

Uppermost Mantle Structure Beneath the Southeastern Tibetan Plateau and Its Implications

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Key Points

- New high-resolution Pn anisotropic tomography in the uppermost mantle beneath the southeastern Tibetan Plateau;
- The model reveals two prominent N–S trending low-velocity belts in the uppermost mantle;
- The stable Sichuan Basin and western Chuan-Dian Block control the deflection and partitioning of uppermost-mantle low-velocity anomalies

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Abstract

The southeastern Tibetan Plateau is a crucial region for understanding the relationship between crustal weakening and uppermost-mantle deformation during the outward growth of the Tibetan Plateau. Using 48,221 Pn arrivals and an improved Pn anisotropic tomography method with Moho depth correction, we imaged the velocity and anisotropic structure of the uppermost mantle beneath the southeastern Tibetan Plateau and adjacent regions. The model reveals pronounced lateral heterogeneity, including two prominent N–S trending low-velocity belts centered at approximately 98.5°E and 102°E. The Pn fast directions within these low-velocity belts are broadly parallel to their trends, suggesting coherent deformation fabrics in the uppermost mantle. We suggest that these features may represent uppermost-mantle weak zones influenced by mantle-derived thermal input. The stable blocks beneath the Sichuan Basin and western Chuan-Dian Block, together with lithospheric heterogeneity related to the Emeishan Large Igneous Province, appear to control the deflection, partitioning, and modulation of this low-velocity system. Our results provide new seismic constraints on the uppermost-mantle material redistribution of lithospheric weakening and its modulation by surrounding rigid blocks beneath the southeastern Tibetan Plateau.

Keywords

Pn anisotropic tomography; Moho depth correction; Seis-PickNet; Uppermost mantle; Southeastern Tibetan Plateau

1. Introduction

Since approximately 50 Ma, the collision and continued convergence between the Indian and Eurasian plates have resulted in the complex tectonic deformation of the Tibetan Plateau (Rowley, 1996; Yin A and Harrison, 2000). The study region is divided by several major fault systems into five geological blocks: the Qiangtang Block (QTB), the Songpan–Ganzi Block (SGB), the Chuan–Dian Block (CDB), the Yangtze Craton, and the Indochina Block (Figure 1). As a major tectonic transition zone between the Tibetan Plateau and its southeastern margin, this region provides a crucial window into the outward growth of the Tibetan Plateau (Jin H et al., 2019; Zhang Z and Gao Y, 2019; Yao H,

2020).

In recent years, numerous geophysical studies have revealed significant low-velocity, high-conductivity, high-Poisson's ratio and high-attenuation layers in the middle-lower crust beneath the southeastern Tibetan Plateau, providing important evidence for crustal weakening and possible middle-lower crustal flow (Bai DH et al., 2010; Zhao LF et al., 2013; Li MK et al., 2016; Wang WL et al., 2017; Qiao L et al., 2018; He X et al., 2021). However, considerable debate persists regarding the geometry and connectivity of these weak zones, whether they are confined to the crust or influenced by uppermost-mantle processes, and how surrounding rigid blocks modulate their distribution. Three-dimensional shear-wave velocity models reveal widespread low-velocity layers in the middle-lower crust beneath the southeastern Tibetan Plateau (Zheng X et al., 2015). S-wave velocity models derived from the joint inversion of body-wave arrivals, surface-wave dispersion, and receiver functions reveal widespread and significant low-velocity anomalies in the middle-lower crust beneath the SGB and CDB, which have been interpreted as possible evidence for southeastward crustal flow (Han SC et al., 2022). In contrast, the S-wave velocity model reported by Bao XW et al. (2015) revealed two low-velocity belts surrounding the Eastern Himalayan Syntaxis (EHS), which were interpreted as possible channels for middle-lower crustal flow. Based on the observed low-velocity layers, Li L et al. (2024) proposed that the middle-lower crustal flow beneath the southeastern Tibetan Plateau is obstructed by the Sichuan Basin (SCB) and consequently bifurcates into two southward branches. Magnetotelluric observations revealed two large-scale channel-like high-conductivity anomalies in the middle-lower crust, which were interpreted as plastic weak material flows (Bai DH et al., 2010). Attenuation tomography identified two high-attenuation channels in the lower crust: a major channel extending eastward from the northern Tibetan Plateau and then turning southeastward around the western SCB, and a secondary channel originating in the southern Tibetan Plateau, crossing the EHS, and merging with the major channel (Zhao LF et al., 2013). Regarding the origin of the low-velocity anomalies, ambient noise adjoint tomography by Chen M et al. (2014) showed that the middle-lower crustal low-velocity layer is connected to the uppermost mantle, associated with the upwelling of hot upper-mantle material. Pn tomography studies likewise revealed two low-velocity belts in the uppermost mantle beneath the southeastern Tibetan Plateau (Lei JS et al., 2014; Zhou ZG and Lei JS, 2016). Recent studies have highlighted the possible influence of deep mantle processes on crustal weakening and material redistribution in this region (Hou ZQ et al., 2024;

He X et al., 2026; Wang JC et al., 2026).

The Pn wave propagates through the uppermost mantle beneath the Moho as a critically refracted phase and is therefore particularly sensitive to velocity variations in this layer, providing higher lateral resolution than other regional seismic phases. Variations in Pn velocity typically reflect changes in temperature, composition, and volatile content in the uppermost mantle (Lee, 2003; Perry et al., 2006). Pn anisotropy typically reflects the current stress state or the last dynamic processes in the uppermost mantle (Becker et al., 2006; Karato et al., 2008). In this study, we compile an expanded Pn dataset from the latest ISC–EHB bulletin (Engdahl et al., 2020), the National Earthquake Data Center (NEDC), and automatically picked arrivals from temporary broadband arrays in Yunnan. Using an improved anisotropic Pn tomography method that incorporates Moho depth corrections, we image the velocity and anisotropic structure of the uppermost mantle beneath the southeastern Tibetan Plateau. High-resolution Pn anisotropic tomography may provide new constraints on uppermost-mantle weak zones, their relationship with crustal weakening, and the modulation of deep material redistribution by surrounding rigid blocks.

2. Seismic Data

The study region is bounded by 20°–36°N and 96°–108°E. The new Pn dataset used in this study was compiled from two data components. First, we collected bulletin Pn arrivals from the ISC–EHB bulletin and the National Earthquake Data Center (NEDC). The ISC–EHB bulletin (1964–2020) provides 51,773 Pn arrivals from 2,825 seismic events recorded at 149 stations, whereas the Yunnan and Sichuan bulletins from the NEDC (2008–2024) provide 22,926 Pn arrivals from 2,072 seismic events recorded at 62 stations. Second, to further improve ray-path coverage in the study region, we incorporated 3,730 additional Pn arrivals from 285 seismic events recorded at 67 stations from temporary broadband arrays deployed in Yunnan during 2002–2004. These additional arrivals were automatically picked using the Seis-PickNet algorithm (Figure 2; Kong H et al., 2024). The earthquake catalog used for automatic picking ($M_s > 2.0$) was constructed by integrating records from the China Earthquake Networks Center (CENC), the USGS, and the ISC, with duplicate events removed. The Seis-PickNet model is a retrained version of PickNet (Wang J et al., 2019), developed using the global million-scale Pn and Sn seismic phase dataset (Seis-PnSn). Such retraining has been demonstrated to significantly improve the picking performance for both Pn and Sn phases,

particularly for the Pn phase, and has already been applied in practice (Cai MY et al., 2026; Xiang JH et al., 2026).

To ensure data quality and reduce the influence of misidentified or unstable arrivals, all Pn data were subjected to a uniform quality control procedure before inversion. The filtering criteria were as follows. (1) Only seismic events with focal depths shallower than the Moho depth from the Crust 1.0 model were retained (Figure S1; Laske et al., 2013). (2) Arrivals with large deviations were excluded (Figure 3). (3) Epicentral distances were limited to 2° – 15° . (4) Each seismic event had to be recorded by at least five stations, and each station had to contribute at least five Pn arrivals. (5) After applying the Moho depth correction, only arrivals with traveltimes residuals within ± 5 s were retained. Relatively large deviations occur in some NEDC Pn arrivals, possibly owing to differences in phase-picking criteria and data quality among regional networks, as well as misidentification between Pg and Pn phases at transitional epicentral distances. Such deviations are likely random rather than systematic. Removing arrivals with residuals beyond the threshold markedly improved the internal consistency of the dataset. After filtering, a total of 48,221 Pn arrivals were retained for the tomographic inversion, providing robust ray-path coverage over most of the study region (Figure 4).

3. Tomographic Method

This study employs an improved Pn anisotropic tomography method that accounts for the effect of Moho depth variations on the traveltimes (Figure S1) and hence on the imaging of uppermost-mantle structure (Hearn, 1996; Lü Y et al., 2017). The uppermost mantle is parameterized as a set of two-dimensional grid cells, denoted by k , and the inversion solves simultaneously for the slowness perturbation (S_k) together with the anisotropy coefficients (A_k , B_k). Following previous Pn anisotropy tomography studies, incorporation of anisotropic parameters into the inversion not only constrains anisotropy in the uppermost mantle but also improves the velocity model (Hearn, 1999; Lü Y et al., 2021). The Pn traveltimes residuals for each event-station pair are expressed as:

$$T_{ij} - \Delta T_{ij} = a_i + b_j + \sum_k d_{ijk}(S_k + A_k \cos 2\phi_{ijk} + B_k \sin 2\phi_{ijk}) \quad (1)$$

where T_{ij} and ΔT_{ij} denote the traveltimes residual and Moho depth correction from event j to station i , respectively; a_i and b_j denote the static delays of station i and event j , respectively; d_{ijk} and ϕ_{ijk} denote the travel distance and the back azimuth angle of ray ij in mantle cell k . The

anisotropy magnitude and Pn fast direction can be expressed as equations $\sqrt{A_k^2 + B_k^2}$ and $(\pi + \tan^{-1}(B_k/A_k))/2$ (Pei SP et al., 2007). The Moho depth correction term ΔT_{ij} is defined as:

$$\Delta T_{ij} = (h_{in} + h_{out} - h_{ave}) \cdot \sqrt{\bar{s}_c^2 - \bar{s}_m^2} \quad (2)$$

where h_{in} and h_{out} denote the Moho depths at the entrance and exit points, respectively; h_{ave} denotes the average Moho depth; $\bar{s}_c$ and $\bar{s}_m$ denote the average crustal slowness and the average uppermost mantle slowness, respectively. An error in Moho depth is linearly mapped into a traveltimes error through the factor $\sqrt{\bar{s}_c^2 - \bar{s}_m^2}$. For typical average crustal velocities of 6.3–6.5 km/s and uppermost-mantle velocities of 8.0–8.2 km/s, this factor is approximately 0.085–0.10 s/km. Therefore, a Moho depth uncertainty of 2–5 km would introduce a traveltimes correction error of approximately 0.2–0.5 s for a single Moho depth term. Therefore, uncertainties in Moho depth may slightly affect the absolute magnitude of the recovered Pn velocity perturbations, particularly in regions with pronounced Moho relief. However, their influence on the recovered anisotropic parameters is expected to be more limited, because these parameters are primarily constrained by the azimuthal dependence of traveltimes residuals. The inverse problem was solved iteratively using the LSQR algorithm (Paige and Saunders, 1982). The same damping factor was applied to both the velocity and anisotropy terms. Large damping values tend to oversmooth the model, whereas small damping values may introduce small-scale heterogeneity and spurious oscillations. Based on the trade-off analysis between velocity perturbations and traveltimes residuals, an optimal damping value of 300 was selected (Figure 5a). After testing different grid configurations, a cell size of $0.25^\circ \times 0.25^\circ$ was adopted. During the inversion, the traveltimes residuals stabilized after 150 iterations. After inversion, the root mean square (RMS) traveltimes residual decreased from 2.10 s (Figure 5b) to 1.25 s (Figure 5c), indicating obvious convergence of the inversion.

4. Resolution Analysis

4.1. Checkerboard and Synthetic Recovery Tests

To evaluate the spatial resolution of the velocity and anisotropy models, we performed a series of checkerboard tests. In the input checkerboard models, sinusoidal perturbations were assigned to

both velocity and anisotropy in each inversion cell. The average amplitude ($\max \Delta v / \sqrt{2}$) of the sinusoidal perturbations in both models was set to 0.3 km/s. Synthetic traveltimes were then calculated using the same dataset as that employed in the actual tomographic inversion. Gaussian noise with a standard deviation of 1.25 s was added to the synthetic traveltimes, corresponding to the RMS of traveltime residuals after inversion. The recovered patterns indicate that the velocity model is resolvable at a scale of $1.5^\circ \times 1.5^\circ$, whereas the anisotropic model is resolvable at $2.0^\circ \times 2.0^\circ$ (Figures 6 and 7). In regions of dense ray coverage, the velocity and anisotropic models are resolvable at $1.0^\circ \times 1.0^\circ$ and $1.5^\circ \times 1.5^\circ$, respectively. By contrast, the southeastern part of the study region is less well resolved because of sparse ray coverage. Therefore, only the well-resolved regions are considered in this study.

To further assess model robustness, we conducted additional synthetic recovery tests targeting the major observed anomaly regions. The synthetic datasets were generated on the basis of the observed tomographic features and were then inverted using the same procedure and parameter settings as those used in the actual inversion. The recovered results show that the main velocity anomalies and anisotropic features are reproduced well in terms of both location and overall geometry (Figures S2 and S3). Although some local details are moderately smoothed, the principal structural features remain stable. These recovery tests demonstrate that the tomographic inversion reliably resolves the main features of the model, thereby providing further support for the robustness of the inversion results.

4.2. Effects of Pn Ray Lengths

Pn rays with different lengths can sample different depth ranges within the uppermost mantle (Du MF et al., 2022). By imaging the Chinese mainland using ray-path datasets of different path lengths, a previous study has revealed structural differences between the shallow and deep mantle lid (Hearn et al., 2004). In this study, we assess the sensitivity of the tomographic results to ray-path length by performing inversions using both long- and short-path datasets while keeping all inversion parameters unchanged. To ensure a meaningful comparison, the selection of the long- and short-path datasets should account for overall dataset size. We define the model inverted using epicentral distances of 2° – 12° as the short-path model and that inverted using epicentral distances of 2° – 15° as

the long-path model (Figure S4). Further reducing the ray-path length would substantially degrade ray coverage. Comparison of the two models reveals only minor differences in both velocity and anisotropic structures, and the overall patterns remain highly consistent. These results indicate that variations in ray-path length exert little influence on the tomographic results, further demonstrating the robustness of our model.

4.3. Sensitivity to the Moho Depth Model

Because the study region is characterized by strong lateral variations in Moho depth, the choice of Moho depth model may introduce uncertainties into the Pn traveltimes correction. To assess the potential influence of the Moho depth model on the tomographic results, we repeated the tomographic inversion using the regional SETPM Moho model for southeastern Tibetan Plateau (Xu MJ et al., 2020). For grid points where SETPM does not provide valid Moho depths, Crust 1.0 values were used instead to ensure complete ray-path coverage. In this sensitivity test, events were reselected according to the updated Moho depth model, retaining only those shallower than the Moho depth. All other inversion settings, including grid spacing, damping value, and iterative procedure, were kept identical to those used for the preferred Crust 1.0 model.

The resulting Pn velocity and anisotropy models are highly consistent with those obtained using Crust 1.0 model (Figure S5). The two N–S trending low-velocity belts, the high-velocity anomalies beneath the SCB and the western CDB, and the Pn fast directions are all preserved. Only minor local differences are observed in anomaly amplitudes and boundary details. This comparison indicates that uncertainties in the Moho depth model may locally affect the magnitude of velocity perturbations, but they do not change the principal structural features in this study.

4.4. Sensitivity to Data Selection Criteria

To evaluate whether the preferred model depends on specific quality-control thresholds, we repeated the inversion using different residual cutoffs and minimum event/station count criteria. For the residual cutoff test, thresholds of ± 4 , ± 5 , and ± 6 s were applied after Moho depth correction (Figure S6). For the event/station count test, minimum thresholds of 4, 5, and 6 observations were tested (Figure S7). In all tests, the grid spacing, damping value, Moho correction, and iterative

procedure were kept identical to those used in the preferred inversion. The resulting models show highly consistent velocity and anisotropic patterns, including the two N–S trending low-velocity belts, the U-shaped low-velocity anomaly beneath the SGB, the high-velocity anomaly beneath the SCB, and the main spatial variations in Pn fast directions. Specifically, overly strict thresholds would substantially reduce ray coverage, particularly near the margins of the study region, whereas overly loose thresholds could introduce poorly constrained arrivals, events, and stations into the inversion. The residual cutoff and minimum event/station count criteria were chosen to balance data retention, ray-path coverage, and inversion stability. These tests indicate that the main conclusions are not controlled by the specific quality-control thresholds adopted in the preferred model.

5. Result

5.1. Pn Velocity

Figure 8 illustrates the lateral variations in Pn velocity in the uppermost mantle beneath the study region. Because checkerboard recovery is poor in the southeastern part of the study region, this area was masked out to define the reliably imaged region. Overall, the study region exhibits lateral heterogeneity and is predominantly characterized by low-velocity anomalies. Prominent N–S trending low-velocity anomalies are observed beneath both the QTB and the CDB. Beneath the SGB, a prominent low-velocity anomaly with a broadly U-shaped geometry is identified. A broad low-velocity anomaly is also observed beneath the Indochina Block, and similar low-velocity anomalies are present beneath the MLV and TCV in the study region. The low-velocity anomalies beneath the MLV may be related to upwelling of hot asthenospheric material induced by slab tearing (Zhang LY et al., 2020). In contrast, pronounced high-velocity anomalies are imaged beneath the EHS and the old, stable SCB. The high-velocity anomalies beneath the EHS may be interpreted as underthrusting of cold Indian continental lithosphere beneath southeastern Tibetan Plateau (Liang CT et al., 2004; Li Y et al., 2025). In addition, a high-velocity anomaly belt is present along the western margin of the CDB near the QTB, separating the major low-velocity anomalies to the west and east.

5.2. Pn Anisotropy

Figure 9 illustrates the Pn fast directions in the uppermost mantle beneath the study region. The checkerboard test results indicate that the overall recoverable scale reaches $2^\circ \times 2^\circ$. The fast directions exhibit marked lateral variations among different tectonic units. Within the SGB, the Pn fast directions trend NW–SE west of 102°E and NE–SW to the east. In the QTB, the Pn fast directions within the low-velocity belt exhibit an approximately N–S trend. In the CDB, the fast directions within the low-velocity belt vary systematically from north to south, trending NW–SE in the north and NE–SW in the south. Along the western margin of the SCB, the fast directions are broadly tangential to the basin boundary, whereas within the basin they trend predominantly E–W. Beneath the MLV, the Pn fast directions trend NE–SW. In the Indochina Block, the fast directions vary systematically from north to south, trending NW–SE in the north, NE–SW in the central part, and E–W in the south, broadly consistent with the overall orientation of the low-velocity belt.

6. Discussion

6.1. Comparison With Previous Results

Early Pn studies imaged NE–SW or nearly N–S trending high-velocity anomalies beneath the SCB (Hearn et al., 2004; Liang CT et al., 2004; Pei SP et al., 2007; Cui ZX and Pei SP, 2009; Li F et al., 2011), whereas later models suggested that the high-velocity anomaly more closely follows the basin outline (Lei JS et al., 2014; Zhou ZG and Lei JS, 2016). Our model similarly images a basin-related high-velocity anomaly beneath the SCB, but it appears more discontinuous and more clearly confined to the basin margin. Beneath the SGB and CDB, earlier models imaged relatively broad and weak low-velocity anomalies (Cui ZX and Pei SP, 2009; Li F et al., 2011), whereas later studies resolved more pronounced channel-like low-velocity structures (Lei JS et al., 2014; Zhou ZG and Lei JS, 2016; Liu YX et al., 2026). Our model is broadly consistent with later models, but further resolves a clearer U-shaped low-velocity anomaly beneath the SGB and a more distinct separation between the major low-velocity belts by a high-velocity body beneath the western CDB. The Pn fast directions are also generally consistent with previous Pn anisotropy models, including directions tangential to the western margin of the SCB and systematic directional variations within the major low-velocity

belts. In addition, the fast directions beneath the MLV are broadly consistent with the results of [Li Y et al. \(2025\)](#).

Body-wave and surface-wave tomographic studies commonly image the SCB as a relatively fast and stable lithospheric block ([Zhang FX et al., 2018](#); [Wang W et al., 2021](#)), whereas widespread low-velocity anomalies have been reported beneath the eastern and southeastern Tibetan Plateau in the upper mantle ([Bao XW et al., 2015](#); [Zhang FX et al., 2018](#); [Yang XZ et al., 2023](#)). These velocity patterns are generally consistent with our Pn model, which images high velocities beneath the SCB and low velocities beneath the SGB and CDB. However, because body-wave and surface-wave models differ from Pn tomography in depth sensitivity and resolution, the detailed geometry of the anomalies is not always identical. In particular, the U-shaped low-velocity anomaly beneath the SGB and the separation between the two N–S trending low-velocity belts are less clearly resolved in some previous models. Magnetotelluric studies have imaged high-conductivity channels in the middle-lower crust beneath the southeastern Tibetan Plateau ([Bai DH et al., 2010](#); [Li X et al., 2020](#)), which are spatially associated with the our Pn low-velocity belts. Therefore, compared with previous body-wave, surface-wave, and Magnetotelluric models, our Pn model provides more direct constraints on the velocity and anisotropic structure immediately below the Moho.

6.2. Two N–S Trending Low-Velocity Belts

Our Pn model reveals two prominent N–S trending low-velocity anomaly belts in the uppermost mantle beneath the southeastern Tibetan Plateau, centered near 98.5°E and 102°E, respectively. Anomalies exceeding 5% may indicate the presence of high-temperature or partially molten material in this area ([Lü Y et al., 2022](#)). In addition, the Pn fast directions within these two low-velocity belts are broadly parallel to their overall trends, consistent with previous Pn tomographic study ([Liu YX et al., 2026](#)). The corresponding synthetic recovery tests further support the robustness of the main structures ([Figures S2 and S3](#)). The eastern belt is spatially associated with previously reported crustal high-attenuation anomalies ([Zhao LF et al., 2013](#); [He X et al., 2021](#)), whereas both belts broadly correspond to the clockwise crustal motion pattern indicated by GPS observations ([Shen ZK et al., 2005](#)) and to the crustal high-conductivity channels revealed by magnetotelluric observations ([Bai DH et al., 2010](#)). Their broad spatial agreement suggests that the weakened structure beneath the southeastern Tibetan Plateau is not confined to the middle–lower crust, but may also involve the

uppermost mantle.

Thermal effects, compositional heterogeneity, mantle upwelling, and partial melting may all contribute to reduced Pn velocities (Lee, 2003; Perry et al., 2006). Similarly, the observed Pn anisotropy may reflect both inherited lithospheric fabrics and late Cenozoic deformation (Becker et al., 2006; Karato et al., 2008). Recent studies provide further constraints on the possible origin of these low-velocity anomalies. Although the uppermost-mantle low-velocity anomalies broadly coincide with crustal low-velocity structures, these features are constrained independently and should not be taken as direct evidence for vertical continuity. A recent attenuation study suggested that the middle–lower crustal high-attenuation anomaly beneath the southeastern Tibetan Plateau may extend across the Moho into the uppermost mantle (Wang JC et al., 2026). This anomaly is also spatially associated with Cenozoic magmatism, mantle-derived geochemical signatures, and elevated heat flow. In addition, previous seismic velocity results have shown that some low-velocity zones beneath the southeastern Tibetan Plateau are not restricted to the crust, but may extend into the uppermost mantle (Yao HJ et al., 2010). In the geodynamic context of shallow mantle partial melting induced by tearing of the Indian lithosphere and rollback of its southern segment (Hou ZQ et al., 2024), we suggest that the two nearly N–S trending Pn low-velocity belts imaged in this study more likely represent uppermost-mantle weak zones influenced by mantle-derived thermal input. The anisotropic features may reflect the lateral redistribution or shear deformation of thermally weakened uppermost-mantle material under the mechanical control of surrounding rigid blocks. This deep thermal–dynamic process may further contribute to the weakening of the overlying middle–lower crust.

The Emeishan Large Igneous Province (ELIP) may have played an important but laterally heterogeneous and depth-dependent role in modulating this weakened crust–mantle system. Notably, our Pn model reveals low velocities in the uppermost mantle beneath the ELIP, rather than the high-velocity feature expected for a uniformly rigid lithospheric block. This observation is compatible with recent attenuation results. He X et al. (2026) suggested that the cooled and magma-modified shallow crust of the ELIP is relatively strong and can partially hinder crustal flow, whereas the deeper crust beneath the ELIP may remain weak owing to asthenospheric upwelling, allowing weak zones to become progressively connected with depth. Wang JC et al. (2026) further showed that two high-attenuation belts are separated by the ELIP in the shallow-to-middle crust, but converge in the lower crust and continue into the uppermost mantle. At a more local scale, Zhou ZK et al. (2026) identified

a near-vertical high-resistivity anomaly beneath a segment of the Huayingshan Fault (HYSF) in the outer zone of the ELIP. This anomaly extends from the shallow crust to below the Moho and was interpreted as a mechanically strong remnant of crystallized plume-derived melts. Although this locally reinforced structure appears to contrast with the low Pn velocities imaged near the HYSF (Figure 8), magnetotelluric imaging resolves the anomaly at a lateral scale of tens of kilometers, whereas the best lateral resolution of our Pn model is approximately 1.5° – 1.0° . Given their different spatial resolutions and sensitivities to physical properties, such a localized reinforced body may be smoothed in the Pn inversion and coexist with a broader uppermost-mantle low-velocity zone. Therefore, the ELIP should not be regarded as a uniformly rigid barrier to southeastward material redistribution. Instead, it may act as a laterally heterogeneous and depth-dependent modulator within this weakened crust–mantle system, locally impeding and partitioning crustal flow in the shallow-to-middle crust, while uppermost-mantle weakening induced by mantle-derived heating may allow the low-velocity system to persist or reorganize at greater depths.

6.3. Tectonic Interpretation

Based on the observations discussed above, we suggest that the two N–S trending low-velocity belts imaged in the uppermost mantle may represent lithospheric weak zones beneath the southeastern Tibetan Plateau. These weak zones are likely influenced by mantle-derived thermal input and may have contributed to the development of crustal low-velocity, high-conductivity, and high-attenuation anomalies. The geometry of this weak system appears to be strongly controlled by surrounding rigid or relatively strong lithospheric blocks (Figure 9). The stable lithosphere beneath the SCB acts as a major mechanical barrier, forcing the eastern low-velocity belt to deflect along its western and southwestern margins. The relatively high-velocity body beneath the western CDB separates the two major low-velocity belts and may control their southward partitioning. In addition, the ELIP may have acted as a depth-dependent modulator. Its cooled and magma-modified shallow crust may locally impede and partition crustal flow, whereas deeper mantle-derived heating may allow the weak zones to remain connected or reorganized at lower-crust and uppermost-mantle depths.

The accompanying variations in Pn fast directions further support this interpretation. The fast directions are broadly parallel to the low-velocity belts and change near the western margin of the SCB, suggesting that the anisotropic fabric may reflect the lateral redistribution or shear deformation

of thermally weakened uppermost-mantle material under the mechanical control of rigid blocks. Within this framework, the middle-lower crustal weak zones beneath the southeastern Tibetan Plateau may not be controlled solely by independent crustal flow. Rather, their distribution and connectivity may be modulated by uppermost-mantle deformation, mantle-derived thermal input, and the blocking or filtering effects of the SCB, western CDB, and ELIP-related lithospheric heterogeneity. This model provides a more integrated tectonic framework for understanding how deep mantle processes and shallow crustal deformation are linked during the southeastward expansion of the Tibetan Plateau.

7. Conclusions

In this study, we constructed a high-resolution Pn velocity and anisotropy model beneath the southeastern Tibetan Plateau using the latest seismic data. Compared with previous models, the expanded dataset provides improved ray-path coverage and resolution, allowing us to resolve smaller-scale structural features. We observe pronounced high-velocity anomalies beneath the SCB and the western CDB, indicating that these regions are relatively stable. We observe two N–S trending low-velocity anomaly belts, one centered at approximately 98.5°E and the other at approximately 102°E. In addition, our model reveals a clear U-shaped low-velocity anomaly beneath the SGB. The Pn fast directions within the low-velocity anomalies are mostly parallel to their strike. We suggest that these low-velocity belts may represent uppermost-mantle weak zones influenced by mantle-derived thermal input, rather than direct evidence for a purely crustal flow system. The stable block beneath the SCB and western CDB, and the ELIP-related lithospheric heterogeneity likely acted together to deflect, partition, and modulate the low-velocity system, thereby controlling deep material redistribution beneath the southeastern Tibetan Plateau.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

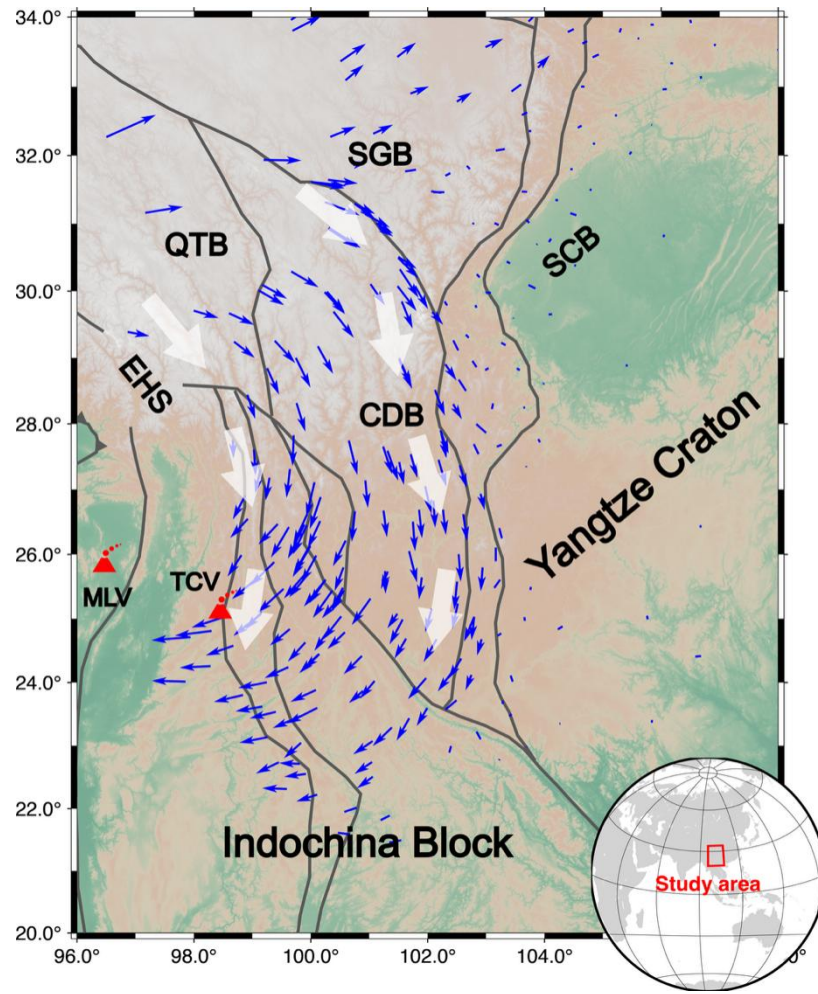


Figure 1. Geological background of the southeastern Tibetan Plateau and adjacent regions. The gray solid lines represent major tectonic boundaries. The red triangles represent volcanoes. The blue arrows represent GPS velocity field relative to the South China Block (Shen Z-K et al., 2005). The white arrows represent two crustal high-conductivity channels from magnetotelluric observation (Bai DH et al., 2010). The insert map shows the location of study region. Abbreviations: SGB, Songpan–Ganzi Block; QTB, Qiangtang Block; CDB, Chuan–Dian Block; SCB, Sichuan Basin; EHS, Eastern Himalayan Syntaxis; MLV, Mt. Loimye volcano; TCV, Tengchong volcano.

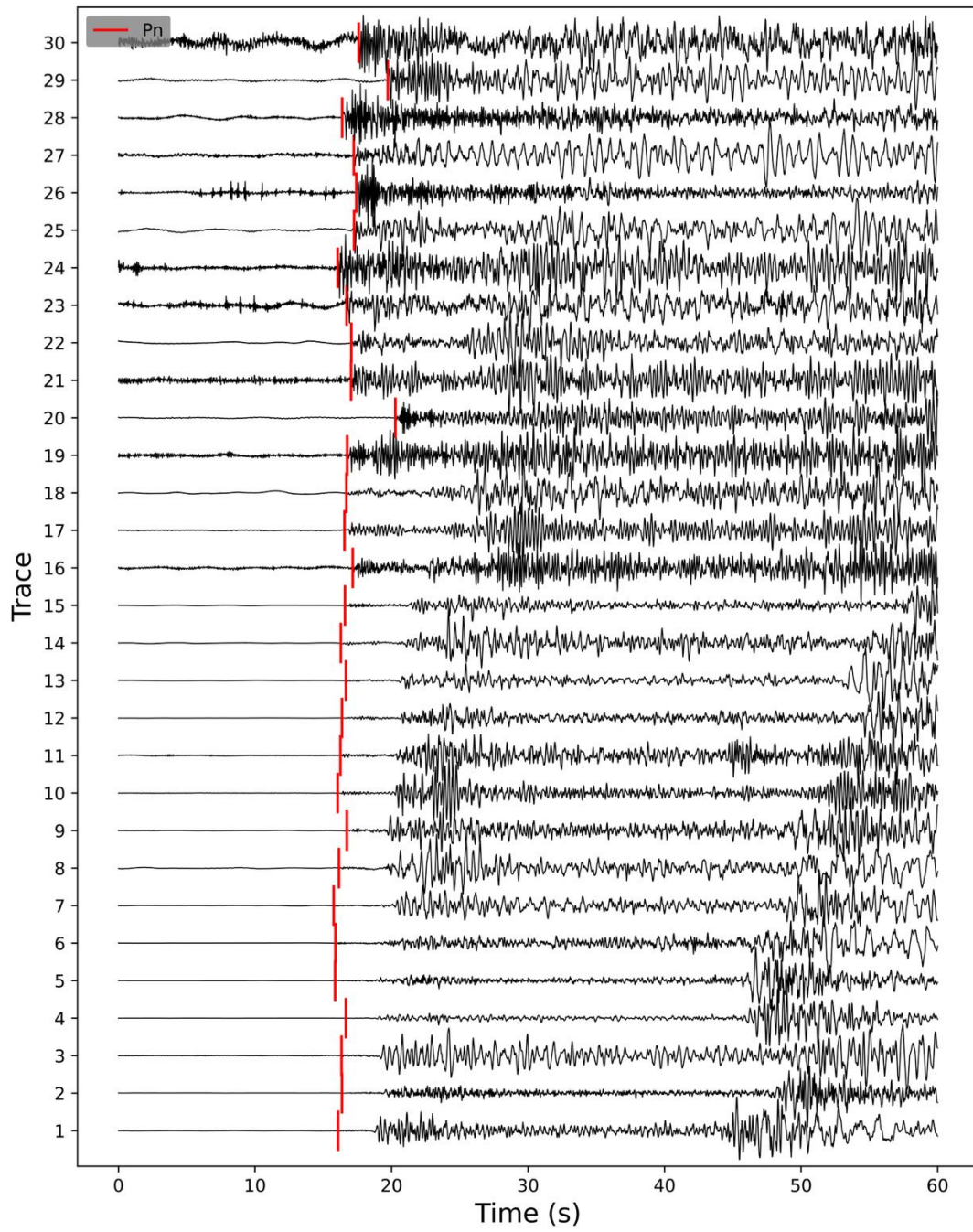


Figure 2. Seismic waveforms of the same earthquake recorded at different temporary stations. The Pn arrivals picked by the Seis-PickNet algorithm are marked by red lines, and the black lines represent the seismic waveforms.

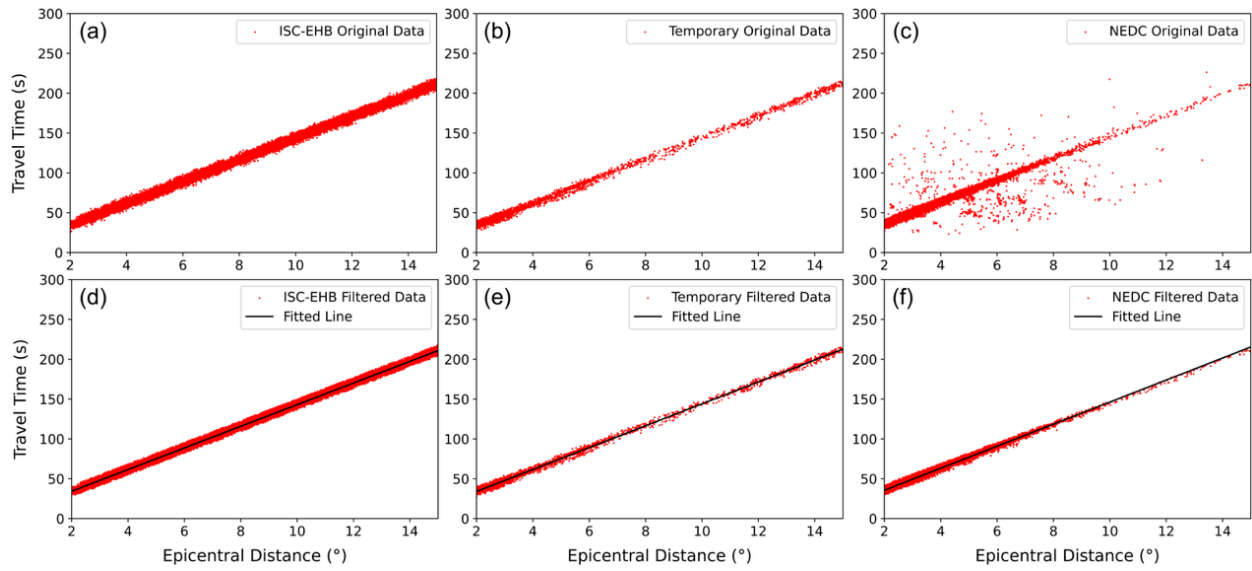


Figure 3. Travel-time curve of the Pn arrivals used in this study. Panels (a), (b), and (c) show the ISC-EHB, Temporary array, and NEDC Pn arrivals before filtering, respectively. Panels (d), (e), and (f) show the Pn arrivals after filtering. The black line indicates the fitted traveltime line.

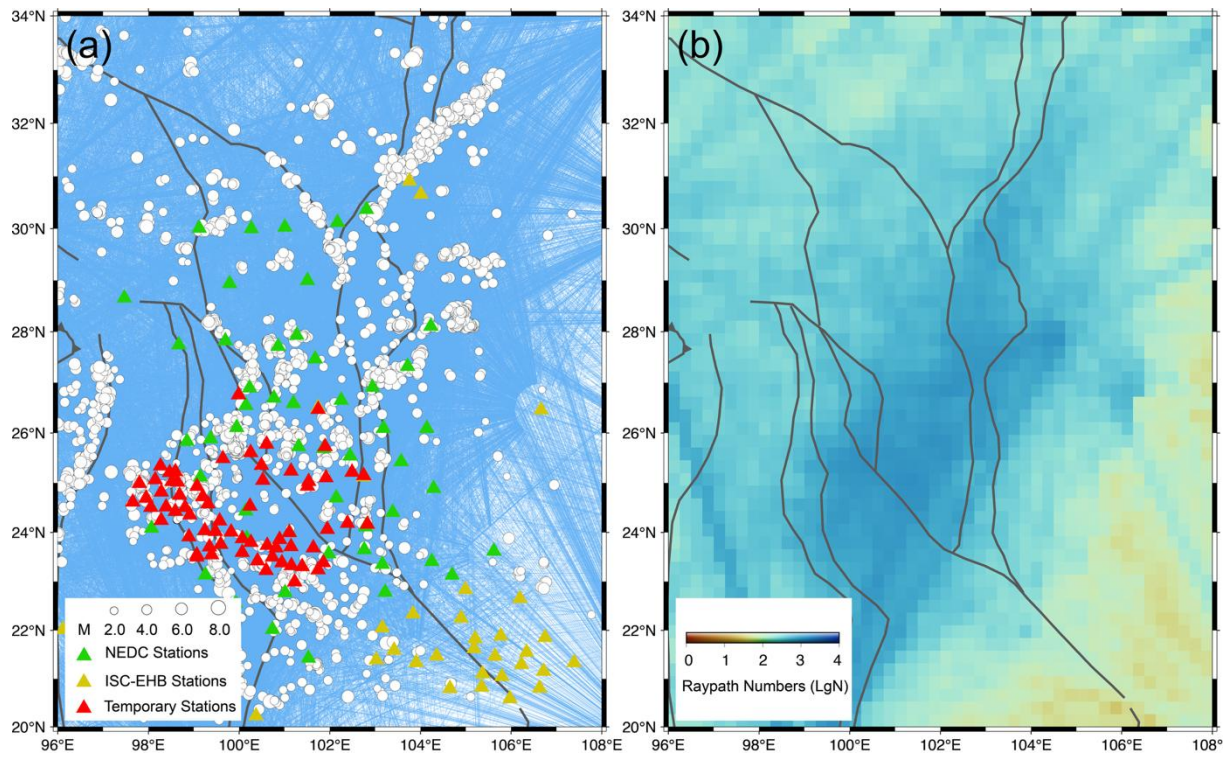


Figure 4. Pn ray-path coverage map of the southeastern Tibetan Plateau and adjacent regions.

(a) Spatial distribution of the seismic stations, events, and Pn ray paths used in this study. Triangles in different colors denote different seismic stations, and white circles of varying sizes denote seismic events of different magnitudes. (b) Ray-path density within each inversion grid cell. The color bar is displayed on a logarithmic scale and positioned in the lower-left corner.

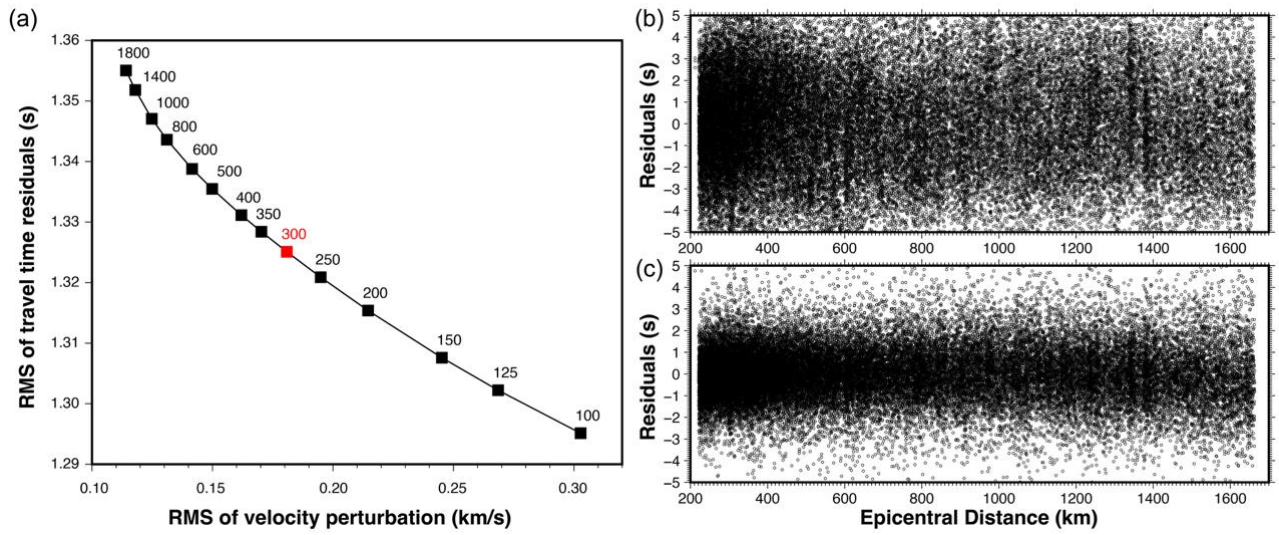


Figure 5. (a) Trade-off curve between velocity perturbations and traveltime residuals for different damping values. The red square indicates the optimal value selected through testing and adopted for the inversion. Distribution of traveltime residuals before (b) and after inversion (c).

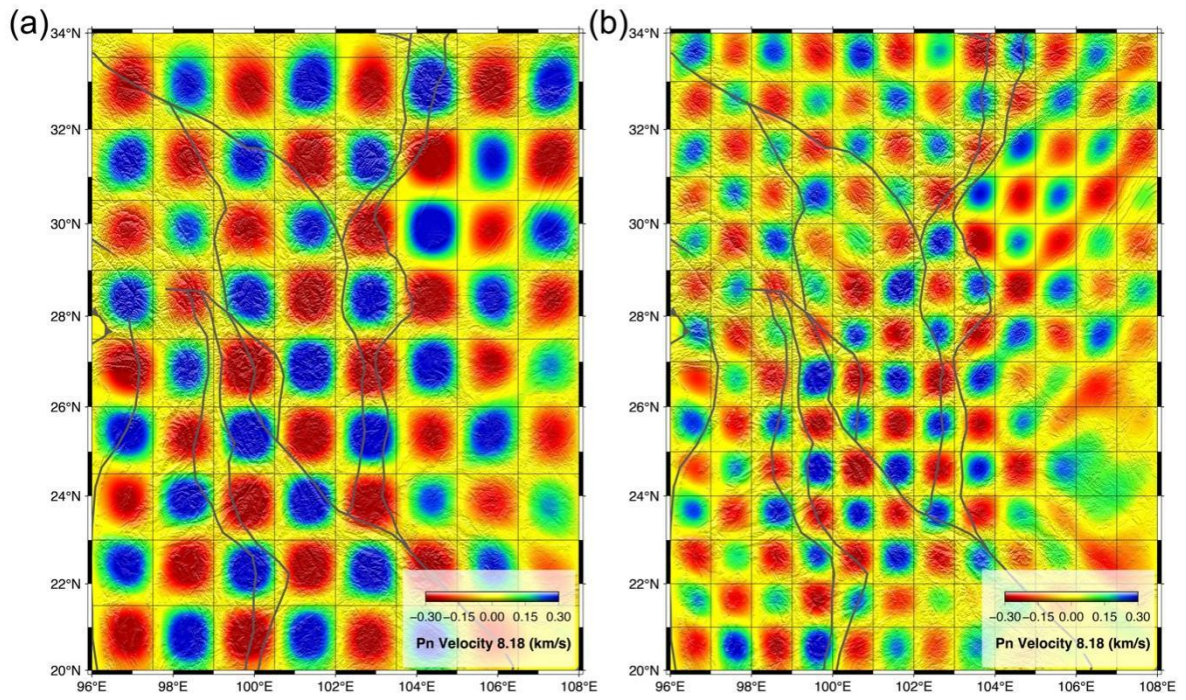


Figure 6. Results of the checkerboard resolution tests for Pn velocity anomalies at different spatial scales. (a) $1.5^\circ \times 1.5^\circ$. (b) $1.0^\circ \times 1.0^\circ$. Red and blue denote low- and high-velocity anomalies, respectively. The color bar is positioned in the lower-right corner.

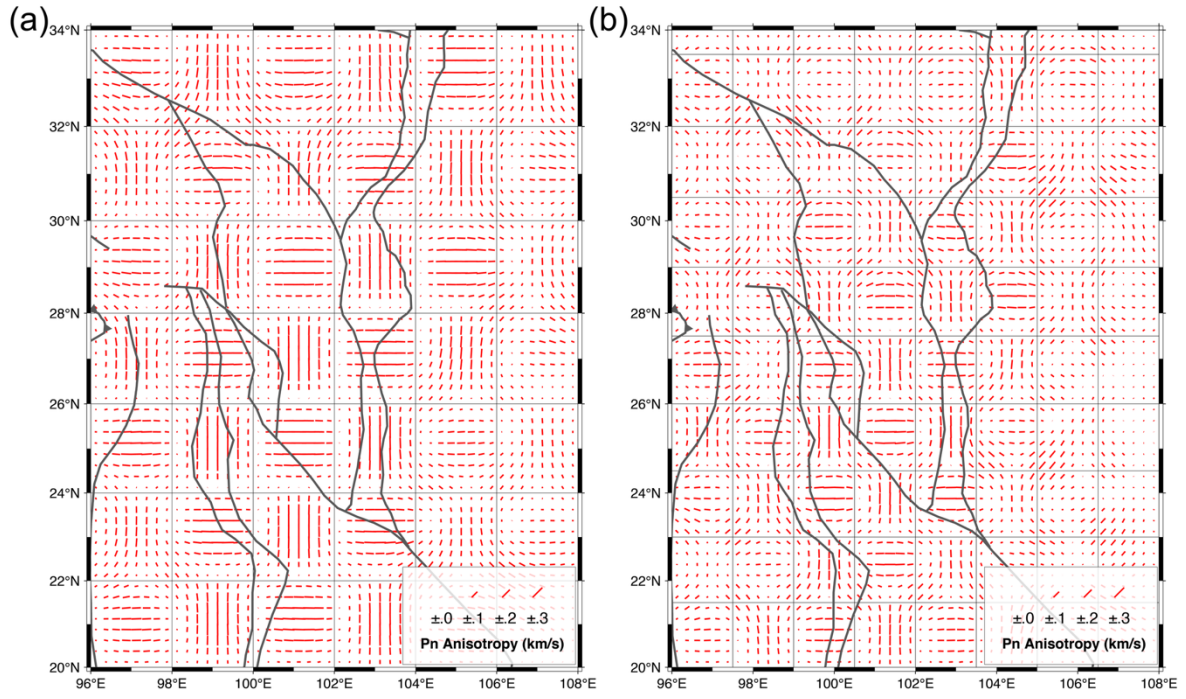


Figure 7. Results of the checkerboard resolution tests for Pn anisotropy anomalies at different spatial scales. (a) $2.0^\circ \times 2.0^\circ$. (b) $1.5^\circ \times 1.5^\circ$. Red bars denote Pn anisotropy, with bar length and orientation representing the anisotropy amplitude and fast direction, respectively. The legend is positioned in the lower-right corner.

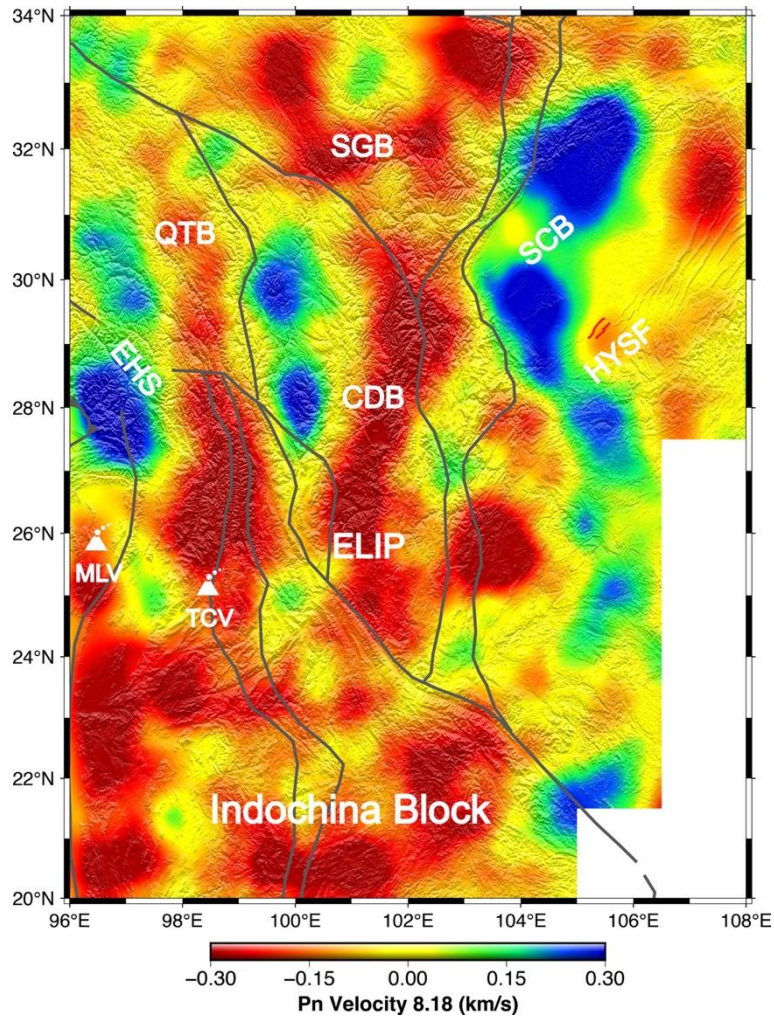


Figure 8. Pn velocity model in the study region. Red and blue denote low- and high-velocity anomalies, respectively. The color bar is positioned in the lower center. The white triangles represent volcanoes. The red lines represent the segments of the Huayingshan Fault. The white L-shaped mirrored areas indicate regions of low resolution and were therefore masked out from the final model. Abbreviations: HYSF, Huayingshan Fault; ELIP, Emeishan Large Igneous Province. All other elements are the same as those in Figure 1.

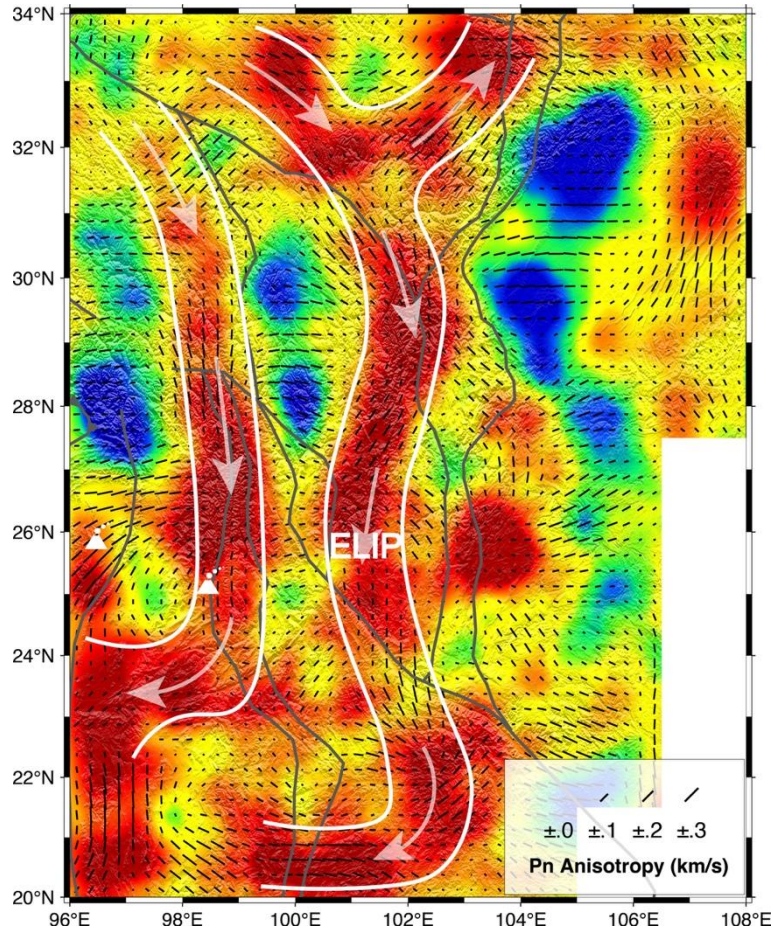


Figure 9. Pn velocity model and anisotropy model in the study region. Black bars denote Pn anisotropy, with bar length and orientation representing the anisotropy amplitude and fast direction, respectively. The legend is positioned in the lower-right corner. White solid lines and arrows indicate possible channels of hot material transport in the uppermost mantle. All other elements are the same as those in Figures 1 and 8.

Reference

- Bai, D., Unsworth, M. J., Meju, M. A., Ma, X., Teng, J., Kong, X., Sun, Y., Sun, J., Wang, L., Jiang, C., et al. (2010). Crustal deformation of the eastern Tibetan plateau revealed by magnetotelluric imaging. *Nat. Geosci.*, 3(5), 358–362. <https://doi.org/10.1038/ngeo830>.
- Bao, X., Sun, X., Xu, M., Eaton, D. W., Song, X., Wang, L., Ding, Z., Mi, N., Li, H., Yu, D., et al. (2015). Two crustal low-velocity channels beneath SE Tibet revealed by joint inversion of Rayleigh wave dispersion and receiver functions. *Earth Planet. Sci. Lett.*, 415, 16–24. <https://doi.org/10.1016/j.epsl.2015.01.020>.
- Becker, T. W., Chevrot, S., Schulte-Pelkum, V., and Blackman, D. K. (2006). Statistical properties of seismic anisotropy predicted by upper mantle geodynamic models. *J. Geophys. Res. Solid Earth*, 111(B8). <https://doi.org/10.1029/2005JB004095>.
- Cai, M., Ai, Y., Yuan, X., Jiang, M., He, Y., Schurr, B., Lü, Y., Xiao, Z., Mon, C. T., Feng, Y., et al. (2026). Pn Velocity Structure and Anisotropy of the Uppermost Mantle Beneath Myanmar. *J. Geophys. Res. Solid Earth*, 131(5), e2026JB034210. <https://doi.org/10.1029/2026JB034210>.
- Chen, M., Huang, H., Yao, H., van der Hilst, R., and Niu, F. (2014). Low wave speed zones in the crust beneath SE Tibet revealed by ambient noise adjoint tomography. *Geophys. Res. Lett.*, 41(2), 334–340. <https://doi.org/10.1002/2013GL058476>.
- Cui Z., and Pei S. (2009). Study on Pn velocity and anisotropy in the uppermost mantle of the Eastern Himalayan Syntaxis and surrounding regions. *Chin. J. Geophys.*, 52(9), 2245–2254. <https://doi.org/10.3969/j.issn.0001-5733.2009.09.008>.
- Du, M., Lei, J., Zhao, D., and Lu, H. (2022). Pn Anisotropic Tomography of Northeast Asia: New Insight Into Subduction Dynamics and Volcanism. *J. Geophys. Res. Solid Earth*, 127(1), e2021JB023080. <https://doi.org/10.1029/2021JB023080>.
- Engdahl, E. R., Di Giacomo, D., Sakarya, B., Gkarlaoui, C. G., Harris, J., and Storchak, D. A. (2020). ISC-EHB 1964–2016, an Improved Data Set for Studies of Earth Structure and Global Seismicity. *Earth Space Sci.*, 7(1), e2019EA000897. <https://doi.org/10.1029/2019EA000897>.
- Han, S., Zhang, H., Gao, L., Liu, Y., Chai, C., and Maceira, M. (2022). Joint Inversion of Body Wave Arrival Times, Surface Wave Dispersion Data and Receiver Functions: Method and Application to South China. *J. Geophys. Res. Solid Earth*, 127(9), e2022JB024083. <https://doi.org/10.1029/2022JB024083>.
- He, X., Zhao, L.-F., Xie, X.-B., Li, R.-J., Lu, T., and Yao, Z.-X. (2026). Hindered but Not Halted Crustal Flow: Implications From Lg-Wave Attenuation Tomography Based on High-Density ChinArray in SE Tibetan Plateau. *J. Geophys. Res. Solid Earth*, 131(3), e2025JB032994. <https://doi.org/10.1029/2025JB032994>.
- He, X., Zhao, L.-F., Xie, X.-B., Tian, X., and Yao, Z.-X. (2021). Weak Crust in Southeast Tibetan Plateau Revealed by Lg-Wave Attenuation Tomography: Implications for Crustal Material Escape. *J. Geophys. Res. Solid Earth*, 126(3), e2020JB020748. <https://doi.org/10.1029/2020JB020748>.
- Hearn, T. M. (1996). Anisotropic Pn tomography in the western United States. *J. Geophys. Res. Solid Earth*, 101(B4), 8403–8414. <https://doi.org/10.1029/96JB00114>.
- Hearn, T. M. (1999). Uppermost mantle velocities and anisotropy beneath Europe. *J. Geophys. Res. Solid Earth*, 104(B7), 15123–15139. <https://doi.org/10.1029/1998JB900088>.
- Hearn, T. M., Wang, S., Ni, J. F., Xu, Z., Yu, Y., and Zhang, X. (2004). Uppermost mantle velocities beneath China and surrounding regions. *J. Geophys. Res. Solid Earth*, 109(B11). <https://doi.org/10.1029/2003JB002874>.
- Hou, Z., Liu, L., Zhang, H., Xu, B., Wang, Q., Yang, T., Wang, R., Zheng, Y., Li, Y., Gao, L., et al. (2024). Cenozoic eastward growth of the Tibetan Plateau controlled by tearing of the Indian slab. *Nat. Geosci.*, 17(3), 255–263. <https://doi.org/10.1038/s41561-024-01382-9>.
- Jin, H., Gao, Y., Su, X., and Fu, G. (2019). Contemporary crustal tectonic movement in the southern Sichuan-Yunnan

- block based on dense GPS observation data. *Earth Planet. Phys.*, 3(1), 53–61. <https://doi.org/10.26464/epp2019006>.
- Karato, S., Jung, H., Katayama, I., and Skemer, P. (2008). Geodynamic Significance of Seismic Anisotropy of the Upper Mantle: New Insights from Laboratory Studies. *Annu. Rev. Earth Planet. Sci.*, 36(1), 59–95. <https://doi.org/10.1146/annurev.earth.36.031207.124120>.
- Kong, H., Xiao, Z., Lü, Y., and Li, J. (2024). Seis-PnSn: A Global Million-Scale Benchmark Data Set of Pn and Sn Seismic Phases for Deep Learning. *Seismol. Res. Lett.*, 95(6), 3746–3760. <https://doi.org/10.1785/0220230379>.
- Laske, G., Masters, G., Ma, Z., and Pasyanos, M. (2013). Update on CRUST1.0 - A 1-degree global model of Earth's crust. *Abstr. EGU2013-2658 Present. 2013 Geophys Res Abstr.* 15, 15, 2658.
- Lee, C.-T. A. (2003). Compositional variation of density and seismic velocities in natural peridotites at STP conditions: Implications for seismic imaging of compositional heterogeneities in the upper mantle. *J. Geophys. Res. Solid Earth*, 108(B9). <https://doi.org/10.1029/2003JB002413>.
- Lei, J., Li, Y., Xie, F., Teng, J., Zhang, G., Sun, C., and Zha, X. (2014). Pn anisotropic tomography and dynamics under eastern Tibetan plateau. *J. Geophys. Res. Solid Earth*, 119(3), 2174–2198. <https://doi.org/10.1002/2013JB010847>.
- Li F., Zhou S., Su Y., Li P., Deng C., Li L., and Wang L. (2011). Study on Pn-wave velocity structure and anisotropy in the Sichuan-Yunnan and its adjacent areas. *Chin. J. Geophys.*, 54(1), 44–54. <https://doi.org/10.3969/j.issn.0001-5733.2011.01.006>.
- Li, L., Wang, X., Hou, G., Ling, Y., and Ai, Y. (2024). Two thin middle-crust low-velocity zones imaged in the Chuan-Dian region of southeastern Tibetan Plateau and their tectonic implications. *Sci. China Earth Sci.*, 67(5), 1675–1686. <https://doi.org/10.1007/s11430-023-1256-0>.
- Li, M., Zhang, S., Wang, F., Wu, T., and Qin, W. (2016). Crustal and upper-mantle structure of the southeastern Tibetan Plateau from joint analysis of surface wave dispersion and receiver functions. *J. Asian Earth Sci.*, 117, 52–63. <https://doi.org/10.1016/j.jseaes.2015.12.002>.
- Li, X., Ma, X., Chen, Y., Xue, S., Varentsov, I. M., and Bai, D. (2020). A plume-modified lithospheric barrier to the southeastward flow of partially molten Tibetan crust inferred from magnetotelluric data. *Earth Planet. Sci. Lett.*, 548, 116493. <https://doi.org/10.1016/j.epsl.2020.116493>.
- Li, Y., Lei, J., Huang, J., and Zhao, D. (2025). Pn Velocity Structure and Anisotropy of the Uppermost Mantle Beneath Southeast Asia. *J. Geophys. Res. Solid Earth*, 130(6), e2025JB031116. <https://doi.org/10.1029/2025JB031116>.
- Liang, C., Song, X., and Huang, J. (2004). Tomographic inversion of Pn travel times in China. *J. Geophys. Res. Solid Earth*, 109(B11). <https://doi.org/10.1029/2003JB002789>.
- Liu, Y., Lü, Y., and Liu, L. (2026). Pn velocity and anisotropy tomography with nonuniform grid beneath the Tibetan Plateau and adjacent regions. *Tectonophysics*, 935, 231278. <https://doi.org/10.1016/j.tecto.2026.231278>.
- Lü, Y., Li, J., He, Y., Zhao, L.-F., and Zhang, J. (2022). Velocity and Anisotropic Structure of the Uppermost Mantle Beneath Central America and Northwestern South America From Pn Tomography. *J. Geophys. Res. Solid Earth*, 127(4), e2021JB023643. <https://doi.org/10.1029/2021JB023643>.
- Lü, Y., Liu, J., He, Y., and Guan, Y. (2021). New Uppermost Mantle Pn Velocity and Anisotropy Model of the Eastern Caribbean. *J. Geophys. Res. Solid Earth*, 126(3), e2020JB021523. <https://doi.org/10.1029/2020JB021523>.
- Lü, Y., Ni, S., Chen, L., and Chen, Q.-F. (2017). Pn tomography with Moho depth correction from eastern Europe to western China. *J. Geophys. Res. Solid Earth*, 122(2), 1284–1301. <https://doi.org/10.1002/2016JB013052>.
- Paige, C. C., and Saunders, M. A. (1982). LSQR: An Algorithm for Sparse Linear Equations and Sparse Least Squares. *ACM Trans. Math. Softw.*, 8(1), 43–71. <https://doi.org/10.1145/355984.355989>.

- Pei, S., Zhao, J., Sun, Y., Xu, Z., Wang, S., Liu, H., Rowe, C. A., Toksöz, M. N., and Gao, X. (2007). Upper mantle seismic velocities and anisotropy in China determined through Pn and Sn tomography. *J. Geophys. Res. Solid Earth*, 112(B5). <https://doi.org/10.1029/2006JB004409>.
- Perry, H. K. C., Jaupart, C., Mareschal, J.-C., and Shapiro, N. M. (2006). Upper mantle velocity-temperature conversion and composition determined from seismic refraction and heat flow. *J. Geophys. Res. Solid Earth*, 111(B7). <https://doi.org/10.1029/2005JB003921>.
- Qiao, L., Yao, H., Lai, Y.-C., Huang, B.-S., and Zhang, P. (2018). Crustal Structure of Southwest China and Northern Vietnam From Ambient Noise Tomography: Implication for the Large-Scale Material Transport Model in SE Tibet. *Tectonics*, 37(5), 1492–1506. <https://doi.org/10.1029/2018TC004957>.
- Rowley, D. B. (1996). Age of initiation of collision between India and Asia: A review of stratigraphic data. *Earth Planet. Sci. Lett.*, 145(1), 1–13. [https://doi.org/10.1016/S0012-821X\(96\)00201-4](https://doi.org/10.1016/S0012-821X(96)00201-4).
- Shen, Z.-K., Lü, J., Wang, M., and Bürgmann, R. (2005). Contemporary crustal deformation around the southeast borderland of the Tibetan Plateau. *J. Geophys. Res. Solid Earth*, 110(B11). <https://doi.org/10.1029/2004JB003421>.
- Wang, J., Xiao, Z., Liu, C., Zhao, D., and Yao, Z. (2019). Deep Learning for Picking Seismic Arrival Times. *J. Geophys. Res. Solid Earth*, 124(7), 6612–6624. <https://doi.org/10.1029/2019JB017536>.
- Wang, J., Zhang, H., Hou, Z., Xu, B., Guo, H., Thurber, C. H., and van der Hilst, R. D. (2026). Crustal weakening by mantle upwelling in the southeastern Tibetan Plateau. *Geology*, 54(5), 451–455. <https://doi.org/10.1130/G54154.1>.
- Wang, W., Wu, J., Fang, L., Lai, G., and Cai, Y. (2017). Crustal thickness and Poisson's ratio in southwest China based on data from dense seismic arrays. *J. Geophys. Res. Solid Earth*, 122(9), 7219–7235. <https://doi.org/10.1002/2017JB013978>.
- Wang, W., Wu, J., and Hammond, J. O. S. (2021). Mantle Dynamics Beneath the Sichuan Basin and Eastern Tibet From Teleseismic Tomography. *Tectonics*, 40(2), e2020TC006319. <https://doi.org/10.1029/2020TC006319>.
- Wessel, P., Luis, J. F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H. F., and Tian, D. (2019). The Generic Mapping Tools Version 6. *Geochem. Geophys. Geosystems*, 20(11), 5556–5564. <https://doi.org/10.1029/2019GC008515>.
- Xiang, J., Lei, J., Li, Y., and Zhao, D. (2026). Uppermost mantle anisotropic tomography in and around the Tanlu fault zone derived from PickNet automatically picked Pn data. *Geophys. J. Int.*, 244(2), ggaf455. <https://doi.org/10.1093/gji/ggaf455>.
- Xu, M., Huang, Z., Wang, L., Xu, M., Zhang, Y., Mi, N., Yu, D., and Yuan, X. (2020). Sharp Lateral Moho Variations Across the SE Tibetan Margin and Their Implications for Plateau Growth. *J. Geophys. Res. Solid Earth*, 125(5), e2019JB018117. <https://doi.org/https://doi.org/10.1029/2019JB018117>.
- Yang, X., Luo, Y., Jiang, C., Yang, Y., Niu, F., and Li, G. (2023). Crustal and Upper Mantle Velocity Structure of SE Tibet From Joint Inversion of Rayleigh Wave Phase Velocity and Teleseismic Body Wave Data. *J. Geophys. Res. Solid Earth*, 128(7), e2022JB026162. <https://doi.org/10.1029/2022JB026162>.
- Yao, H. (2020). Building the community velocity model in the Sichuan-Yunnan region, China: Strategies and progresses. *Sci. China Earth Sci.*, 63(9), 1425–1428. <https://doi.org/10.1007/s11430-020-9645-3>.
- Yao, H., van der Hilst, R. D., and Montagner, J.-P. (2010). Heterogeneity and anisotropy of the lithosphere of SE Tibet from surface wave array tomography. *J. Geophys. Res. Solid Earth*, 115(B12). <https://doi.org/10.1029/2009JB007142>.
- Yin, A., and Harrison, T. M. (2000). Geologic Evolution of the Himalayan-Tibetan Orogen. *Annu. Rev. Earth Planet. Sci.*, 28(Volume 28, 2000), 211–280. <https://doi.org/10.1146/annurev.earth.28.1.211>.
- Zhang, F., Wu, Q., Li, Y., Zhang, R., Sun, L., Pan, J., and Ding, Z. (2018). Seismic Tomography of Eastern Tibet: Implications for the Tibetan Plateau Growth. *Tectonics*, 37(9), 2833–2847.

<https://doi.org/10.1029/2018TC004977>.

- Zhang, L. Y., Fan, W. M., Ding, L., Ducea, M. N., Pullen, A., Li, J. X., Sun, Y. L., Yue, Y. H., Cai, F. L., Wang, C., et al. (2020). Quaternary Volcanism in Myanmar: A Record of Indian Slab Tearing in a Transition Zone From Oceanic to Continental Subduction. *Geochem. Geophys. Geosystems*, 21(8), e2020GC009091. <https://doi.org/10.1029/2020GC009091>.
- Zhang, Z., and Gao, Y. (2019). Crustal thicknesses and Poisson's ratios beneath the Chuxiong-Simao Basin in the Southeast Margin of the Tibetan Plateau. *Earth Planet. Phys.*, 3(1), 69–84. <https://doi.org/10.26464/epp2019008>.
- Zhao, L.-F., Xie, X.-B., He, J.-K., Tian, X., and Yao, Z.-X. (2013). Crustal flow pattern beneath the Tibetan Plateau constrained by regional Lg-wave Q tomography. *Earth Planet. Sci. Lett.*, 383, 113–122. <https://doi.org/10.1016/j.epsl.2013.09.038>.
- Zheng, X., Zhao, C., Zhou, L., and Zheng, S. (2015). 3D Shear-Wave Velocity Structure beneath the Southeastern Tibetan Plateau from Ambient Noise. *Bull. Seismol. Soc. Am.*, 105(3), 1371–1382. <https://doi.org/10.1785/0120140211>.
- Zhou, Z., and Lei, J. (2016). Pn anisotropic tomography and mantle dynamics beneath China. *Phys. Earth Planet. Inter.*, 257, 193–204. <https://doi.org/10.1016/j.pepi.2016.06.005>.
- Zhou, Z., Yu, N., Li, X., Zhang, S., Wang, T., Kong, W., and Li, T. (2026). Ancient plume-reinforced lithosphere modulates present-day crustal fluid migration and deformation. *Nat. Commun.*, 17(1), 8298. <https://doi.org/10.1038/s41467-026-75203-5>.

Supplementary Materials

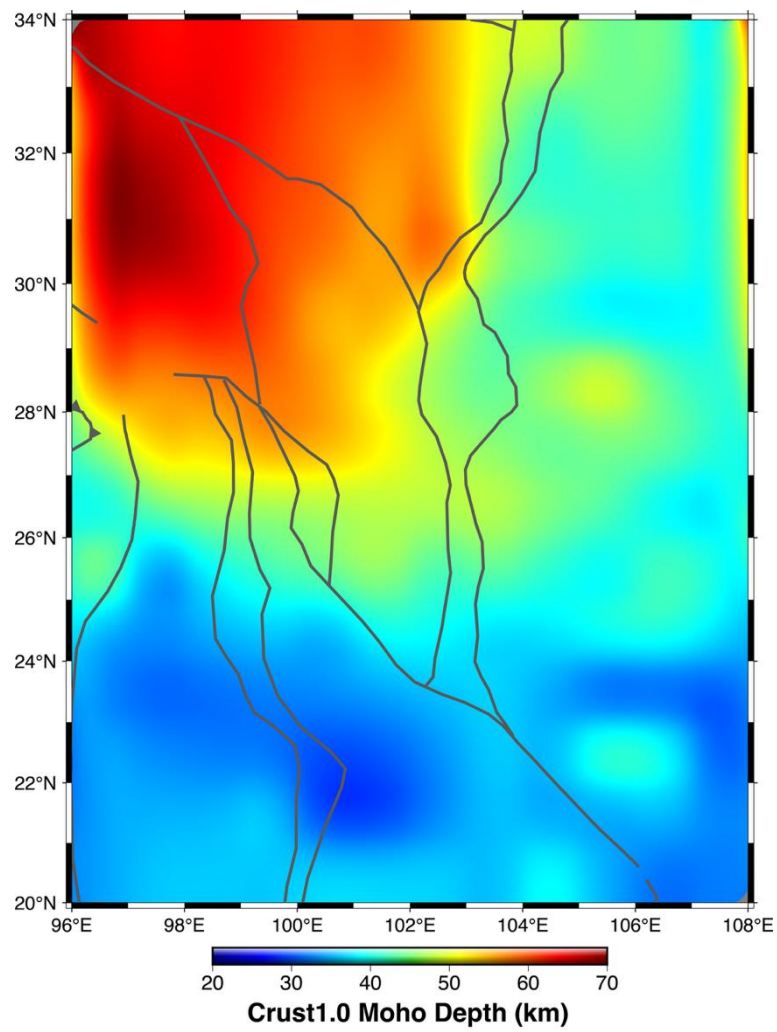


Figure S1. Moho depth in the study region from the Crust1.0 model. The color bar is positioned in the lower center.

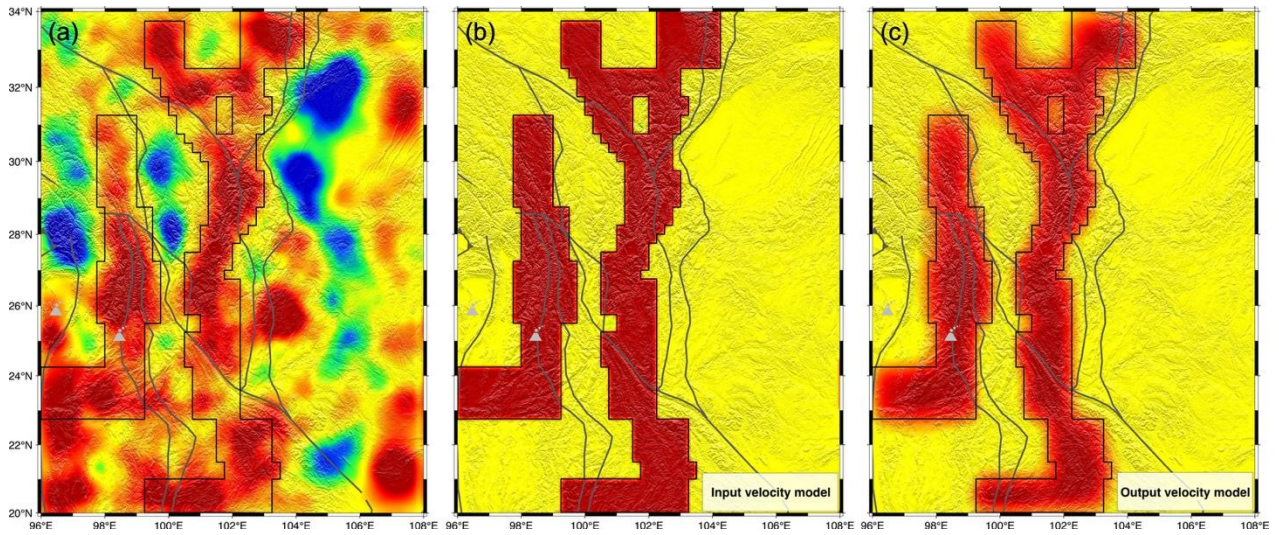


Figure S2. Synthetic recovery tests for the major velocity structural features in the study region.

(a) Locations of the velocity anomalies. (b) Input velocity model. (c) Output velocity model. The black lines outline the velocity anomalies. All other elements are the same as in Figures 1 and 8.

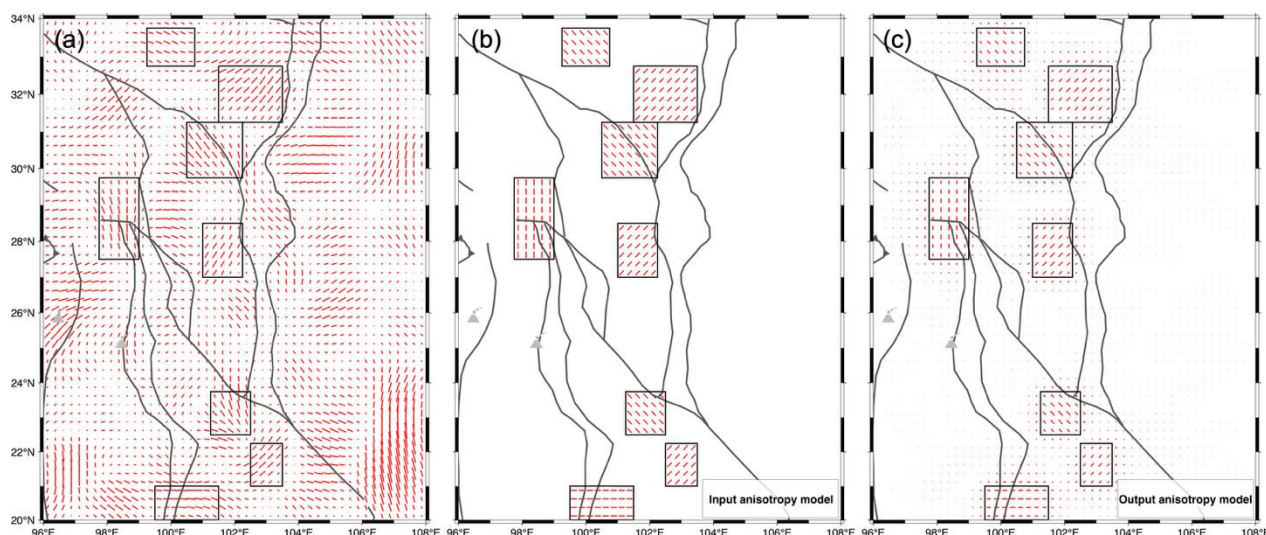


Figure S3. Synthetic recovery tests for the major anisotropy structural features in the study region. (a) Locations of the anisotropy anomalies. (b) Input anisotropy model. (c) Output anisotropy model. The black lines outline the anisotropy anomalies. All other elements are the same as in Figures 1 and 9.

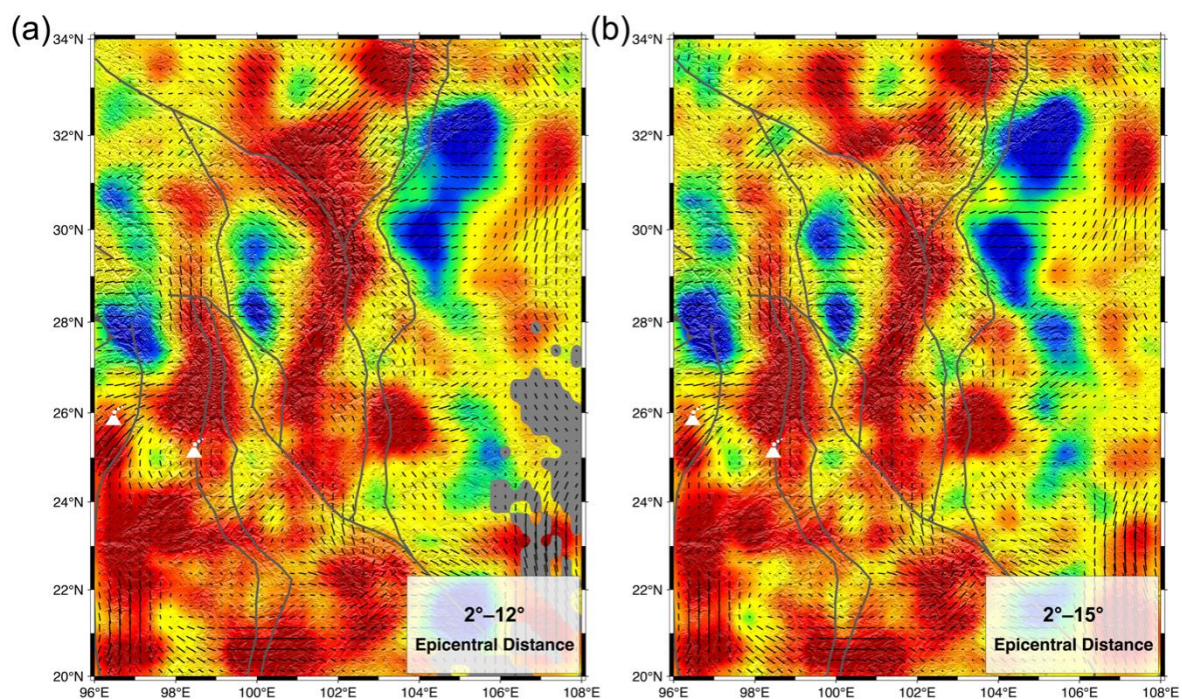


Figure S4. Comparison of Pn anisotropic tomography in the study region inverted using (a) shorter ray paths with epicentral distances of 2°–12° and (b) longer ray paths with epicentral distances of 2°–15°. All other elements are the same as in Figures 1, 8 and 9.

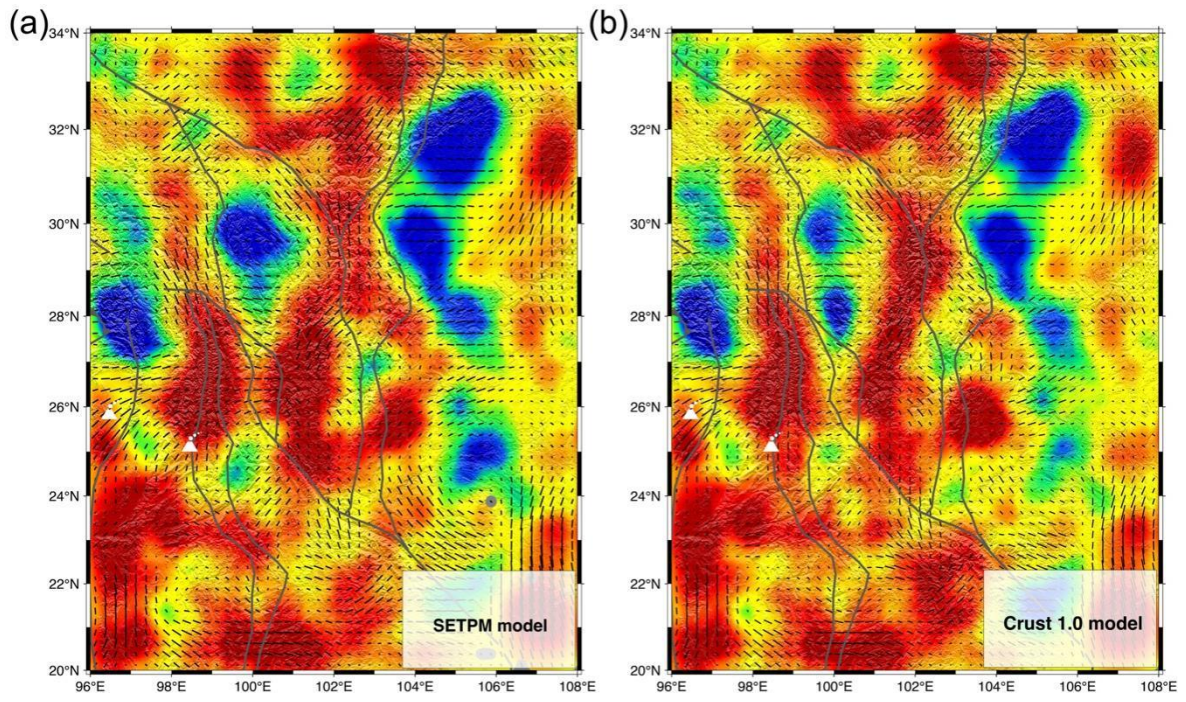


Figure S5. Comparison of Pn anisotropic tomography in the study region inverted using (a) SETPM model and (b) Crust 1.0 model. All other elements are the same as in Figures 1, 8 and 9.

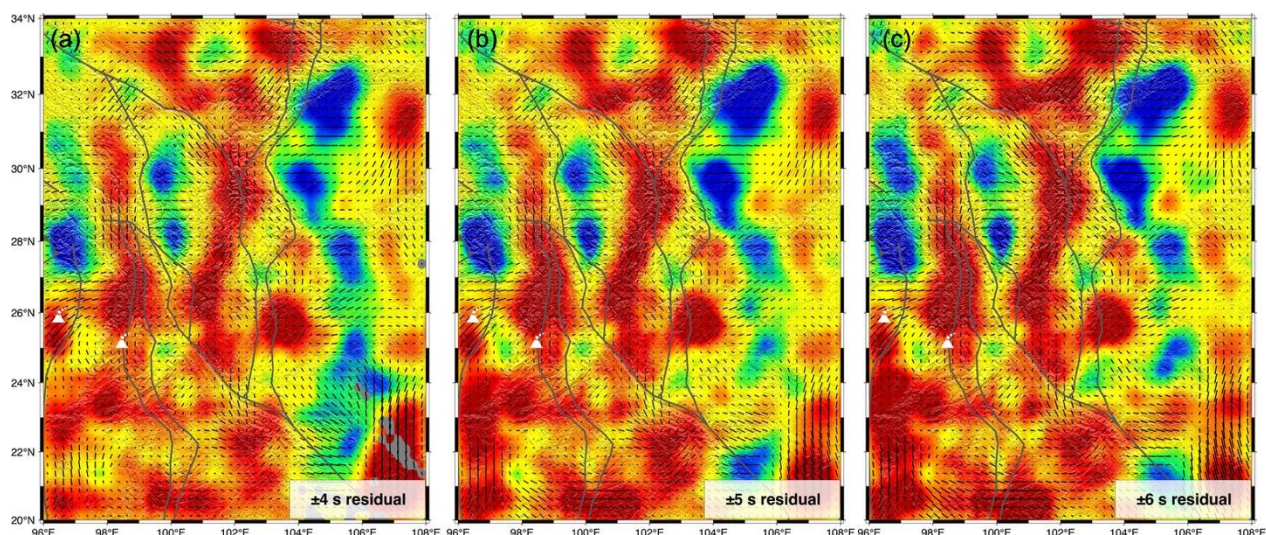


Figure S6. Sensitivity of the Pn tomographic results to traveltime residual cutoffs. The inversions were performed using residual cutoffs of (a) ± 4 s, (b) ± 5 s, and (c) ± 6 s, while keeping the minimum event/station count criteria unchanged. All other elements are the same as in Figures 1, 8 and 9.

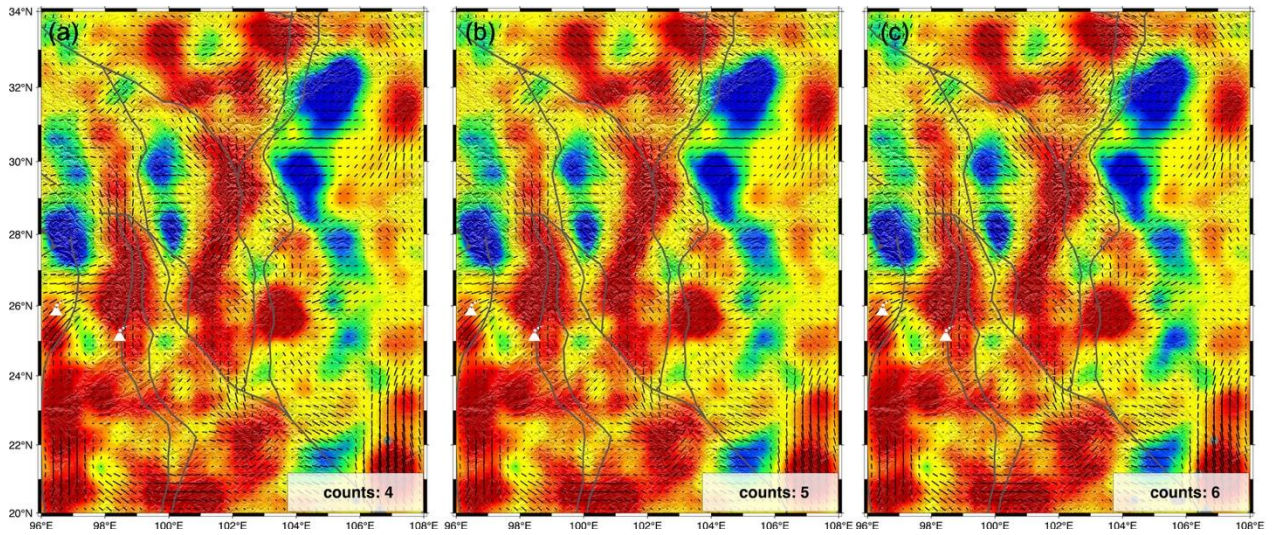


Figure S7. Sensitivity of the Pn tomographic results to minimum event/station count thresholds.

The inversions were performed using minimum event/station count thresholds of (a) 4, (b) 5, and (c) 6, while keeping the traveltime residual cutoff unchanged. All other elements are the same as in Figures 1, 8 and 9.