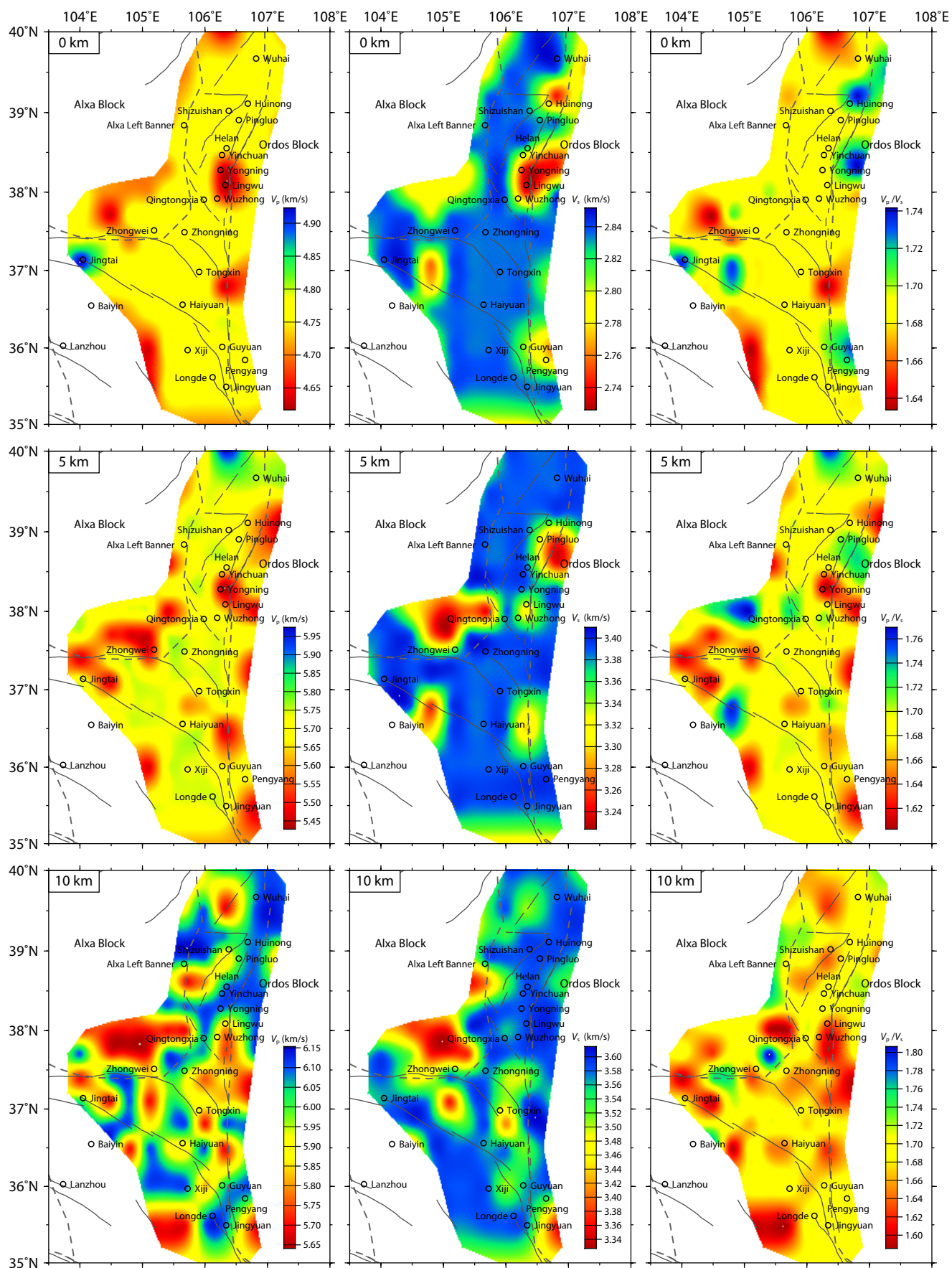
3. Results

3.1 Distribution Patterns of Crustal Velocity Structure

Combined with the results of horizontal slices at different depths (Figure 6), the shallow velocity structure at 0–5 km depth is significantly affected by surface sediments and topography. A prominent low-velocity zone exists in the Yinchuan–Wuzhong area in the northern part of the study region, which corresponds to the central-southern Yinchuan Basin with a thick sedimentary cover, the concentration of multiple subsidence centers of the Yinchuan Graben, and the location of the thickest sedimentary layer in the basin. The low-velocity zone, thick sedimentary area, and subsidence centers are spatially consistent. Low-velocity anomalies are rare in other parts of the study area, especially in the southern regions of Zhongning, Tongxin, Haiyuan, and Jingyuan, where no large-scale thick sedimentary layers exist. This area belongs to the orogenic belt of the arcuate tectonic zone at the northeastern margin of the Tibetan Plateau, where the surface is dominated by bedrock, with only thin sediments locally distributed near the southern margin of the Alxa Block. In addition, at the 0–5 km depth range, regions with synchronous low P- and S-wave velocities indicate sedimentary cover and thin sediments. In contrast, regions with normal P-wave velocities, high S-wave velocities, and low V_P/V_S ratios reflect fractured bedrock areas with low fluid content in most parts of the study area. Velocity distributions at

10 and 15 km depths reflect structural variations in the upper crust. A relatively low-velocity zone with synchronous low P- and S-wave velocities occurs in the Qingtongxia–Zhongwei area along the southern margin of the Alxa Block. High velocities in the Yinchuan Basin are mainly distributed in the basin interior, whereas the basin margins show relatively low velocities. In the southern part of the study area, the Jingtai, Xiji, and Longde regions are generally characterized by high velocities and low V_P/V_S ratios. The regions with relatively low V_P/V_S ratios at 10–15 km depth are mainly concentrated in Haiyuan–Longde, Wuzhong–Lingwu, and Pingluo–Huinong. The 20–30 km depth range mainly corresponds to the middle and lower crust. Among them, the Jingtai–Baiyin–Haiyuan region shows obvious high P-wave velocities but relatively low S-wave velocities, accompanied by significant variations in high and low V_P/V_S ratios. The Helan–Pingluo area also exhibits obvious high velocities for both P and S waves. The remaining regions, especially the southern part of the study area, are dominated by relatively low velocities with alternating high- and low-velocity anomalies, reflecting that the middle and lower crust in the northern part of the study area has a relatively stable velocity structure, whereas the southern part shows significant lateral heterogeneity. The middle and lower crust in the arcuate tectonic zone at the northeastern margin of the Tibetan Plateau generally exhibits a fractured and relaxed structural feature dominated by multi-layer alternating high- and low-velocity zones.

The crustal velocity results of this study are basically consistent with previous understandings of the crustal velocity structure from the northeastern margin of the Tibetan Plateau to the Yinchuan Basin. Existing studies show clear regional distinctions: Liu BJ et al. (2017) and Wang WL et al. (2023) focused on the crustal structure of the northern Helan Mountain–Yinchuan Basin tectonic belt, whereas Cheng B et al. (2016), Guo HL and Ding ZF (2018), and Zhang YP et al. (2025) mainly characterized the crustal architecture of the northeastern Tibetan Plateau arcuate tectonic zone. Our layered velocity features match these published results well in both the northern and southern subregions. In the northern Yinchuan Basin area, our widespread shallow low-velocity anomalies, controlled by thick basin sediments, agree well with the velocity model of the Yinchuan Fault System (Wang WL et al., 2023). The upper-crust velocity differentiation between high-velocity basin interiors and low-velocity margins, as well as the stable high velocities in the middle and lower crust of the Helan–Pingluo area, are also consistent with the lithospheric structural framework of the Yinchuan–Helan tectonic belt (Liu BJ et al., 2017). The southern study area corresponds to the complex arcuate orogenic belt of the northeastern Tibetan Plateau. The prominent lateral heterogeneity, alternating high- and low-velocity layers, and variable V_P/V_S ratios in the middle and lower crust are consistent with the regional results of Cheng B et al. (2016), Guo HL and Ding ZF (2018), and Zhang YP et al. (2025). These models constrain the fractured and heterogeneous crustal structure of the Tibetan Plateau margin well, supporting our geological interpretations for the southern study area. Overall, previous studies have generally focused separately on either the northern basin or southern orogenic belt. Our high-resolution model provides a unified velocity characterization across the entire transition zone,



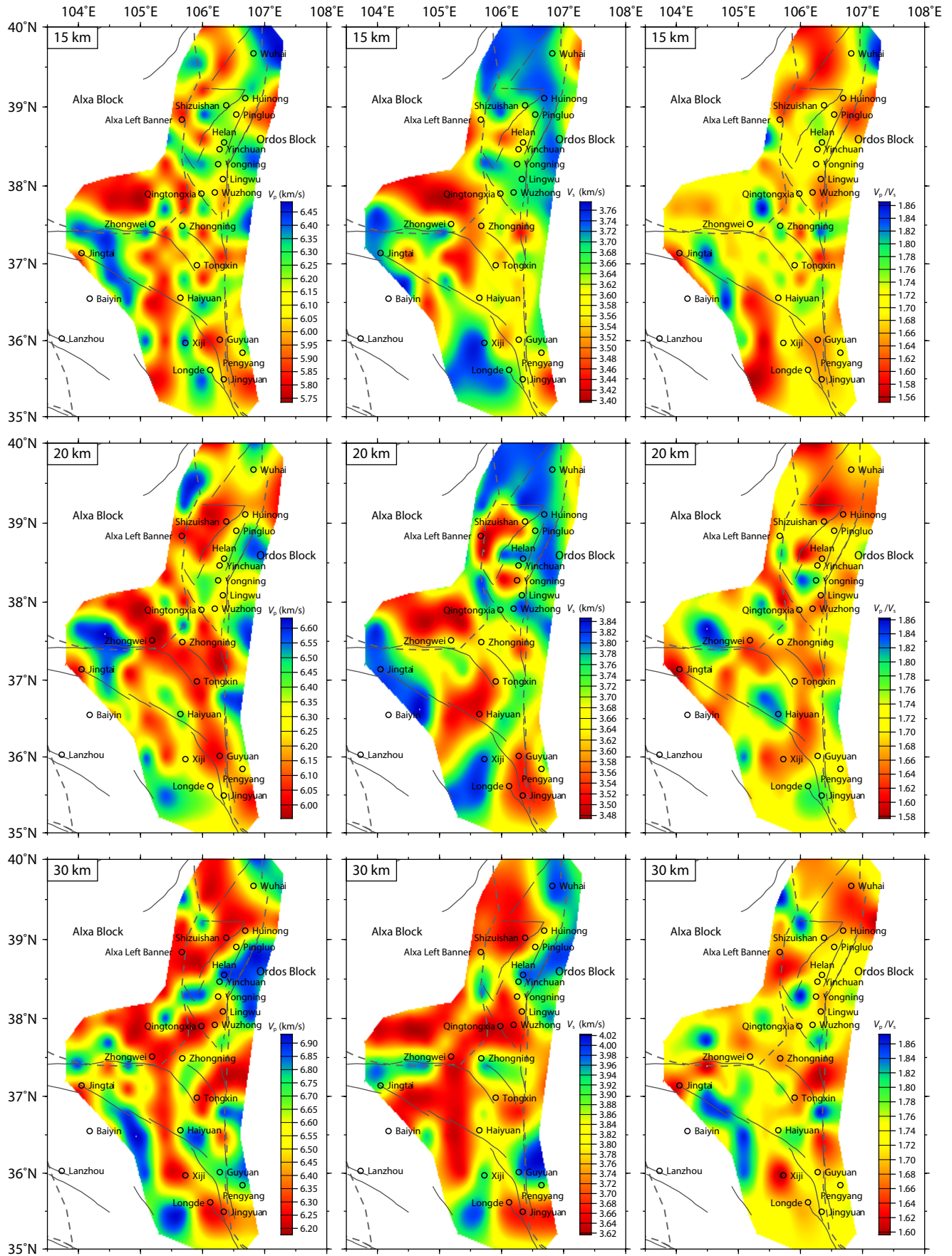


Figure 6. Horizontal slices of the P-wave velocity, S-wave velocity, and V_p/V_s ratio at different depths on the western Ordos margin.

improving the credibility of the derived crustal structure and the rationality of the geological interpretation.

3.2 Spatial Characteristics of Relocated Earthquake Hypocenters and b -Value

From the planar map (Figure 7a), it can be seen that precisely relocated earthquakes are mainly distributed along active fault zones, including the Yinchuan Basin Fault System with dominant NNE–SSW strikes, the Xiangshan–Tianjingshan to Yantongshan Fault System with dominant NWW–SEE strikes, and the Haiyuan–Liupanshan Fault System with dominant NW–SE strikes. From the planar b -value map derived from the precisely relocated earthquake catalog (Figure 7b), regions with relatively low b -values below 0.7 are mainly distributed in Huinong on the northern margin of the Yinchuan Basin, Yinchuan–Yongning–Lingwu in the central-southern Yinchuan Basin, Zhongning to Tongxin along the southeastern segment of the Tianjingshan Fault, and Jingtai to Haiyuan along the western segment of the Haiyuan Fault. Regions with relatively high b -values above 1.1 are mainly located in Qingtongxia–Zhongning west of the Niushoushan Fault Zone and Guyuan to Jingyuan along the Liupanshan Fault Zone. The spatial distribution pattern of relatively high and low b -values in this study is generally consistent with previous results across most regions (Liang XJ et al., 2019; Zeng XW et al., 2021; Feng P, 2022). Depth profiles (Figures 7c–7e) across the three major fault systems show characteristic seismicity generally concentrated within 0–30 km depth, with clear along-strike variations in seismic density. Multiple prominent seismic gaps are identified along these profiles (Table 2), with lengths ranging from several kilometers to approximately 100 km. Corresponding b -value distributions reveal characteristic widespread low b -value zones (<0.7) along most fault sections, particularly around identified seismic gaps. In some sections, b -values also exhibit characteristic strong depth-dependent stratification, mostly with low b -values in the deeper seismogenic layer and high b -values in the shallow part.

4. Discussion

4.1 Fault Sparse Segment Magnitude Assessment, Potential Asperities, and the Linkage to Historical and Modern Earthquakes

When historical earthquakes of $M \geq 6$ and modern earthquakes of $M_L \geq 5.0$ (Figure 7a) were combined with map-view b -value distributions (Figure 7b), it was apparent that some large historical earthquakes had occurred in low b -value regions, including the 1143 Yinchuan $M 6\frac{1}{2}$, the 1477 Yinchuan $M 6\frac{1}{2}$, the 1561 Zhongning $M 7\frac{1}{4}$, the 1622 Guyuan $M 7$, the 1920 Haiyuan $M 8\frac{1}{2}$, the 1920 Haiyuan $M 7$, and 1921 Haiyuan $M 6$ earthquakes. Some historical earthquakes lie outside low b -value domains, likely because of mismatched occurrence times between historical earthquakes and the 2009–2025 earthquake catalog used for b -value calculation. By contrast, all modern $M_L \geq 5.0$ earthquakes since 2009—the 2012 Yongning $M_L 5.0$, the 2017 Guyuan $M_L 5.0$, and the 2025 Yinchuan $M_L 5.2$ events—occurred within low b -value regions, consistent with the modern background b -value computed for 2009–2025. Map-view low b -value domains may be interpreted as

potential asperities. From Figures 7c–7e, we can see that sparse earthquake segments of the fault zone are not necessarily all low b -value areas, and low b -value areas may also be earthquake-concentrated areas; not all sparse earthquake segments completely coincide with low b -value areas ($b < 0.7$). However, when sparse earthquake segments spatially overlap significantly with low b -value areas, these overlapping areas are more likely to represent regions of high stress accumulation.

Along the A–A' depth profile from Zhongning to Wuhai (representing the NNE–SSW fault system of the Yinchuan Basin), two modern $M_L \geq 5.0$ earthquakes occurred: the 2012 Yongning $M_L 5.0$ ($M_S 4.6$) and 2025 Yongning $M_L 5.2$ ($M_S 4.8$) events (Figure 7c), both near the edge of sparse earthquake segment ① at ~ 5 km depth. The use of $L = 5$ km in magnitude–rupture length scaling relations (Table 2) yields theoretical magnitudes of $M 4.77$ – 6.71 . With this relation (Guo ZJ and Qin BY, 1979), the magnitude M_S is calculated to be 4.77, consistent with the observed magnitude of the 2025 Yongning $M_S 4.8$ earthquake. Five historical $M \geq 6.0$ earthquakes occurred along this profile, and the theoretical magnitudes for sparse earthquake segments ② to ⑤ are $M 6.03$ – 7.23 , $M 7.31$ – 7.83 , $M 6.54$ – 7.44 , and $M 7.03$ – 7.67 , respectively (Table 2). The 1739 Pingluo $M 8$ earthquake, with focal depths of ~ 20 km (Chai CZ et al., 2011) and ~ 24 km (Yang MZ et al., 2007), lies near the lower boundary of sparse earthquake segment ③. Its magnitude is close to the upper limit of sparse earthquake segment ③ ($M 7.31$ – 7.83). Combining sparse earthquake segments ③ and ④ yields $M 7.50$ – 7.94 (Table 2), even closer to the 1739 Pingluo $M 8$ earthquake. Because most of gaps ③ and ④ have normal b -values, the Helan–Pingluo area has a relatively low probability of large near-future earthquakes. In contrast, sparse earthquake segments ①, ②, and ⑤ are mostly low b -value domains and hosted historical events, including the 876 Qingtongxia $M 6\frac{1}{2}$, the 1477 Yinchuan $M 6\frac{1}{2}$, and the 1921 Yinchuan $M 6$ earthquakes, consistent with their theoretical magnitude ranges. A high b -value domain ($b > 1.1$) in the Qingtongxia–Wuzhong area coincides with modern earthquake swarms (Yang MZ et al., 2007; Xu YC et al., 2022) and likely represents a creeping segment.

Along the B–B' depth profile from Zhongwei to Tongxin (NWW–SEE striking the Yantongshan–Tianjingshan Fault Zone), no $M_L \geq 5.0$ earthquakes occurred during the 2009–2025 period, but three historical $M \geq 6.0$ events lie within or near the lower boundary of sparse earthquake segment ① (Figure 7d). Its theoretical magnitude range ($M 7.24$ – 7.79) is almost consistent with the 1709 Zhongwei $M 7\frac{1}{2}$ earthquake. Given its normal b -value, the Zhongwei segment poses a relatively low hazard. In the southeastern Zhongning–Tongxin section, sparse earthquake segments ②, ③, and ④ yield theoretical magnitudes of $M 5.77$ – 7.12 , $M 5.77$ – 7.12 , and $M 6.03$ – 7.23 , respectively (Table 2). Combining these shallowly adjacent gaps gives $M 6.86$ – 7.57 . The highest b -value region ($b > 1.1$) near Zhongning likely represents a creeping or low-stress zone.

Along the C–C' depth profile from Baiyin to Pengyang (dominated by the NW–SE-striking Haiyuan–Liupanshan Fault System), two modern $M_L \geq 5.0$ earthquakes occurred during the 2009–2025

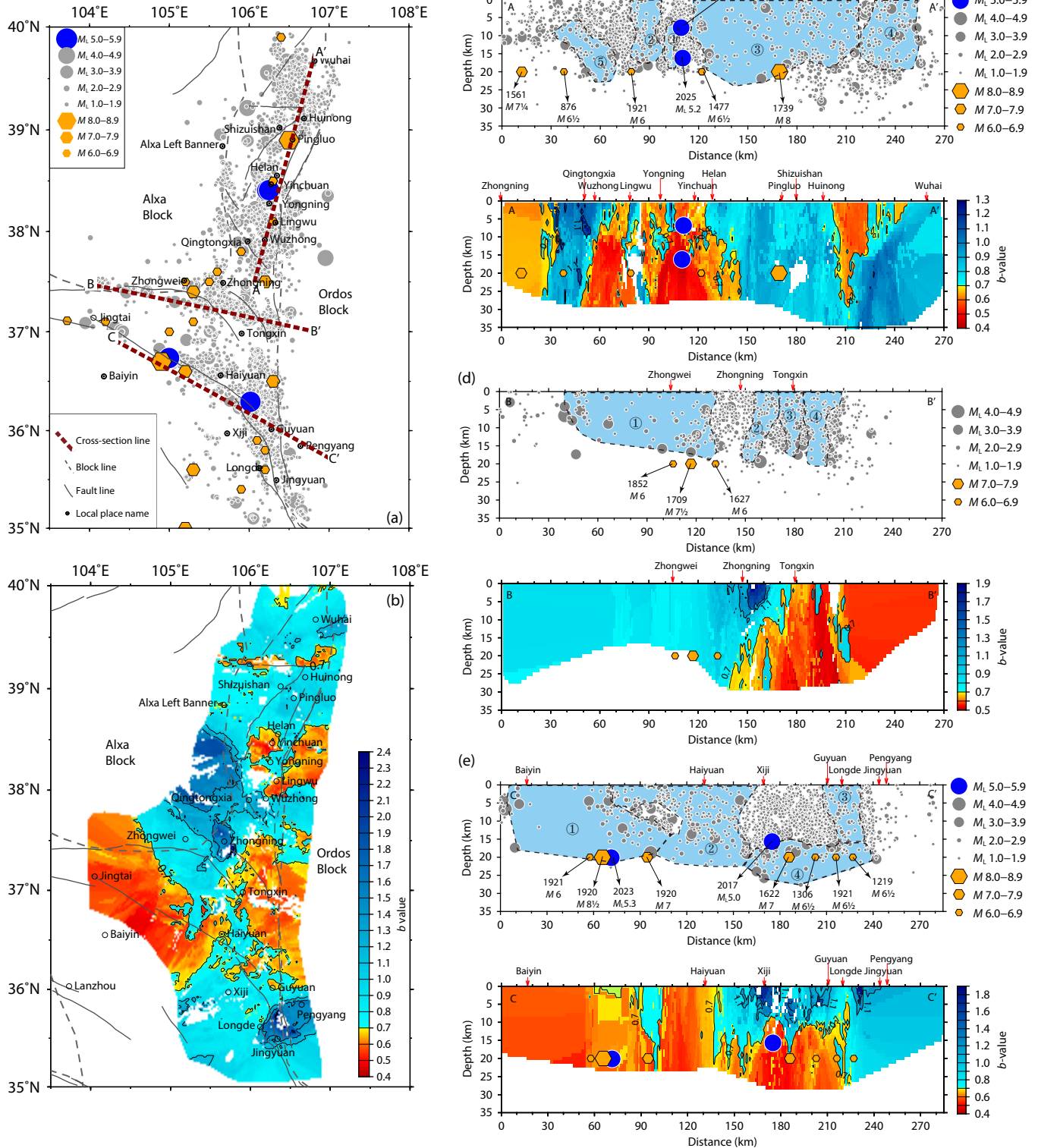


Figure 7. Epicentral and depth-profile distributions, and corresponding map- and profile-view b -value patterns on the western Ordos margin. (a) Epicenter distribution of relocated earthquakes, historical earthquakes with $M \geq 6.0$, and layout of cross-section lines; (b) Spatial planar distribution of the b -value calculated from the relocated earthquake catalogue; (c) Earthquake depth distribution and b -value distribution along profile A-A'; (d) Earthquake depth distribution and b -value distribution along profile B-B'; (e) Earthquake depth distribution and b -value distribution along profile C-C'.

period: the 2017 Guyuan M_L 5.0 (M_S 4.6) and 2023 Pingchuan M_L 5.3 (M_S 4.9) events (Figure 7e), both near gap boundaries and within low b -value domains. Seven historical $M \geq 6.0$ earthquakes occurred along this profile. The 1920 Haiyuan M 8½, the 1920 Haiyuan M 7, and the 1921 Haiyuan M 6 events lie within sparse earthquake segments ① and ②, with theoretical magnitude ranges of M 7.31–7.83 and M 7.24–7.79, respectively (Table 2). Combining segments ① and ② yields M 7.73–8.09 (Table 2), consistent with the revised magnitude M_W 7.9 ± 0.2 (Liu J et al., 2023) for the 1920 Haiyuan earthquake. Sparse earthquake segments ① and ② are extensive low b -value domains, indicating a significant hazard on the western Haiyuan Fault (Baiyin to Haiyuan). The 1622 Guyuan M 7, the 1306 Guyuan M 6½, the 1921 Guyuan M 6½, and the 1219 Guyuan M 6½ events mainly lie within sparse earthquake segments ④ and ③ (eastern Haiyuan to Liupanshan Fault), with theoretical ranges of M 7.17–7.75 and M 6.24–7.31 (Table 2), matching the observed M 6½–7. Low b -values persist below 15 km in sparse earthquake segment ④, suggesting seismogenic depths >15 km for large historical earthquakes in Guyuan. Integrated geological, geodetic, and seismological studies (Du F et al., 2018; Yu SH, 2023) have indicated strong fault locking and high hazard on the Liupanshan Fault, which exhibits both seismic gaps and low b -values. Since the 1921 Guyuan M 6½ event, the Liupanshan Fault has likely accumulated stress equivalent to an event of M_W 6.7–7.3. A prominent high b -value domain ($b > 1.1$) at depths of <15 km in Guyuan and adjacent areas may correspond to a creeping zone and hosts earthquake swarms in southern Ningxia (Yang MZ et al., 2007; Xu YC et al., 2024). These

inferences regarding possible locked and creeping segments from b -values, moreover, require further validation with constraints from the crustal velocity structure of this work.

4.2 Crustal Velocity Constraints on b -Value-Inferred Locked and Creeping Fault Segments

Various studies have established a consensus that fault slip behavior is jointly constrained by seismic b -values (Wiemer and Wyss, 1997; Yi GX et al., 2004, 2005; Wen XZ et al., 2013) and V_p/V_s ratios (Guo H et al., 2018; Chiba, 2020; Contreras-Reyes et al., 2024). Specifically, low b -values (<0.7) coupled with low V_p/V_s ratios (<1.7) mark strongly locked fault segments, whereas low b -values (<0.7) with high V_p/V_s ratios (≥ 1.8) suggest unstable locked structures affected by local fluid disturbance. High b -values (>1.1) generally indicate creeping behavior, which can be further subdivided based on velocity ratio features: fluid-mediated creep corresponds to high V_p/V_s ratios (≥ 1.8), and friction-governed creep occurs under normal (1.70–1.79) or low V_p/V_s (<1.7) conditions with limited fluid participation. The three geophysical profiles (A–A', B–B', and C–C') crossing the study area provide clear evidence to verify this relationship.

Along the A–A' profile from Zhongning to Wuhai (Figure 8a, Table 3), multi-parameter distributions reveal a highly heterogeneous fault mechanical state along the strike. The 0–50 km segment (Zhongning to Qingtongxia) displays a clear bimodal b -value pattern. The left half (0–30 km, including the 1561 M 7¼ event) has low b -values (<0.7) paired with moderate V_p , V_s , and partly low

Table 2. Estimation of theoretical earthquake magnitudes of sparse segments in major active fault profiles of the western Ordos margin.

Profile	Sparse earthquake segments	L	$M_S = 3.3 + 2.1 \lg L$ (Guo ZJ and Qin BY, 1979)	$M_S = 6.11 + 0.86 \lg L$ (Deng QD et al., 1992)	$M_S = 6.0705 + 0.8205 \lg L$ (Ye WH et al., 1996)	$M_S = 1.860 \lg L + 3.821$ (Long F et al., 2006)	$M_W = 4.33 + 1.49 \lg L$ (Wells and Coppersmith, 1994)
A–A'	①	5	4.77	6.71	6.64	5.12	5.37
	②	20	6.03	7.23	7.14	6.24	6.27
	③	100	7.50	7.83	7.71	7.54	7.31
	④	35	6.54	7.44	7.34	6.69	6.63
	③ + ④	135	7.77	7.94	7.82	7.78	7.50
	⑤	65	7.11	7.67	7.56	7.19	7.03
B–B'	①	90	7.40	7.79	7.67	7.46	7.24
	②	15	5.77	7.12	7.04	6.01	6.08
	③	15	5.77	7.12	7.04	6.01	6.08
	④	20	6.03	7.23	7.14	6.24	6.27
	② + ③ + ④	50	6.87	7.57	7.46	6.98	6.86
C–C'	①	100	7.50	7.83	7.71	7.54	7.31
	②	90	7.40	7.79	7.67	7.46	7.24
	③	25	6.24	7.31	7.22	6.42	6.41
	④	80	7.30	7.75	7.63	7.36	7.17
	① + ②	190	8.09	8.07	7.94	8.06	7.73

Note: L denotes the length of the sparse segment along the strike of the profile. The numeric labels correspond to the positions of sparse-earthquake segments in Figure 7.

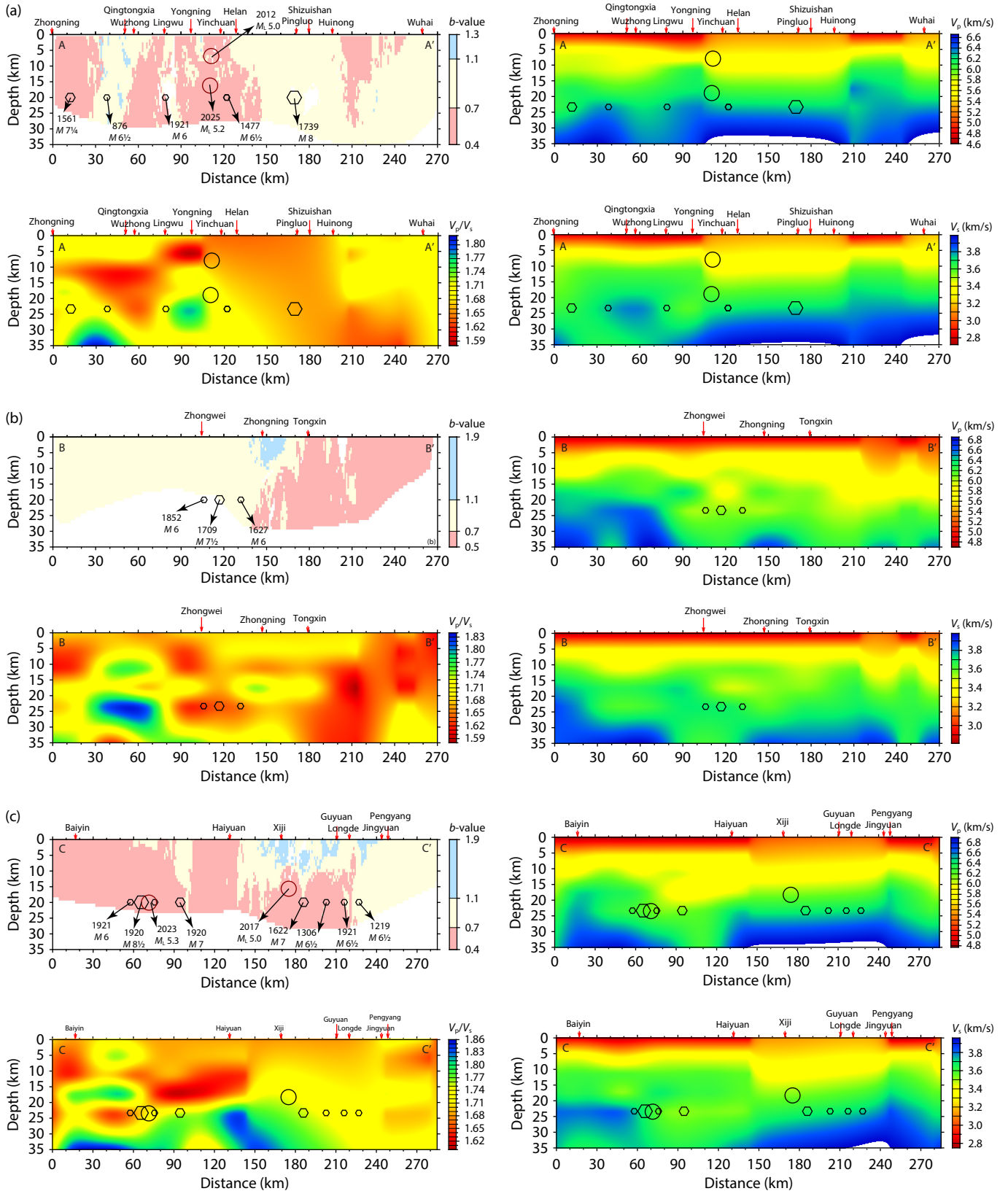


Figure 8. Comparison of b -value profiles and corresponding P-wave velocity, S-wave velocity, and V_p/V_s ratio profiles. (a) Distributions of b -value, P-wave velocity, S-wave velocity and V_p/V_s ratio along profile A-A'; (b) Distributions of b -value, P-wave velocity, S-wave velocity and V_p/V_s ratio along profile B-B'; (c) Distributions of b -value, P-wave velocity, S-wave velocity and V_p/V_s ratio along profile C-C'. In the velocity models, red represents low-velocity zones and blue represents high-velocity zones; in the b -value sections, pale red indicates low values (locked zones), pale yellow indicates intermediate values (normal stress regions), and pale blue indicates high values (creeping zones).

Table 3. Statistical characteristics of b -value, V_p/V_s ratio, and fault mechanical state classification in the western Ordos Block.

Profile	Segment	Depth (km)	Mean b -value	Mean V_p/V_s	Coupled characteristics	Present-day fault mechanical state
A–A' (Zhongning to Wuhai)	Zhongning to Qingtongxia (along profile 0–30 km)	0–25	0.65	1.68	Low b -value; low V_p/V_s	Locked asperity
	Qingtongxia to Wuzhong (along profile 40–50 km)	5–10; 15–25	1.17	1.66	High b -value; low V_p/V_s	Creep segment
	Wuzhong to Yinchuan (along profile 50–140 km)	0–25	0.58	1.63	Low b -value; low V_p/V_s	Locked asperity
	Pingluo earthquake segment (along profile 150–200 km)	0–25	0.84	1.66	Normal b -value; low V_p/V_s	Stable barrier
	Huinong to Wuhai (along profile 200–240 km)	0–25	0.62	1.68	Low b -value; low V_p/V_s	Locked asperity
B–B' (Zhongwei to Tongxin)	Zhongning shallow segment (along profile 140–160 km)	0–10	1.44	1.70	High b -value; normal V_p/V_s	Creep segment
	Zhongwei earthquake segment (along profile 90–140 km)	20–25	0.85	1.65	Normal b -value; low V_p/V_s	Stable barrier
	Tongxin segment (along profile 180–270 km)	0–25	0.58	1.64	Low b -value; low V_p/V_s	Locked asperity
C–C' (Baiyin to Pengyang)	Haiyuan earthquake segment (along profile 0–140 km)	0–25	0.60	1.67	Low b -value; low V_p/V_s	Locked asperity
	Guyuan shallow segment (along profile 150–240 km)	0–10	1.39	1.70	High b -value; normal V_p/V_s	Creep segment
	Guyuan deep segment (along profile 140–230 km)	10–25	0.61	1.74	Low b -value; normal V_p/V_s	Locked asperity

V_p/V_s ratios, indicating a high-stress fault zone without significant fluid anomalies. The right half (30–50 km, including the 876 M 6½ event) features normal to high b -values (0.7–1.1) and predominantly low V_p/V_s ratios under lower ambient stress. High b -value zones are restricted to this section (40–50 km), with a small zone of high b -values (1.1–1.3) between Qingtongxia and Wuzhong associated with earthquake swarms. The persistently low V_p/V_s ratios across these high b -value regions demonstrate that local creep is friction governed rather than fluid mediated. Moving eastward, the segment from 50–140 km (Wuzhong to Yinchuan) exhibits widespread low b -values (<0.7) at 0–25 km depth, forming a continuous high-stress zone that overlaps with the 1477 M 6½, 1921 M 6, 2012 M_L 5.0, and 2025 M_L 5.2 event. Here, low b -values mostly coincide with low V_p/V_s ratios as well as high V_p and V_s , indicating strongly locked asperities with ongoing stress accumulation. Further along strike, the 1739 Pingluo M 8 earthquake lies within a large zone (150–200 km) where V_p/V_s ratios are low but b -values remain normal. This combination indicates that although the area still hosts rigid, intact rock media (the material basis of an asperity or barrier), the 1739 Pingluo M 8 earthquake rupture has already released most of its accumulated strain energy, resulting in postseismic stress relaxation and a normal b -value signature today. The segment (200–240 km, Huinong to Wuhai) is characterized by partly low b -values across most depths, with generally high V_p and V_s as well as low V_p/V_s ratios, indicative of a rigid fault zone under elevated stress and free of fluid influence. Overall, these observations highlight the need for heightened seismic hazard assessment in the Wuzhong–Lingwu and Yongning–

Yinchuan areas.

Along the B–B' profile from Zhongwei to Tongxin (Figure 8b, Table 3), the small-scale segment beneath Zhongning at 0–10 km depth shows high b -values (>1.1), possibly indicative of creeping behavior. However, the corresponding V_p/V_s ratios in this region (0–10 km depth) remain normal, with no significant high-ratio anomalies observed. The V_p and V_s reveal generally low velocities in this area, consistent with a highly fractured fault zone. This combination (high b -value and normal V_p/V_s ratio) is characteristic of friction-governed creep in fractured rock, where slip is controlled by fragmented fault gouge rather than fluid mediation. This explains the absence of high V_p/V_s anomalies in these shallow, creeping zones. The 1709 Zhongwei M 7½ earthquake, together with the 1852 and 1627 M 6 events, occurred in a region with normal b -values (0.7–1.1) and low V_p/V_s ratios. The corresponding V_p and V_s are relatively high and spatially stable, indicating an intact and rigid rock mass. This combination (normal b -value and low V_p/V_s ratio) is interpreted as a stable asperity or barrier on the fault plane. Unlike strongly locked segments defined by low b -values, this zone lacks sustained high stress accumulation and does not currently show the low b -value signature of a strong locked region, suggesting a low probability of large earthquakes occurring here again, even though its high rigidity made it a key location for stress release during past strong earthquakes. In contrast, the segment from 180 to 270 km along the profile near Tongxin shows a coexisting low b -value anomaly (<0.7) and low V_p/V_s ratio, with corresponding high V_p and V_s . This

combination meets the criteria for a strongly locked fault segment, corresponding to the southeastern segment of the Tianshanjing Fault Zone, which lacks historical records of strong earthquakes. The persistent low b -values (indicating high stress accumulation), together with the low V_p/V_s ratio and the absence of major historical ruptures, suggests that the Tongxin area on the southeastern segment of the Tianshanjing Fault Zone currently has a relatively high seismic hazard potential for strong earthquakes.

Along the C–C' profile from Baiyin to Pengyang (Figure 8c, Table 3), the 0–140 km segment (Baiyin to Haiyuan) hosting the 1920 Haiyuan M 8½ earthquake exhibits pronounced low b -values (<0.7), paired with mostly low V_p/V_s ratios as well as high V_p and V_s . This combination (low b -values, low V_p/V_s ratios, and high seismic velocities) confirms the presence of a strongly locked asperity. The rigid, intact rock mass here has historically accumulated and released large amounts of strain energy, culminating in the catastrophic 1920 Haiyuan M 8½ earthquake rupture. In contrast, the Guyuan segment (150–240 km) displays a prominent high b -value (>1.1) at shallow depths of 0–10 km, with corresponding V_p/V_s ratios ranging from normal to slightly low and no significant fluid-related high-ratio signals. Seismic velocity models show generally low V_p and V_s in this area, reflecting a highly fractured fault zone. This signature (high b -values coupled with near-normal to modestly lower V_p/V_s ratios) aligns with the friction-governed creep mechanism, where slip is accommodated by fragmented fault gouge and low-friction materials rather than fluid overpressure. Deeper within the Guyuan segment (10–25 km depth), the pattern shifts dramatically to a regime of persistently low b -values coupled with near-normal V_p/V_s ratios. Unlike the shallow, fractured zone, V_p and V_s velocities at these depths show no significant reduction, indicating a rigid, low-fluid crystalline basement. This combination of low b -values and near-normal V_p/V_s ratios, together with relatively high seismic velocities, still delineates a brittle, high-stress locked segment beneath the shallow creep zone. Collectively, these observations highlight elevated seismic hazard potential in two key segments: the western Haiyuan Fault Zone (strongly locked asperity with a historical M 8½ rupture) and the eastern Haiyuan–Liupanshan Fault section at 15–20 km depth (persistent low b -values and locked conditions). These zones warrant heightened attention in seismic hazard assessment.

Thus, joint analysis of b -values and V_p/V_s ratios is necessary to differentiate locked and creeping fault segments. Conventionally, high b -values with high V_p/V_s ratios are interpreted as fluid-driven creep. However, no high b -value zones with high V_p/V_s ratios were identified in the study area, suggesting that fluid-mediated creep is not a dominant process here. Instead, the high b -value creeping zones with normal or low V_p/V_s ratios found in this work are controlled by fault stress and friction. As lower differential stress yields higher b -values (Schorlemmer et al., 2005), stable creep occurs under low stress and produces only minor earthquakes without fluid participation. Stress friction-dominated creep features have been confirmed by b -value and creep rate variations (Tormann et al., 2013). Related friction tests also prove fault materials can maintain steady creep with negligible fluid effect (Carpenter et al., 2015). Two typical fault states revealed in this

work are classified herein: low b -values paired with low V_p/V_s ratios represent strongly locked segments, whereas high b -values with normal or low V_p/V_s ratios correspond to friction-governed creep, rather than fluid-mediated creep. In this study, locked asperities are characterized by low b -values (<0.7) coupled with low or normal V_p/V_s , reflecting a high stress concentration and competent, fluid-poor crustal materials. In contrast, stable barriers show normal b -values and low V_p/V_s , indicating moderate stress levels and rigid, intact rock masses that resist rupture propagation. These barrier zones were major rupture areas of great earthquakes that occurred in the past nearly 300 years and that have evolved into stable barriers ever since.

5. Conclusions

In this study, we conduct a macro-scale assessment of strong earthquake hazards along the major active fault zones on the western Ordos margin. It integrates velocity structure, earthquake relocation, b -value analysis, sparse earthquake segments of the fault zone, and magnitude–rupture length relationships. By analyzing these factors, we delineate the seismogenic potential of key tectonic belts in the region.

Seismicity within the study area is spatially clustered along active fault strike directions, with focal depths predominantly ranging from 0 to 25 km. Sparse earthquake segments of the fault zone are widely distributed across all major tectonic units, and their spatial relationship with b -value anomalies exhibits clear heterogeneity: low b -values (<0.7) do not universally coincide with these sparse segments, but their spatial overlap may reliably indicate high-stress accumulation, and these high-stress areas are predominantly characterized by low V_p/V_s ratios, representing locked fault segments and potential seismogenic asperities. This finding is strongly supported by the fact that all modern earthquakes ($M_L \geq 5.0$) in the 2009–2025 period occurred within low b -value zones, consistent with the contemporary stress background captured by our dataset. Empirical magnitude–length scaling relationships confirm that the geometric extent of sparse earthquake segments of the fault zone closely matches the magnitude range of historical strong earthquakes ($M \geq 6.0$) in each belt. A notable example is the Haiyuan Fault Zone, where the combined seismogenic potential of adjacent sparse segments aligns well with the revised magnitude of the 1920 Haiyuan M 8½ earthquake, validating the utility of this approach for constraining historical seismogenic parameters. Localized high b -value zones (>1.1) with normal or low V_p/V_s ratios correspond to friction-governed creep rather than fluid-mediated creep, generally accompanied by seismic swarms and presenting a low short-term strong earthquake risk.

Regionally, our results identify several core areas of elevated seismic hazard requiring prioritized monitoring on the western Ordos margin: (1) the NNE–SSW-trending fault system in the Yinchuan Basin, especially the Wuzhong–Lingwu and Yongning–Yinchuan regions; (2) the Tongxin region in the southeastern segment of the NWW–SEE-trending Tianshanjing–Yantongshan Fault Zone; (3) the NW–SE-trending Haiyuan–Liupanshan Fault Zone, especially the Baiyin–Haiyuan region in the western Haiyuan Fault Zone and the Guyuan region from the eastern Haiyuan Fault Zone to the Liupanshan Fault Zone.

In summary, the integrated analysis of sparse earthquake segments of the fault zone and b -value anomalies provides a robust framework for identifying high-stress, seismogenically capable segments on active faults. This study advances the identification of potential asperities and their seismogenic potential on the western Ordos margin. It also provides critical scientific support for regional seismic hazard assessment and disaster mitigation planning.

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Supplementary Material

Sensitivity Tests of b -Value Estimates

Sensitivity tests using a minimum of 20 and 50 events above the completeness magnitude (M_C) were performed to ensure the reliability of b -value estimates, together with additional tests using independent assessments for sparsely sampled segments, variable fixed-event sampling schemes, and expanded search ranges. Figure S1 presents a comparison between the 20- and 50-event thresholds, along with the independent analysis for sparse segments. Results from these different schemes are generally consistent, and the overall spatial pattern of b -values shows negligible differences. However, using the 50-event threshold yields a lower spatial resolution and more blank nodes (white spots), leading to insufficient detail in the resulting b -value distribution. This consistency also demonstrates the stability of our b -value calculations across different strategies. Overall, the result based on the 20-event threshold performs better and is mainly adopted in this study, whereas those from the 50-event threshold and other schemes are used for supplementary comparison and reference.

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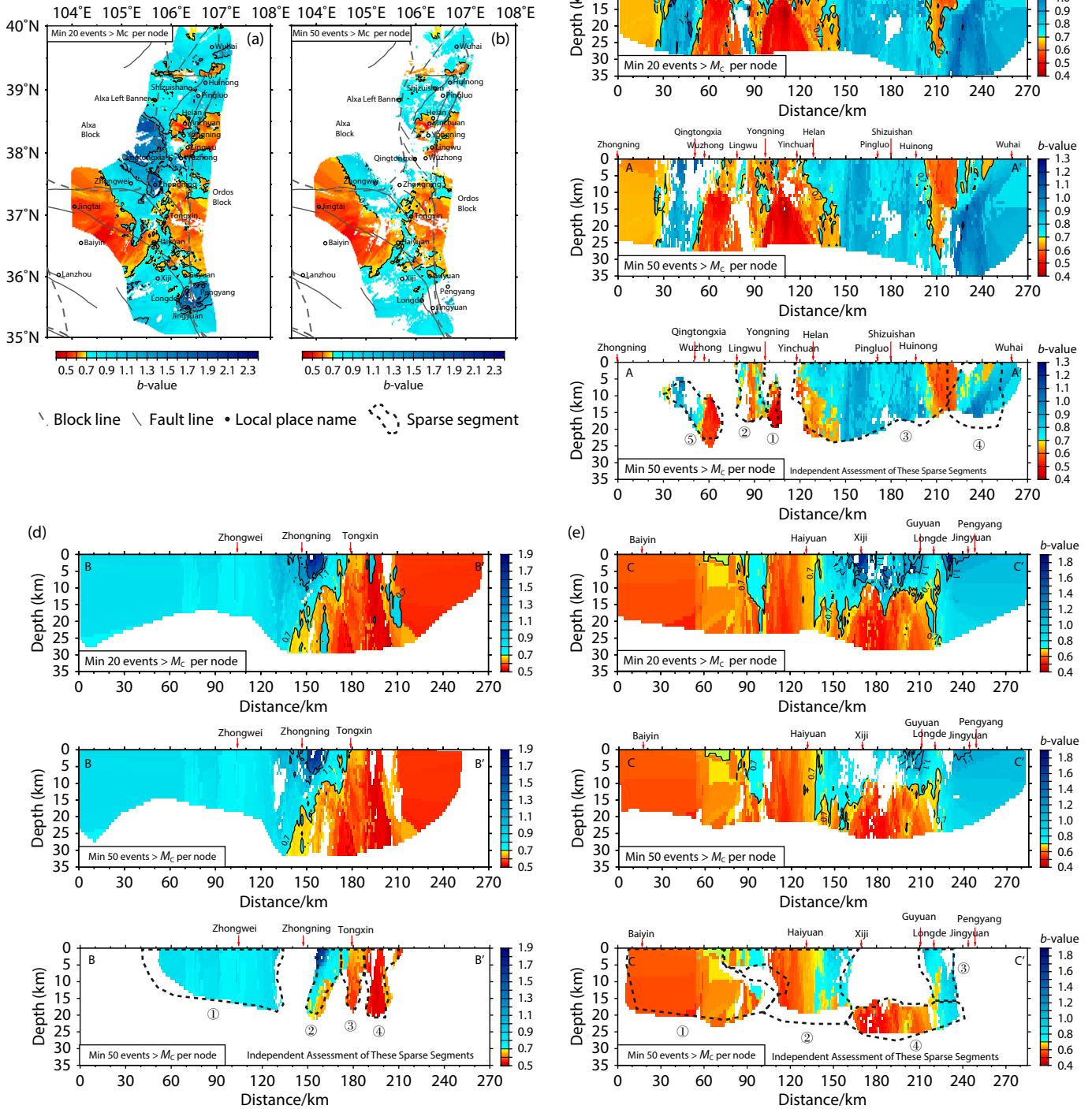


Figure S1. Sensitivity tests of b -value estimates using different event thresholds and independent assessments for sparse segments. (a) Spatial distribution of b -value calculated with a minimum of 20 events above M_c per node (b) Spatial distribution of b -value calculated with a minimum of 50 events above M_c per node (c) b -value distributions along profile AA' under minimum-event thresholds of 20 and 50 above M_c per node, and independent assessment of sparse seismic segments (d) b -value distributions along profile BB' under minimum-event thresholds of 20 and 50 above M_c per node, and independent assessment of sparse seismic segments (e) b -value distributions along profile CC' under minimum-event thresholds of 20 and 50 above M_c per node, and independent assessment of sparse seismic segments

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