
Research article

A novel integrated seismic approach from acquisition to identification: Unveiling gas hydrates in the complex permafrost of the Qiangtang Basin

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Abstract: Seismic exploration for gas hydrates in the permafrost of the Qiangtang Basin faces severe challenges, including low signal-to-noise ratio, complex static corrections, and poor imaging of shallow permafrost and hydrate-related anomalies. To address these issues, this study developed a systematic high-precision seismic technology tailored to this region. For the first time in the area, this study combined a low-frequency vibrator source with a wide-line, high-density geometry and point-receiver technology, which enhances low-frequency penetration and preserves subtle reflection signals. Advanced processing innovations included pseudo-3D wide-line tomographic static corrections, a hybrid residual static correction algorithm integrating maximum energy, simulated annealing, and genetic algorithms, and a multi-domain noise suppression workflow followed by finite-difference time migration. Key outcomes reveal that permafrost base reflections are optimally expressed in the 10–35 Hz band. Using 5 Hz single-frequency relative impedance volumes delineates permafrost thickness and identifies prospective hydrate zones spatially associated with active fault systems. Integrated geophysical indicators consistently point to the southern river valley as the most favorable hydrate prospect. This study provides a replicable technical workflow and region-specific seismic identification markers, advancing gas hydrate exploration in the Qiangtang Basin and other mid-latitude plateau permafrost regions.

Keywords: gas hydrates; Qiangtang basin; permafrost; low-frequency vibrator; seismic detection

1. Introduction

Natural gas hydrate (NGH) is an ice-like crystalline solid formed under high-pressure and low-temperature conditions, primarily occurring in deep-sea sediments and terrestrial permafrost [1–6]. NGH is widely distributed in permafrost zones, including the Arctic, the Mackenzie Delta, West Siberia, and the Qinghai-Tibet Plateau [7,8]. China's permafrost covers ~2.15 million km², providing favorable conditions for NGH formation.

Geophysical logging and seismic exploration are key tools for hydrate identification, using acoustic anomalies, resistivity, and velocity variations as indicators [9–13]. However, exploration in the Qiangtang Basin faces severe challenges: high altitude, harsh climate, strong interference waves, low signal-to-noise ratio, and complex structures with well-developed folds and faults [14–16]. Previous 2D seismic surveys targeted petroleum and deep structures using large receiver intervals (20–50 m) and shot spacings (80–160 m), resulting in low shallow fold, poor resolution, and a lack of near-surface information. An effective geophysical technology for permafrost gas hydrates has not yet been established [17,18].

This study develops a seismic detection methodology tailored to the Qiangtang Basin permafrost. It evaluates the effectiveness of low-frequency vibrator sources and optimized processing workflows. The goal is to enhance data quality and establish regional seismic identification markers for gas hydrates.

2. Basic geology and permafrost features

The study area is located in the Tso Co region of the Qiangtang Basin on the Tibetan Plateau, within the North Qiangtang Depression (Figure 1). The strata are dominated by Mesozoic marine sequences, including Triassic and Jurassic clastic rocks and carbonates, which serve as important potential source rocks and reservoirs for natural gas hydrates [19,20]. The tectonic framework is characterized by nearly east-west-trending anticlines, commonly offset by later faults, forming a complex structural pattern. Four fault systems are mainly developed: NW-, NE-, SN-, and EW-trending. Among them, the NW-trending faults are large-scale thrusts, while the NE- and SN-trending faults are mostly normal or strike-slip faults that often displace earlier structures [21–23]. Modern mud volcanoes developed southeast of the Tso Co region are controlled by deep-seated faults, indicating pathways for deep-seated gases to migrate upward along fault zones and penetrate the permafrost layer. This is closely related to the accumulation and leakage processes of natural gas hydrates [20,24,25].

The Tso Co area on the Qinghai-Tibet Plateau features typical permafrost that is classified into three types [25–28]. The most developed type is continuous permafrost, with abundant groundwater forming thick ground ice. This type provides excellent sealing and reservoir spaces, including frozen soil and frozen rock, making them most favorable for hydrate formation [29]. The second is sporadic permafrost, which has relatively poor stability, yet small-scale hydrate accumulations can form when gas supply is sufficient [30]. The third type is frozen rocks, where bedrock is exposed or near the surface, limiting the Quaternary cover. Normally, the permafrost in the North Qiangtang Depression averages 80–100 m in thickness, with a maximum of 130–150 m. It comprises an upper sediment-dominated frozen layer (2.06–131.25 m) of Quaternary unconsolidated sediments favoring pore-

filling hydrates, and a lower bedrock frozen layer (17.05–151.92 m) whose pores and fractures also allow fracture-filling hydrates [31].

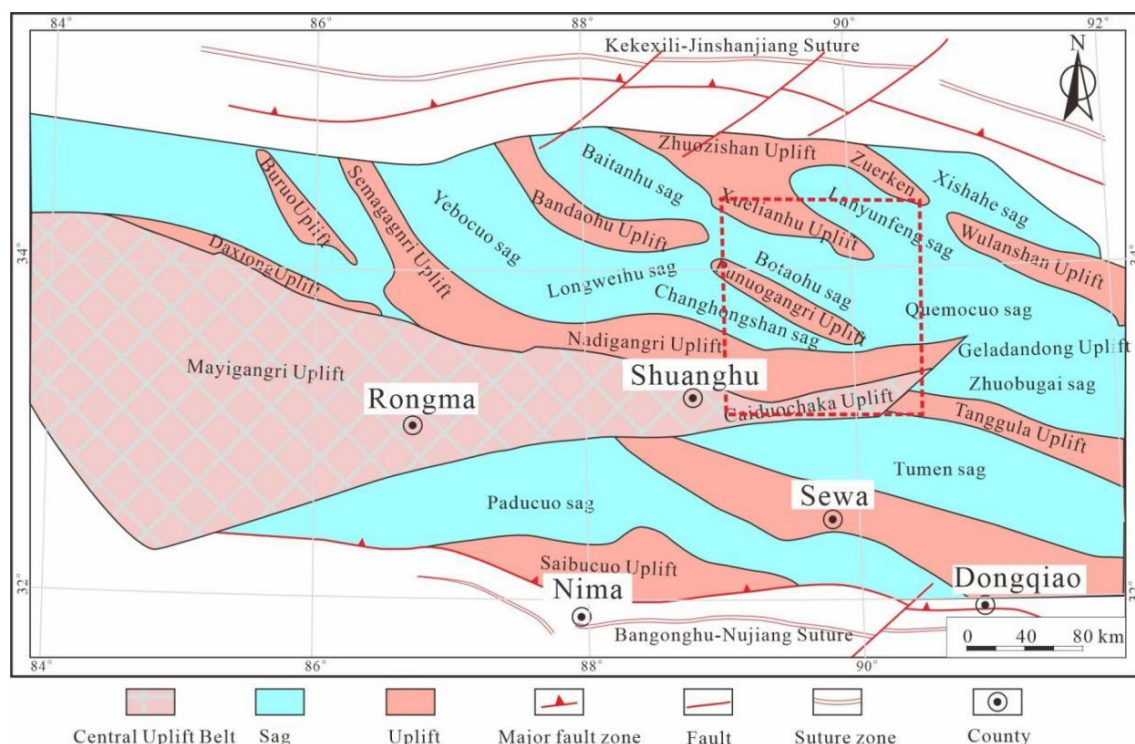


Figure 1. Division of structural units in the Qiangtang Basin. The red dashed box represents the study area.

3. Methods

Four 2D seismic lines, namely TC-01, TC-02, TC-03, and TC-04, were acquired in the Tso Co area (Figure 2), with a total shot length of 116.04 km. A total of 34,963 shot records and 25,887 receiver records were obtained across all lines. The largest numbers of shots and receivers are observed on line TC-01 (13,245 shots and 8803 receivers), while line TC-04 has the smallest numbers (6645 shots and 4407 receivers). Data acquisition was conducted using a wide-line, high-density layout, which effectively increases the spatial sampling of the seismic wavefield, enhances the spatial sampling capability, and improves wavefield positioning in the structurally complex areas. Line TC-03 employed a 2L3S receiver pattern, while the other lines used a 1L3S pattern. The receiver interval was 5–10 m, with a nominal fold of 400 in the longitudinal direction and 3–6 in the transverse direction, achieving a total fold ranging from 1200 to 2400. This high-fold design effectively suppresses various types of interference noise and significantly enhances the signal-to-noise ratio of raw data. The energy source was a BV-620LF low-frequency vibrator, with a sweep frequency range of 1.5–96 Hz. The low-frequency components facilitate seismic wave penetration through the high-velocity permafrost layer and the underlying bedrock, which improves the recovery of deep effective information. A Sercel-428XL digital seismograph was used to record data. The sampling interval was 1 ms, and the record length was 5 s. This study connected 10 geophones in parallel without array grouping; this alias-free spatial sampling style provides dense sampling of the seismic wavefield, allowing both signal and noise to be acquired without prior filtering, thus preventing damage to reflection information that might otherwise result from aggressive noise suppression during acquisition.

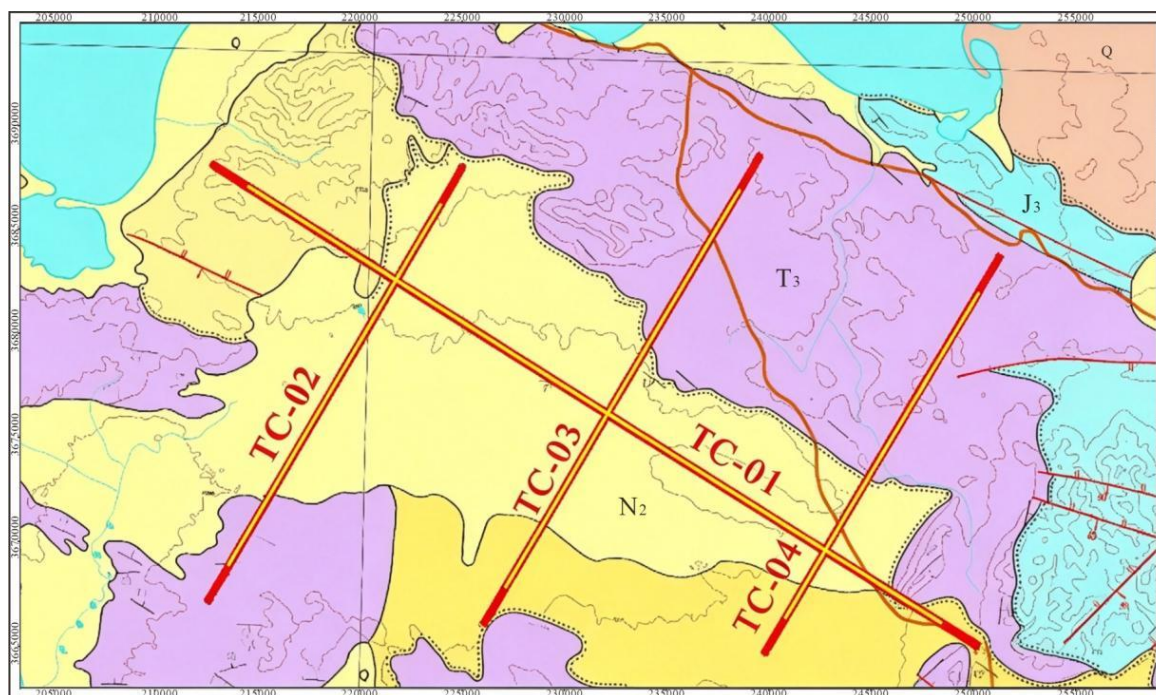


Figure 2. Seismic survey line distribution for gas hydrates in the Tso Co permafrost area. Red bold lines indicate major faults, and thin lines indicate secondary faults.

4. Data processing

4.1. Static correction and amplitude compensation

High-precision static corrections were implemented using a pseudo-3D wide-line tomographic static correction method. All 2D seismic lines were integrated into a unified 3D gridded framework. Abundant gather data ensured computational stability and closure accuracy at line intersections. A fine-scale 3D inversion with small grid cells was performed to build a high-resolution near-surface velocity-depth model, addressing high-frequency imaging issues. Quality control involved comparing near-surface structural maps from tomographic inversion, as well as shot records and stacked sections before and after static corrections. For residual static errors after the static corrections, this study applied a comprehensive global optimization residual static correction technique. Reflection horizon times were picked on Normal Moveout (NMO) corrected Common Midpoint (CMP) gathers to derive residual source and receiver statics.

GeoEast software was used for residual static correction. The algorithm combines the strengths of the maximum energy method, simulated annealing, and genetic algorithms into an alternating hybrid optimization algorithm for estimating residual statics [32,33]. In this approach, solutions generated by the maximum energy method and simulated annealing are used as the initial population for the genetic algorithm. Subsequently, after the genetic algorithm evolves, the maximum energy method and simulated annealing are reapplied to enhance local search capability, compensating for the genetic algorithm's weakness in local refinement. This strategy ultimately achieves fast convergence to the optimal solution (Figure 3).

Significant amplitude variations among traces and shots were corrected using spherical divergence compensation and surface-consistent amplitude compensation. Spherical divergence compensation corrected energy attenuation due to geometric spreading. Using a regional velocity field,

a time- and velocity-dependent compensation curve was applied to each trace to balance near- and far-offset energies and mid- to deep-layer amplitudes [34].

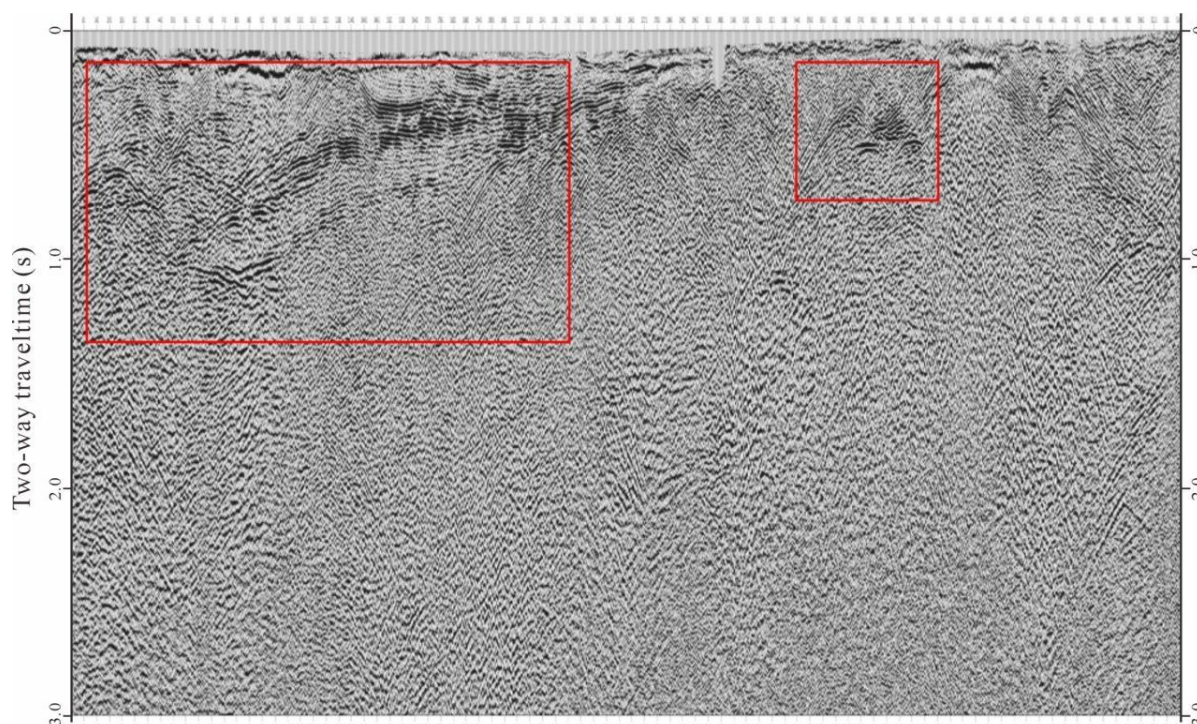


Figure 3. Comprehensive global optimization residual static correction stacked section of Line TC-03. The red box highlights the key area of focus.

Surface-consistent amplitude compensation eliminated lateral amplitude inconsistencies caused by near-surface variations. Within a defined time window, the average or root-mean-square amplitude of each trace was calculated. Compensation factors for common source, common receiver, and common offset bins were derived under the surface-consistent assumption and applied to the traces. After amplitude compensation, shallow, middle, and deep energies were effectively restored.

4.2. Noise suppression and time migration

A four-step pre-stack noise attenuation workflow was implemented using the GeoEast processing system [35,36]. Adaptive surface-wave attenuation was applied in the shot domain. Time-frequency analysis detected surface waves based on differences in frequency, spatial extent, and energy from reflections. Frequency-divided anomalous amplitude attenuation was then performed. Data were decomposed into multiple frequency bands. Within each band, the laterally weighted median of the data envelope was computed to automatically locate high-energy noise. Time- and space-variant suppression was applied within the dominant frequency band of the noise using predefined thresholds and attenuation coefficients. An iterative process of surface-consistent amplitude compensation and frequency-divided anomalous amplitude attenuation was conducted in the shot domain. Amplitude compensation removed non-geological energy variations caused by inconsistent source and receiver conditions. Anomalous amplitude attenuation then suppressed the remaining prominent anomalous points. Several iterations gradually reduced high-energy interference. Finally, the processing domain was switched to the common mid-point domain, where frequency-divided anomalous amplitude attenuation

was applied again to suppress residual anomalies correlated along common reflection point trajectories. This multi-step, multi-domain workflow improved the signal-to-noise ratio of the seismic data.

Post-stack time migration was performed using a finite-difference algorithm. The migration velocity field was built iteratively. The Dip Moveout (DMO) velocity field and well velocity information were used as initial constraints to define a macro velocity control grid. An initial migration velocity field was interpreted and constructed. After a preliminary migration, the velocity model was adjusted based on event positioning, diffraction convergence, and fault imaging clarity. Multiple iterative cycles produced a high-precision post-stack time migration velocity field. The finite-difference method accommodates lateral and vertical velocity variations, addressing sharp velocity changes in complex structural areas [28,37,38]. The resulting section shows weak migration-smile artifacts, well-focused diffractions, and clearly positioned fault terminations (Figure 4).

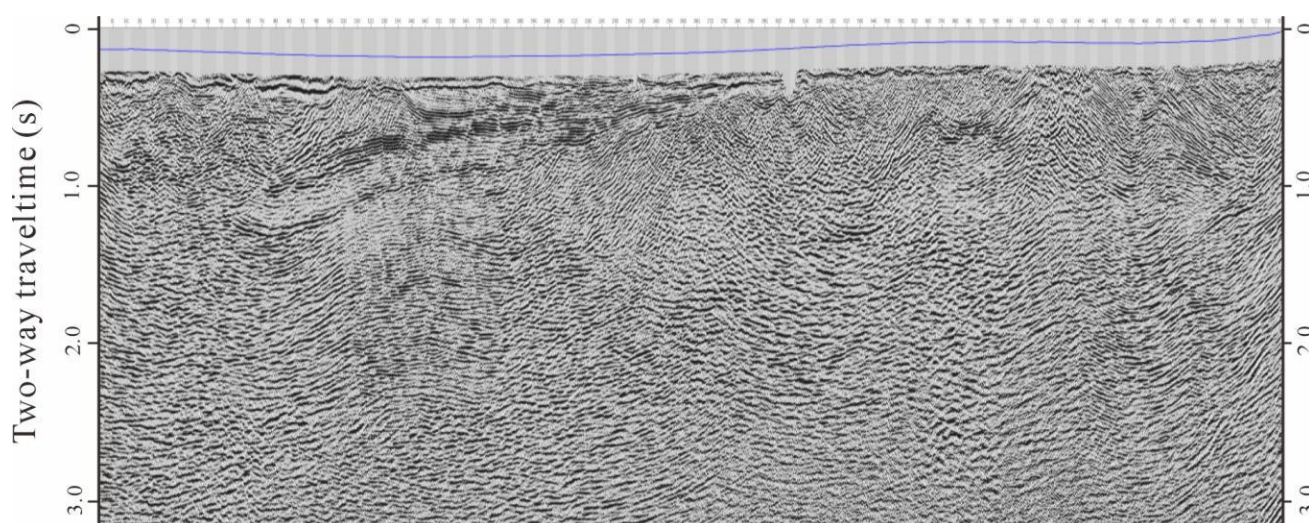


Figure 4. Post-stack time migration section of Line TC-03 demonstrating the time migration effect.

4.3. Shallow frequency scanning and offset stacking

The shallow mute range was determined by stacking different offset ranges. In permafrost areas, the small offset range is highly sensitive to muting: excessive muting may remove the permafrost signal, while insufficient muting leaves significant distortion, both degrading permafrost imaging. To identify the optimal offset range for permafrost imaging, we performed offset stacking using four intervals: 0–30, 50–100, 100–150, and 150–200 m [39,40]. As shown in Figure 5, the mute should not exceed a 150-m offset. This optimized mute allows the best permafrost imaging.

Shallow gathers contain not only permafrost reflections but also low-frequency surface waves, high-frequency refractions, and anomalous amplitude noise. Frequency scanning effectively filters out these interferences and highlights the desired reflections. Analysis of different frequency bands indicates that the cap-layer reflections are concentrated in the 10–30 Hz range.

5. Permafrost frequency and validation

A high-precision near-surface model was constructed using pseudo-3D wide-line tomographic static correction, which effectively removed time shifts induced by complex surface topography and variations in the low-velocity layer. By combining high-precision datum static correction, noise

suppression, and refined imaging within an integrated acquisition-processing-interpretation framework, the signal-to-noise ratio and resolution were progressively improved, yielding high-quality final sections. Frequency scanning reveals that the permafrost reflection is best expressed in the 10–35 Hz band (Figure 6), a range that is broader and higher in frequency than typical surface waves and refractions. For permafrost mapping, seismic record interpretation indicates that first breaks show better continuity and lower velocities in river channels, whereas they disappear rapidly and exhibit higher velocities where Quaternary cover is thin or absent.

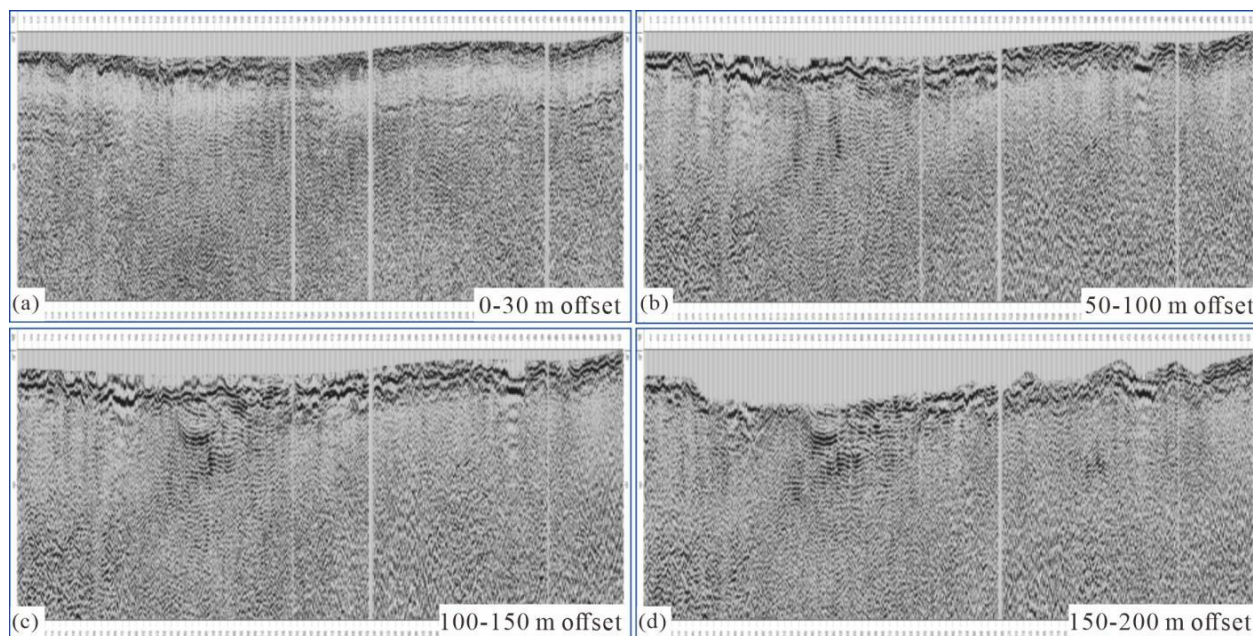


Figure 5. Partial stacked sections of Line TC-02 for cap layer identification using frequency scanning. Offset stacking of four intervals: (a) 0–30 m, (b) 50–100 m, (c) 100–150 m, and (d) 150–200 m. Imaging is weak at offsets of 0–30 m, which is beyond the shallow imaging range; offsets of 150–200 m are also beyond the shallow imaging range.

A detailed frequency-scanning analysis across different frequency bands further constrains the optimal imaging range for shallow permafrost reflections (Figure 6). Effective shallow reflections are primarily concentrated within the 15–30 and 20–40 Hz bands, with coherent events observed between approximately 0.2 and 0.5 s two-way travel time. In the 25–50 and 30–60 Hz bands, reflection energy becomes notably weaker and less continuous, indicating rapid high-frequency attenuation within the permafrost layer. The 35–70 Hz band shows little to no coherent reflection energy, suggesting that frequencies above 35 Hz contribute minimally to imaging the shallow cap layer. These observations confirm that the optimal frequency range for identifying the permafrost reflection lies between 15 and 40 Hz, consistent with the dominant frequency of the permafrost base inferred from other analyses.

To establish the overall tectonic framework, surface outcrop observations were combined with regional geology and structural models [41,42]. The interpreted geological horizons along the 2D seismic lines are defined as follows: R marks the base of the Tertiary, J_{2q} the base of the Jurassic Quemocuo Formation, and T_{3t} the base of the Upper Triassic Tumengela Formation. Using these horizon assignments, the seismic sections were calibrated and interpreted, and cross-line closure was carried out (Figure 7).

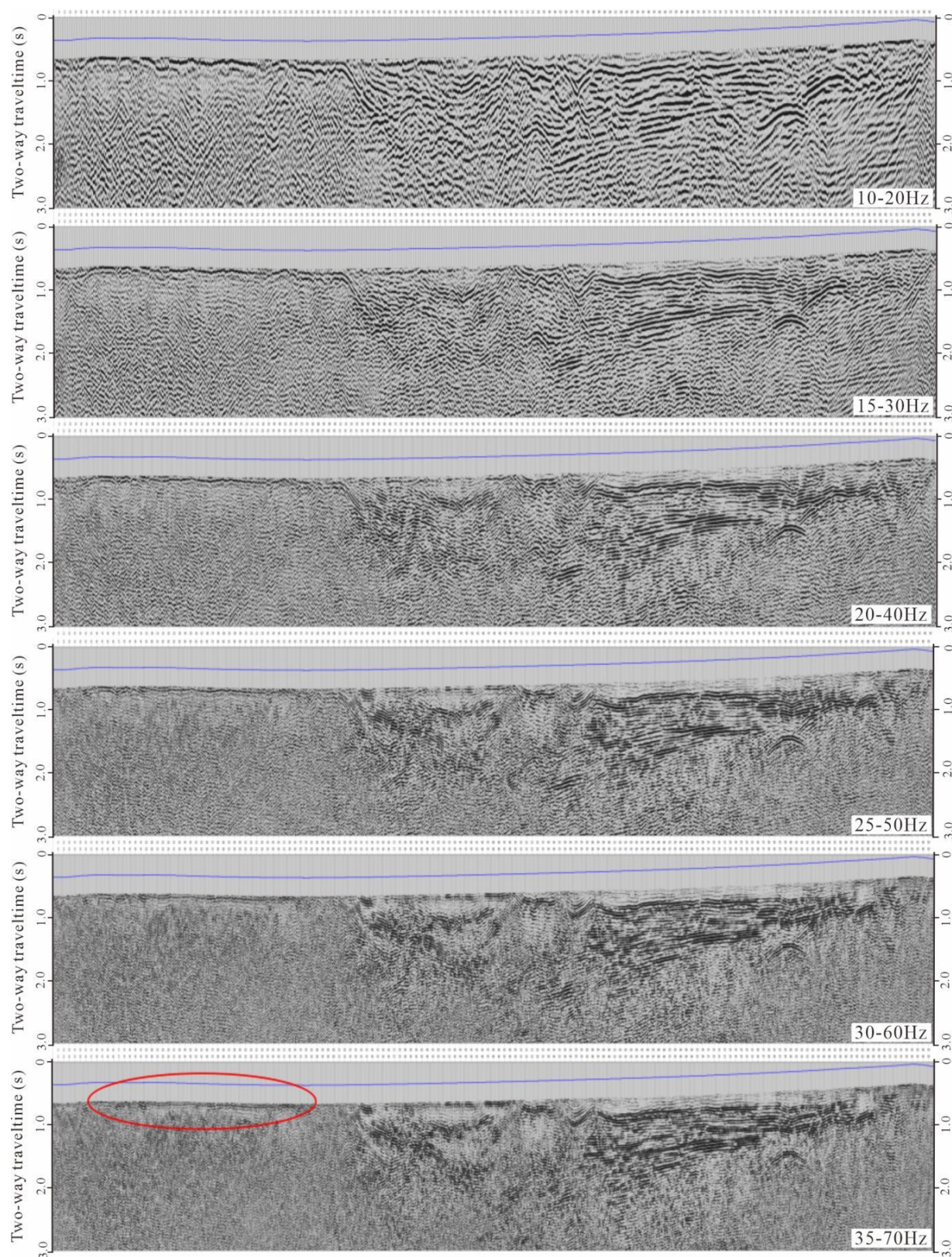


Figure 6. Partial stacked section of bandpass scanning on Line TC-02 showing the permafrost layer, best displayed in the frequency range of 10–35 Hz. The red circle in the 35–70 Hz section shows how shallow effective reflections vanish.

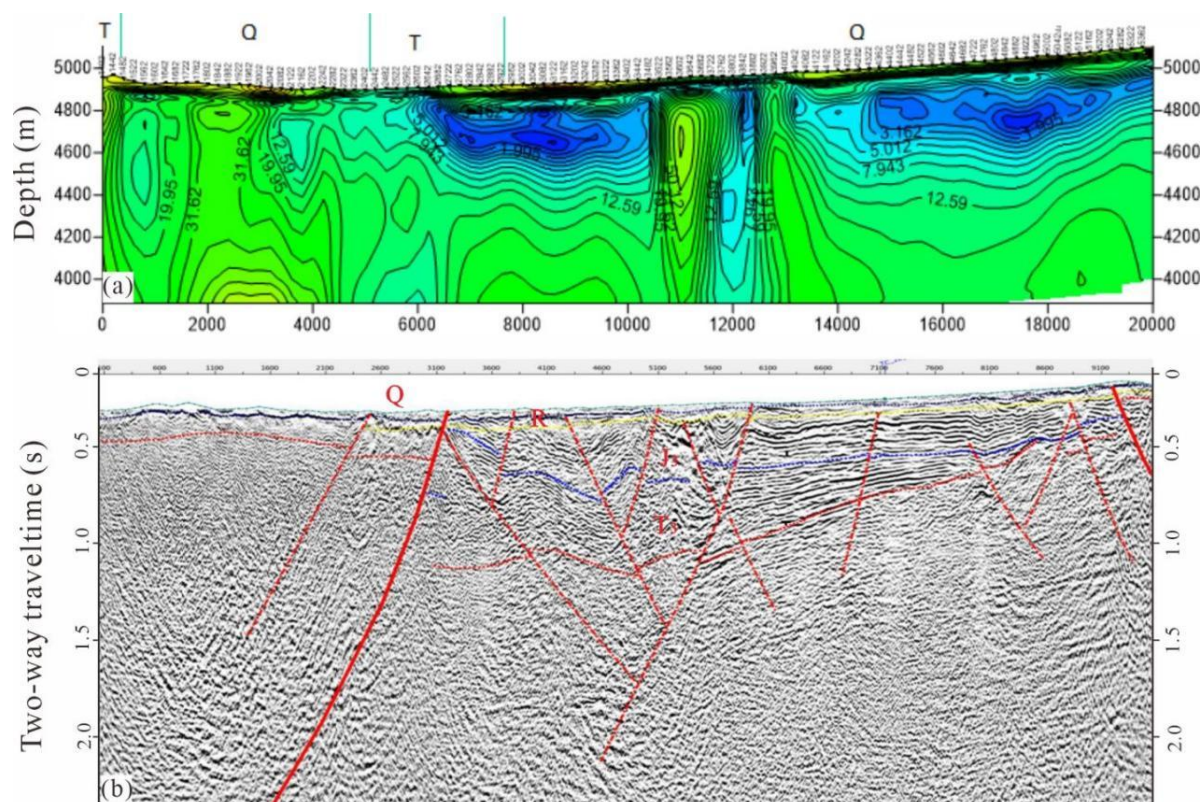


Figure 7. Calibrated section and interpretation of Line TC-03 in the Tso Co area. (a) AMT inversion section of Line TC-02; (b) stratigraphic and fault interpretation of the seismic section of Line TC-03.

6. Results and discussion

6.1. Seismic data quality and structural interpretation

Analysis of the four post-stack time-migrated sections acquired in the survey area indicates that data quality is highest in the northwestern and southeastern parts, while the northeastern and southwestern parts show relatively good quality. The highest signal-to-noise ratios are observed in regions with thicker sedimentary sequences, specifically in the northern part of line TC-02 and the southern part of line TC-04.

Line TC-02 in the western area exhibits abundant, well-defined seismic reflections with clear wave group characteristics. Major marker horizons are well resolved and can be traced continuously. Three major unconformities are clearly visible on the section and, in combination with surface geological data, are interpreted as the bases of the Triassic, Jurassic, and Tertiary systems (Figure 7). Reflections from the shallow, high-velocity permafrost layer are also relatively clear. The overall geological structure is dominated by fault-controlled depressions and uplifts, and seismic data meet the requirements for early-stage exploration interpretation.

The seismic reflection characteristics of the individual stratigraphic units are distinctly different: the base of the Triassic exhibits locally developed mid- to low-frequency strong phases, whereas the overlying Triassic section shows mid- to high-frequency weak phases. The lower Jurassic is characterized by mid- to high-frequency moderate to strong reflections, and the upper Jurassic by low- to mid-frequency strong phases. The Tertiary strata unconformably overlie the Jurassic,

displaying discontinuous weak or chaotic reflections. The base of the permafrost layer is marked by a low-frequency, high-amplitude reflection phase, making it readily identifiable [43,44].

Within the survey area, three first-order faults strike NW-SE. The southern faults dip southward and expose pre-Permian and Triassic strata, whereas the northern faults dip northward and mainly expose Triassic rocks. Secondary faults intersect the main faults at oblique angles and trend NW-SE and E-W. On the tie line TC-01, Triassic and Jurassic strata are widely developed and thin from east to west. On line TC-03, the central-southern part preserves complete Tertiary, Jurassic, and Triassic sequences, all thinning northward and thickening southward. On line TC-04, the southeastern part contains Tertiary, Jurassic, and Triassic sections, while the northeastern part is controlled by two opposing first-order faults that expose large areas of Triassic strata.

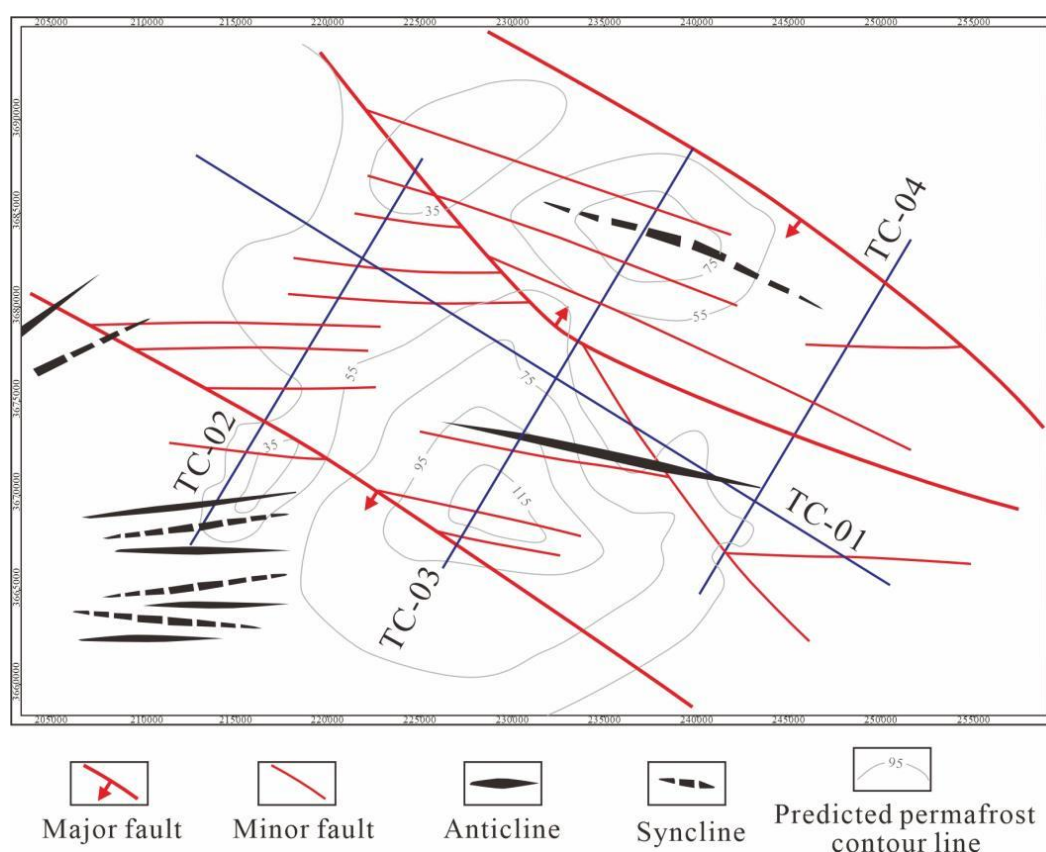


Figure 8. Interpreted structural features and gas hydrate content distribution in the study area.

Comparison of the near-surface tomographic velocity profiles with the tracked permafrost base reflections on the post-stack time-migrated sections shows that the high-velocity top surface on the tomographic profiles corresponds well to the permafrost base, and the relief of this high-velocity top strongly correlates with permafrost thickness variations. Based on these calibrations, the permafrost thickness in the study area ranges from approximately 30 to 140 m, being thicker in the southern river valley and thinner in the north, with a minimum thickness exceeding 30 m (Figure 8). This thick permafrost provides a favorable sealing condition for gas hydrate accumulation [41,45].

The overall tectonic framework of the Tso Co area is controlled by the three major faults, forming a central residual sag flanked by uplifted and eroded zones to the south and north. Secondary faults intersect the main faults, reflecting a regional shear stress field and controlling a series of anticlines and faulted anticlines. The present structural pattern is largely shaped by Neotectonic movement,

exhibiting east-west segmentation and north-south zoning (Figure 8). The base of the Triassic is buried at depths ranging from 300 to 2200 m. The northern part of the study area is strongly uplifted and eroded, with shallow burial (400–600 m). These structural features are critical for understanding hydrate accumulation pathways [28,31,46].

6.2. Integrated geophysical indicators for hydrate prospect delineation

Velocity is a key parameter in the geophysical prediction of gas hydrate accumulations, as seismic waves travel faster in hydrate-bearing sediments than in surrounding rocks. Conversely, the presence of free gas beneath the hydrate stability zone reduces seismic velocity, leading to stacking-velocity inversions [47].

Such velocity reversals can serve as an indicator for hydrate and free gas detection. In the absence of sonic logs, dipole shear logs, or VSP data, a velocity field can be constructed from stacking velocity spectra. On line TC-01, the datum-based interval velocity field shows high-velocity layers from the Tertiary base to the surface in the CMP ranges 4000–7600 and 9800–10,600, interpreted as a possible seismic velocity response to gas hydrates in the permafrost zone. The underlying low-velocity layers may reflect free gas migration along faults and shallow accumulation [48]. Velocity-inversion trends are also observed on the velocity-spectrum trend lines of CMPs 7000 and 10,800 on line TC-01, and on CMPs 4520 and 6200 on line TC-02, although smoothing of the velocity field may have locally reduced resolution. On lines TC-03 and TC-04, the interval velocity sections do not show clear velocity inversions, but subtle inversion trends are still visible on individual CMP spectra, indicating that velocity smoothing may have suppressed some fine details [27,48–50].

Beyond velocity analysis, low-frequency seismic information has proven effective for delineating permafrost and identifying favorable hydrate zones. In this study, a 5 Hz single-frequency relative impedance volume was extracted from sparse-spike inversion (Figure 9). This inversion method extracts reflection coefficients directly from seismic data and requires broadband, low-noise, high-fidelity input data. The Tso Co area exhibits a relatively broad frequency band (3–65 Hz) and rich low-frequency content, providing a good response to permafrost, hydrates, and free gas [51]. On line TC-03, the 5 Hz relative impedance profile shows a maximum permafrost thickness of 345 m, the thickest in the study area (Figure 9). In the southern part of the line, where the permafrost is thick, high-impedance anomalies are observed along fault zones, indicating hydrocarbon migration pathways. In gas hydrate-bearing permafrost areas, faults act as effective conduits for deep-sourced hydrocarbon gases to migrate upward. When these gases enter the gas hydrate stability zone within the permafrost layer, they combine with water to form solid gas hydrates. Gas hydrates exhibit higher P-wave velocities (approximately 3.3–3.8 km/s) and higher densities (approximately 0.9–1.1 g/cm³) compared to the surrounding unconsolidated sediments, resulting in a positive wave impedance contrast, and thus appearing as high-impedance anomalies along fault zones. Shallow high-impedance zones are also present beneath the Tertiary permafrost. Given the thick permafrost, thick Triassic source rocks, and well-developed fault systems, the southern river valley area on line TC-03 is classified as a favorable zone. On line TC-04, the southern part shows moderate permafrost thickness, high-impedance anomalies beneath the Tertiary permafrost, relatively thin permafrost, but thick Triassic source rocks and active faulting. On line TC-01, the favorable zones also exhibit near-source conditions, fault development, and moderate permafrost thickness [20,44].

In summary, integrated velocity-inversion analysis, low-frequency (5 Hz) relative impedance, and AMT high-resistivity layers (Figure 7) are helpful to delineate prospective hydrate areas. The combination of thick permafrost (>30 m), thick Triassic source rocks (locally >500 m), and active fault

systems provides favorable conditions for gas hydrate accumulation in the southern river valley region of the Tso Co area.

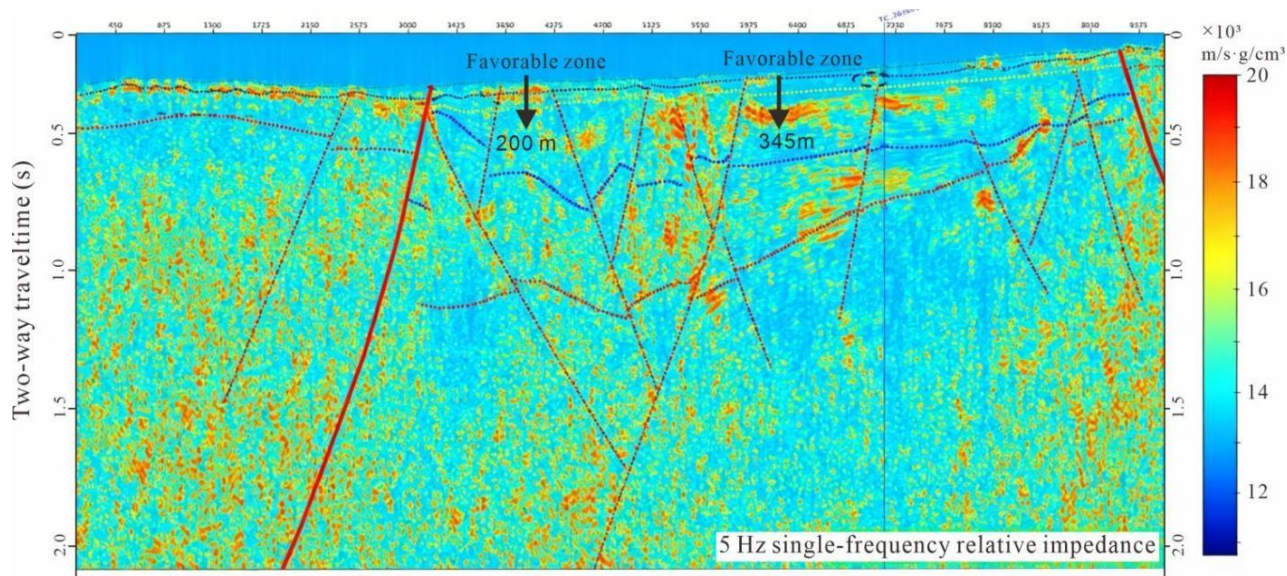


Figure 9. 5 Hz single-frequency relative impedance profile of seismic line TC-02, showing favorable zones.

7. Conclusions

This study provides a replicable technological workflow and geophysical benchmark for gas hydrate exploration in the Qiangtang Basin and other mid-latitude plateau permafrost regions. The main findings and conclusions are summarized as follows:

(1) This study develops a high-precision seismic acquisition and processing system tailored to the Qiangtang Basin permafrost. Unlike conventional explosive-source surveys that suffer from weak low-frequency energy and rapid high-frequency attenuation, we adopt a low-frequency vibrator source (1.5–96 Hz) combined with a wide-line, high-density geometry. This combination enhances low-frequency penetration and raw data fidelity for the first time in this region, effectively suppressing aliasing and preserving subtle reflections. It overcomes limitations of earlier low-fold, large-spacing surveys that failed to image shallow permafrost and hydrate-related anomalies, as evidenced by the improved data quality shown in Figures 4 and 5.

(2) Key innovations include pseudo-3D wide-line tomographic static corrections and a hybrid residual static correction algorithm integrating maximum energy, simulated annealing, and genetic algorithms. A multi-domain, amplitude-preserving noise suppression workflow, followed by finite-difference time migration with iterative velocity updating, achieves accurate structural imaging. For the first time in the Qiangtang Basin, the permafrost base reflections are optimally expressed in the 10–35 Hz band, and sparse-spike inversion shows that 5 Hz single-frequency relative impedance volumes can delineate permafrost thickness and indicate prospective hydrate zones. These low-frequency amplitude anomalies, spatially associated with faults, serve as a novel region-specific identification marker for gas hydrates.

(3) The interpreted seismic profiles reveal a fault-controlled depression-uplift framework with three major unconformities within the Triassic, Jurassic, and Tertiary strata. Permafrost thickness is up to 140 m in the southern valley and 30 m in the north. Integrated velocity-inversion analysis, 5 Hz

relative impedance, and AMT data consistently indicate that the southern river valley area is the most favorable hydrate prospect.

Author contributions

Shuai Zhang: Investigation, Formal analysis, Writing—original draft and Supervision. Guanzhong Shi: Conceptualization, Methodology, Writing—review & editing. Jianguo Yin and Shouji Pang: Data curation, Software. Youhai Zhu and Pingkang Wang: Validation, Visualization. All authors have read and approved the final manuscript.

Use of Generative-AI tools declaration

The authors declare that they used Artificial Intelligence (AI) tools for the English language revision of this article.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (Grant Nos. 2025ZD1400700 and 2025ZD1400704) and the Guangdong Major Project of Basic and Applied Basic Research (Grant No. 2020B0301030003). The authors thank the China Geological Survey for its support and assistance in conducting the seismic survey in the Qiangtang Basin. We are also grateful to all colleagues who worked alongside the authors on the Tibetan Plateau. The authors thank the reviewers and editors for their insightful comments and constructive suggestions.

Conflicts of interest

The authors declare no conflicts of interest.

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