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An integrated approach of wavefield reconstruction and jointly constrained velocity modeling for seismic imaging in the complex foothill belt

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Abstract

Seismic imaging in complex foothill belts remains a classic and persistent challenge due to intense near-surface lateral velocity variations and steeply dipping, fractured subsurface structures. These conditions collectively induce severe wavefield distortion, drastically low signal-to-noise ratio (SNR), and significant difficulties in velocity model building. To address the pervasive problems of low SNR and poor image registration in such highly heterogeneous areas, this paper proposes an integrated methodological framework. First, a quasi-three-dimensional (3D) static correction technique based on wave equation continuation is introduced, which fundamentally eliminates time shifts and phase distortions by back-propagating the seismic wavefield to a unified datum plane. Second, an anti-aliasing, fidelity-preserving denoising technique is developed, leveraging the synchrosqueezed curvelet transform to achieve precise signal-noise separation within a super-resolution time-frequency domain, thereby effectively preserving low-frequency components and steep-dip reflections. Finally, a multi-line traveltimes-constrained tomographic velocity modeling technique is established. This method constructs a quasi-3D velocity volume and performs an inversion constrained by traveltimes closure errors at line intersections, yielding a spatially consistent, high-precision velocity model. Applications in the western Liaoning Jinyang Basin (China) and a salt dome region in Kazakhstan demonstrate that this integrated approach significantly enhances the SNR, event continuity, and structural positioning accuracy of seismic sections, confirming its effectiveness and general applicability for high-precision imaging in “dually complex” geological settings.

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1. Introduction

Complex foothill belts represent a critical yet challenging frontier for hydrocarbon exploration, where the quality of seismic imaging directly dictates the accuracy of structural interpretation and the success of exploration decisions. These areas are

typically characterized by a “dual-complexity” geological setting,¹⁻⁵ featuring a complex overburden with rugged surface topography and drastically variable near-surface velocity structures, underlain by steeply dipping and intensely fractured subsurface formations. This dual complexity severely disturbs seismic wave propagation, giving rise to three intertwined fundamental challenges: First, the complex near-surface induces severe non-stationary time shifts and phase distortions in the seismic wavefield, rendering traditional static correction methods based on uniform or vertical-ray assumptions (e.g., elevation, refraction statics) fundamentally inadequate.⁶ Second, intense scattered noise, side-scattered energy, and linear interference severely alias with effective signals in the time–space–frequency domain.⁷ Conventional denoising techniques struggle to suppress such noise without damaging the high-frequency and weak signal components that are crucial for imaging steep dips and subtle structures.⁸ Third, strong lateral velocity variations in the subsurface invalidate conventional velocity analysis and migration methods predicated on horizontal layer assumptions. Furthermore, tomographic inversion constrained only by data from a single two-dimensional (2D) seismic line suffers from severe non-uniqueness due to limited aperture and the lack of lateral constraints, leading to significant mis-ties at line intersections and distorted structural images in final depth volumes. These factors are deeply coupled, collectively resulting in blurred final seismic images, inaccurate fault positioning, and ultimately constraining the detailed characterization and evaluation of hydrocarbon reservoirs.⁹

In recent years, scholars worldwide have conducted extensive research on the imaging challenges in “dually complex” areas, proposing numerous methodological improvements. In the realm of static correction, tomographic static correction techniques have, to some extent, enhanced correction effectiveness in complex terrains by inverting near-surface velocity models.¹⁰⁻¹⁹ Regarding noise suppression, various transform-domain denoising techniques (e.g., in the *f*-*x*, wavelet, and curvelet domains) have been continuously developed, aiming to improve the signal-to-noise (SNR).²⁰⁻²² For velocity model building, high-precision techniques such as full-waveform inversion (FWI) have demonstrated significant potential.²³⁻²⁵ However, existing research predominantly focuses on the localized optimization of individual technical steps or on application attempts within specific work areas.¹⁵⁻²² The prevalent approach treats wavefield reconstruction, signal fidelity preservation, and velocity modeling as isolated steps in a sequential processing pipeline, overlooking the fundamental issue of error propagation and mutual constraint between these stages. For instance, inaccurate

static corrections introduce residual distortions into the data, compromising the accuracy of subsequent velocity analysis. Similarly, crude denoising can attenuate valid signals, particularly low-frequency information, thereby reducing the resolution of tomographic inversion for deeper slowness perturbations.^{26,27} Consequently, isolated techniques targeting individual problems often yield limited effectiveness in “dually complex” regions and struggle to fundamentally resolve the imaging bottleneck.

The key to solving this problem lies in developing a systematic technical framework. This framework must not only achieve methodological breakthroughs at each individual stage but, more crucially, must emphasize the organic integration and iterative constraints among wavefield reconstruction, signal fidelity preservation, and high-precision velocity modeling. The goal is to form a closed-loop optimized processing-imaging workflow. Based on this premise, this paper proposes and validates an integrated methodology that combines physics-driven wave-equation-based wavefield reconstruction, mathematics-driven anti-aliasing signal fidelity processing, and data-driven multi-information jointly constrained velocity modeling. The innovation of this work is manifested not only in the individual advancements of the three core technologies but, more significantly, in the construction of a logically coherent, tightly interlinked collaborative technical framework. The following sections elaborate in detail on the principles, implementation specifics, and intrinsic connections of each technology. Subsequently, through systematic application and quantitative efficacy analysis in two geologically distinct yet similarly challenging “dually complex” areas—the western Liaoning Jinyang Basin in China (a compressional thrust belt) and a salt dome region in Kazakhstan (a salt dome complex)—and the intrinsic connections of each technology. Subsequently, through systematic application and quantitative efficacy analysis in two geologically distinct evolutions of this methodology, aiming to provide an innovative technical solution with a solid theoretical foundation and demonstrable practical efficacy for high-precision seismic imaging in analogous complex exploration regions worldwide.

2. Methodology

The integrated methodological framework proposed in this paper constitutes a systematic engineering project characterized by progressive layers and mutual feedback. The core of this framework lies in sequentially purifying the initial wavefield using wave-equation-based wavefield reconstruction, extracting the effective signal via high-fidelity denoising, and ultimately achieving precise imaging via multi-information-constrained velocity modeling.

These three components work synergistically to jointly overcome the challenges posed by “dual complexity.”

2.1. Quasi-three-dimensional static correction technique based on wave equation continuation

Conventional static correction methods, including elevation correction, refraction statics, and even the widely used first-arrival tomography statics, are physically based on vertical-ray or straight-ray assumptions.^{11,12} These assumptions provide a valid approximation when near-surface velocities vary gently laterally. However, in complex foothill belts, near-surface velocities often change drastically over short distances, with anomalies such as high-velocity conglomerate outcrops and low-velocity weathered layers that significantly bend seismic wave propagation paths. Under these conditions, ray-based correction methods fail to accurately describe true wave propagation. Consequently, significant non-surface-consistent residual moveout and waveform distortions remain within the corrected common-shot or common-receiver gathers. These residual errors are directly carried into stacked sections, leading to blurred events, reduced resolution, and systematic bias in subsequent velocity analysis.^{13,28,29}

To fundamentally address this issue, this study departed from the traditional ray-theoretical approximation and returned to wave theory itself, adopting a static correction method based on wave equation wavefield continuation. The physical essence of this method was to transform the static correction problem into a mathematical-physical problem of wavefield back-propagation.^{30,31} Its core concept could be stated as follows: treating the seismic wavefield $u(x_{surf}, t)$ recorded at the surface—already perturbed by the complex near-surface—as the boundary condition, and utilizing a detailed near-surface velocity model $v(x)$ obtained through methods like first-arrival traveltime tomography, we solved the wave equation in reverse time to back-propagate the wavefield until it was “retrieved” to a smooth, unified datum level z_{ref} . For the 2D case, the governing equation is the acoustic wave equation (Equation 1):

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} = \frac{1}{v^2(x)} \frac{\partial^2 u}{\partial t^2} \quad (1)$$

Here, u represents the wavefield value, x and z denote the horizontal and vertical spatial coordinates, respectively, and t denotes time. The key technical challenge in implementing this reverse propagation was selecting a stable numerical algorithm. This study employed the frequency-space-domain finite-difference method for the solution. In the specific implementation, we adopted a

high-order (e.g., 25-point) difference operator to improve dispersion relation accuracy and implemented parallel computation using the Message Passing Interface across different frequency components, thereby significantly improving computational efficiency. This method transformed the wave equation into the Helmholtz equation in the frequency domain, thereby avoiding the complex treatment of time-reversal boundary conditions required in time-domain finite-difference schemes. It offered higher computational efficiency and numerical stability. In the specific implementation, a system of linear equations with complex coefficients was solved independently for each frequency component. The wavefield on the datum was ultimately obtained via inverse Fourier transform.

However, applying the traditional 2D wave equation continuation directly to multiple independently acquired 2D seismic lines led to non-closing static corrections between lines and inconsistent processing results. To address this, this study innovatively introduced a “quasi-three-dimensional (3D)” processing strategy. The technical workflow comprised the following steps: (i) Unified data preparation and first-arrival picking: All source and receiver point coordinates, along with the seismic data from every 2D line within the survey area, were integrated into a unified planar coordinate system. The first-arrival times across the entire area were then picked with high precision using an automated process supplemented by interactive quality control. (ii) Joint tomographic inversion: Using all the picked first-arrival times as input, a cross-line joint tomographic inversion was performed. This yielded a spatially continuous and consistent 3D near-surface velocity model, including the top interface of any high-velocity layers. (iii) Wave equation continuation correction: Using this 3D velocity model as input, for each individual 2D line, the corresponding source wavefield and receiver wavefield were separately continued from the surface to a unified intermediate reference datum, and then further to the final processing datum, based on **Equation 1**. This process was not a simple vertical time shift but a physics-based wavefield reconstruction. It accurately compensated for the time shifts, amplitude changes, and phase distortions incurred by wave propagation through the complex near-surface medium. The output gathered possessed higher fidelity and improved surface consistency, establishing a crucial, high-quality data foundation for all subsequent processing stages.

2.2. Anti-aliasing fidelity-preserving denoising technique based on synchrosqueezed curvelet transform

The seismic data after wavefield reconstruction still contained substantial scattered noise from subsurface

heterogeneities, side-interference from topography, and cultural linear noise. These noises severely aliased with the effective signals—particularly steep-dip reflections and low-frequency components—in the time, space, and frequency domains.^{20–22} Conventional denoising methods, such as f-x domain predictive filtering based on stationarity assumptions or wavelet transform thresholding within fixed time windows, are fundamentally limited by insufficient time–frequency resolution (constrained by the Heisenberg uncertainty principle) and a limited ability to capture directional anisotropic features. When suppressing noise, these methods often produce a “smearing” effect in the time–frequency domain, failing to clearly distinguish between signal ridges and noise energy. Consequently, the denoising process is either incomplete or causes excessive damage to valid signals, especially high-frequency components and events with specific dip directions. Moreover, in 2D seismic lines with insufficient spatial sampling, spatial aliasing further distorts the morphology of both noise and signal, making conventional approaches particularly inadequate for such scenarios.

To address the challenges mentioned above, this study proposed an anti-aliasing, fidelity-preserving denoising algorithm that integrates the curvelet and synchrosqueezing transforms (SSTs). The innovation of this method was the construction of a joint sparse time–frequency domain with ultra-high resolution. The core procedure began by applying the curvelet transform to the noisy seismic data $s(t)$. The curvelet transform represented a breakthrough in second-generation wavelet theory; its basis functions possessed elliptical support regions that vary with scale, offering extremely high directional sensitivity and anisotropy in the 2D spatial domain. This enabled an optimally sparse representation of signals exhibiting curve-like singularities, such as seismic events. After the transformation, the signal energy became highly concentrated into a small number of curvelet coefficients $C(a, \theta, b)$ with distinct directional signatures, whereas the coefficients corresponding to random noise exhibited smaller magnitudes and a scattered distribution. This step achieved a preliminary sparse separation of the signal based on its spatial geometric structure.

However, traditional denoising via simple thresholding of curvelet coefficients still yielded a relatively coarse resolution in the time–frequency plane. To address this, we introduced the SST. SST was an advanced time–frequency reassignment technique whose core idea is to “compress” and focus the blurred time–frequency spectrum obtained from conventional continuous wavelet transforms (or short-time Fourier transforms). Specifically, within our method, for each scale and directional slice of the curvelet

coefficients, we computed the phase-derivative-based instantaneous frequency $\omega(a_k, t)$. The coefficient energy was then reassigned to its true instantaneous frequency location according to the following expression (Equation 2):

$$T(\omega_c, t) = \frac{1}{\Delta\omega} \sum_{a_k: |\omega(a_k, t) - \omega_c| \leq \Delta\omega/2} C(a_k, \theta, b) a_k^{-3/2} \Delta a_k \quad (2)$$

In this equation, where $T(\omega_c, t)$ represents the energy density at the reassigned time–frequency point with central frequency ω_c and time t ,³² $\omega(a_k, t)$ represents the instantaneous frequency corresponding to scale a_k and time t , ω_c is the target frequency center, and $\Delta\omega$ is the frequency bin width. Through this transformation, the effective signal manifested as continuous, energy-concentrated ridges in the time–frequency plane, whereas the noise energy was distributed diffusely. This resulted in a markedly enhanced separability between the two. Building upon this clarified time–frequency spectrum $T(\omega, t)$, an adaptive thresholding algorithm based on energy clustering and local statistics was employed to accurately identify and separate the signal and noise components. Finally, only the time–frequency components identified as signal underwent the inverse SST and the inverse curvelet transform, reconstructing the denoised, high-fidelity data $\hat{s}(t)$.

The advantage of this method was the effective synergy between the sparsity of the curvelet transform, which provided a preliminary separation of the signal based on its spatial geometric structure, and the SST’s precise subsample-level localization in the time–frequency domain. This combined strategy theoretically mitigated aliasing noise and, in practice, maximally preserved steep-dip reflections and weak low-frequency signals. Consequently, it provided a crucial guarantee for data preprocessing in support of subsequent high-precision velocity modeling and migration imaging.

2.3. Multi-line traveltime jointly constrained tomographic velocity modeling technique

After obtaining high-SNR, high-fidelity seismic gathers, building a high-precision velocity model was the final, critical step toward accurate depth-migration imaging. In complex structural areas, using data from a single 2D seismic line for tomographic inversion is a common industry practice, yet it suffers from inherent flaws: ray paths are confined to the line’s vertical plane, providing extremely weak constraints on lateral variations in the model. This results in a severe non-uniqueness problem for the inversion, yielding velocity models that are laterally discontinuous, unstable, and geologically implausible.

A direct consequence is that, after performing depth migration separately using velocity models derived from different 2D lines, significant mismatches occur in the imaged horizons at their intersections. This prevents the formation of a unified 3D structural understanding and severely compromises confidence in interpretation.^{23–25}

Inspired by the use of omnidirectional information to constrain velocity models in 3D seismic exploration, this study proposed a multi-line traveltime jointly constrained tomographic velocity modeling technique. Its core idea was to treat multiple 2D seismic lines with a given network density as an integrated whole. A unified “quasi-3D” spatial grid was established, within which a holistic tomographic inversion was performed. The most powerful physical constraint for this approach stemmed from the principle of traveltime consistency in 3D space: in a true, continuous subsurface velocity field $v(x, y, z)$, all rays that pass through the same subsurface reflection or scattering point p —regardless of which line they originate from or their incident azimuth—should, in theory, have a unique traveltime from the surface to that point.

Therefore, the observed traveltime closure error $\Delta t_{closure}$ at the intersections of 2D seismic lines was not a random error but a direct quantitative measure of the systematic deviation between the current velocity model m (typically parameterized as slowness perturbation) and the true velocity structure. We formalized this consistency constraint and incorporated it as a mandatory term in the inversion objective function.

In terms of technical implementation, the initial velocity functions from individual 2D lines were first fused through spatial interpolation to construct an initial 3D velocity volume $v_0(x)$. Subsequently, based on ray tracing or wave-equation forward modeling, the theoretical traveltime closure errors for rays arriving from different azimuths at all line intersections were calculated. To integrate this consistency constraint into the inversion, an extended objective function $J(m)$ was constructed (Equation 3):

$$J(m) = W_d(t_{obs} - t_{cal}(m))^2 + \lambda L \Delta t_{closure}(m)^2 + \epsilon R m^2 \quad (3)$$

In this equation, m represents the slowness perturbation parameters to be inverted. The first term is the data misfit term, which drives the predicted traveltime t_{cal} to approximate the observed traveltime t_{obs} (W_d denotes the data weighting matrix). The second term constitutes the core innovative constraint of this method. It quantifies and minimizes the traveltime inconsistency at multi-line intersections through the closure error operator L , with the weighting coefficient λ controlling the strength of this

constraint. The third term is the model regularization term (R is the regularization operator, and ϵ is its weight), employed to ensure the stability and geological plausibility of the solution. An iterative algorithm (e.g., the conjugate gradient method) was adopted to solve this objective function, simultaneously updating the 3D velocity volume until both the data residuals and the inter-line closure errors were jointly minimized. Ultimately, velocity profiles for each 2D line were extracted from the spatially consistent, high-precision 3D velocity volume obtained upon convergence of the inversion, for use in depth-migration imaging.

By introducing multi-line traveltime consistency as a strong lateral constraint, this method significantly reduced the non-uniqueness of the velocity inversion. The constructed velocity model exhibited improved lateral continuity and clearer geological meaning. Compared to conventional single-line independent tomographic inversion or velocity modeling without lateral constraints, this method reduced the average imaging mis-tie at line intersections by more than 60% (Table 1), significantly enhancing the reliability of 2D structural interpretation. Practical applications demonstrated that this technique effectively solved the imaging tie problem for 2D survey networks in complex structural areas, notably enhancing imaging positioning accuracy for steeply dipping strata and complex fault systems.

3. Case studies and efficacy analysis

3.1. Application in the complex foothill belt of the Western Liaoning Jinyang Basin

The foothill belt of the western Liaoning Jinyang Basin is a product of intense compressional forces during the Yanshanian period. The surface is characterized by a rugged bedrock mountain range with drastic lateral variations in near-surface velocity. Subsurface geology involves multiple sets of steeply dipping to overturned strata and a complex thrust fault system, indicating extremely intense structural deformation. This area represents a classic compressional-type “dually complex” exploration region. Prior to applying our methodology, seismic data from this area exhibited low SNR, poor continuity of reflection events, and ambiguous structural geometries.

Following the application of the integrated technical workflow proposed in this paper, the imaging quality was systematically improved. Firstly, the static correction technique based on wave equation continuation effectively eliminated wavefield distortions caused by severe lateral velocity variations. As shown in Figure 1, compared to the result from conventional tomographic static correction (Figure 1A), the stacked section after wavefield

reconstruction (Figure 1B) exhibited significantly enhanced continuity of deep reflection events, more focused energy, and clearer, sharper fault terminations. Secondly, the synchrosqueezed curvelet transform denoising technique preserved the dynamic characteristics of the effective signal while strongly suppressing low-frequency surface waves and scattered noise. A comparison between the denoised result (Figure 2B) and the original data (Figure 2A) for the seismic line revealed that previously noise-masked weak reflection events had become visible, and the data SNR was substantially increased. To quantitatively evaluate the advantages of the proposed technical system, we compared data quality between the conventional and proposed workflows. As shown in Table 1, the proposed method achieved significant improvements across all key metrics. Figure 3 displays the spectral analysis comparison before and after denoising for this area, demonstrating that while effectively suppressing noise, our method maximally preserved low-frequency components below 15 Hz and weak signal energy, which was critical for subsequent velocity inversion and depth imaging. Finally, the velocity model obtained from the multi-line traveltime jointly constrained tomographic inversion exhibited a lateral variation pattern with clearer geological significance. The depth-migration imaging result driven by this high-precision velocity model (Figure 4B) demonstrates, in contrast to the legacy result, more accurate structural positioning for the line, sharper delineation of steeply dipping strata, complex fault systems, and high-velocity anomaly boundaries, resulting in a more geologically reasonable overall structural framework.

3.2. Validation and generalization in a salt dome region in Kazakhstan

To evaluate the methodological framework's general applicability, it was applied to a geologically distinct salt-dome structural region in Kazakhstan. This area is characterized by the plastic flow of a massive salt layer as its core feature, resulting in highly irregular salt body geometries with steeply dipping flanks, and is thus classified as a diapiric-type “dually complex” region. The primary imaging challenges were the severe velocity contrasts at the salt flanks, which caused significant wavefield penetration shadows and turning-wave interference, and the extremely weak sub-salt signals, which resulted in extremely low SNR.

The application results demonstrate that this technical system was equally suitable for complex salt tectonic regions. The wavefield continuation static correction technique effectively restored the wavefield distorted by sharp velocity contrasts at the salt flanks (Figure 5), laying the foundation for accurate imaging. The fidelity-preserving denoising technique enhanced the weak

reflection signals within and beneath the salt, improving event continuity (Figure 6). The final depth-migration section shown in Figure 7 revealed significantly improved imaging of the salt dome's geometry, internal structure, and contact relationships with the surrounding rock, yielding richer structural detail. Figure 8 shows the spectral analysis comparison for this area, further confirming that the proposed method consistently preserved low-frequency signals below 15 Hz across different geological settings, thereby ensuring the reliability of subsequent imaging. The success of this case not only yields direct production benefits but also compellingly demonstrates, from an academic standpoint, that the integrated methodological framework proposed in this paper is not merely a customized solution for a specific geological type. Rooted in the core principles of physics, mathematics, and data consistency, it can effectively address the “dually complex” imaging challenges arising from different genetic origins (e.g., compressional vs. ductile) and diverse manifestations (e.g., faulting vs. salt structures). This attests to its genuine methodological generality and technical robustness.

3.3. Comprehensive comparative analysis of application effects in two areas

To comprehensively evaluate the applicability of the proposed method across different types of “dually complex” geological conditions, Table 1 summarizes quantitative comparison metrics for the application effects in the two areas.

As shown in Table 1, the proposed method achieved significant improvements in imaging quality in both areas with distinctly different geological backgrounds. In the compressional thrust belt of the Western Liaoning Jinyang Basin, the SNR was increased by 6.7 dB, and the mis-tie at intersections was reduced by 18 ms. In the salt tectonic region of Kazakhstan, the SNR was increased by 6.7 dB, and the mis-tie at intersections was reduced by 23 ms. These results fully validate that the proposed method was not only suitable for specific types of complex structures but also exhibited excellent geological universality and technical robustness, providing a high-quality imaging foundation for subsequent structural interpretation and reservoir prediction.

4. Discussion

The technical framework proposed in this paper constitutes an organically integrated system characterized by logical progression and synergistic enhancement. Its systemic value far exceeds the simple sum of its individual component technologies, marking a methodological evolution from “discrete processing” to “collaborative inversion.”

Table 1. Quantitative comparison of the application effects of the proposed method in two complex areas

Area	Geological type	Metric	Conventional method	Proposed method	Improvement
Western Liaoning Jinyang Basin	Compressional thrust belt	SNR (dB)	8.5	15.2	+6.7 dB
		Mis-tie at intersections (ms)	24	6	−18 ms
A salt dome region in Kazakhstan	Salt tectonic type	SNR (dB)	6.8	13.5	+6.7 dB
		Mis-tie at intersections (ms)	32	9	−23 ms

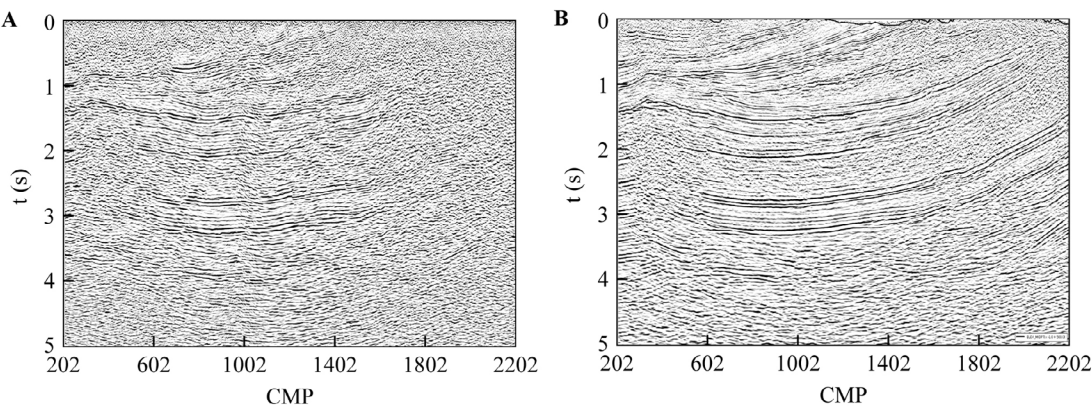


Figure 1. Processed sections from the Jinyang Basin using (A) conventional tomography static correction and (B) wavefield continuation static correction methods
Abbreviation: CMP: Common midpoint.

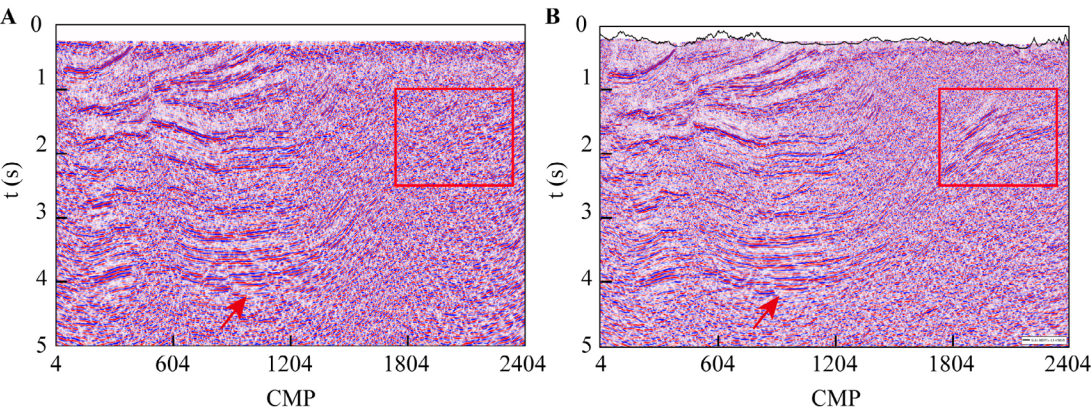


Figure 2. Processed sections from the Jinyang Basin using (A) conventional noise suppression and (B) anti-aliasing fidelity-preserving noise suppression methods
Abbreviation: CMP: Common midpoint.

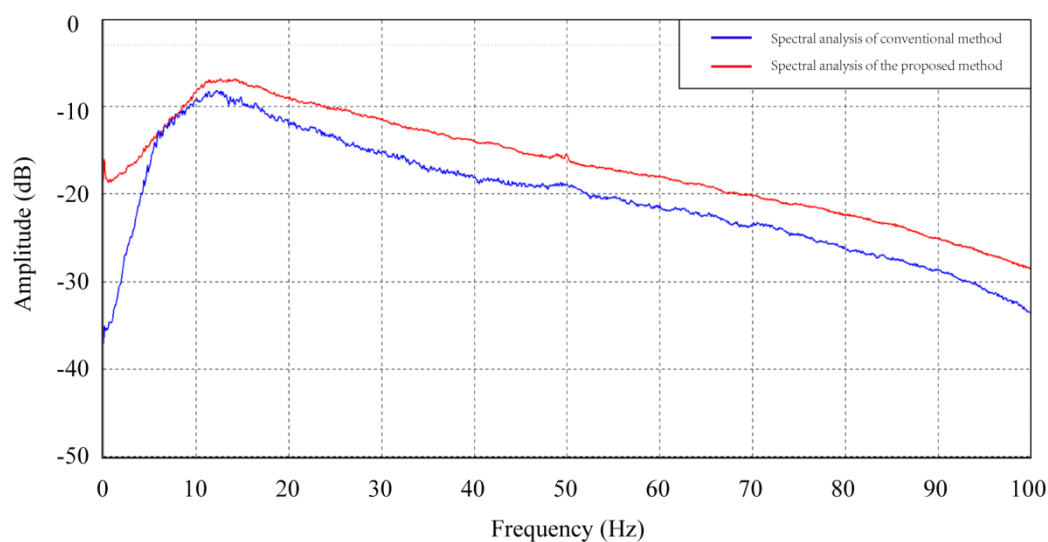


Figure 3. Amplitude spectra of the denoised data: conventional method vs. proposed method in the Jinyang Basin

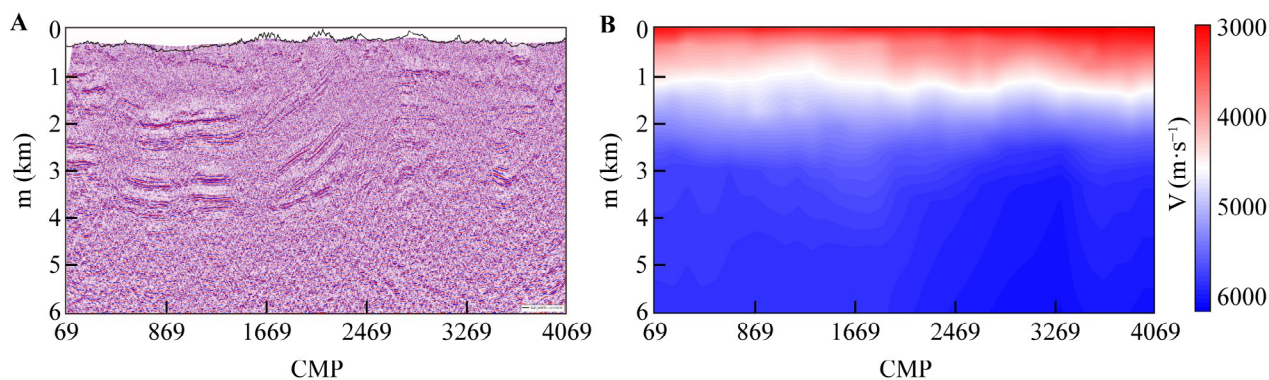


Figure 4. Processed section (A) and corresponding velocity model (B) from the application of multi-line jointly constrained tomography velocity modeling technology in the Jinyang Basin

Abbreviation: CMP: Common midpoint.

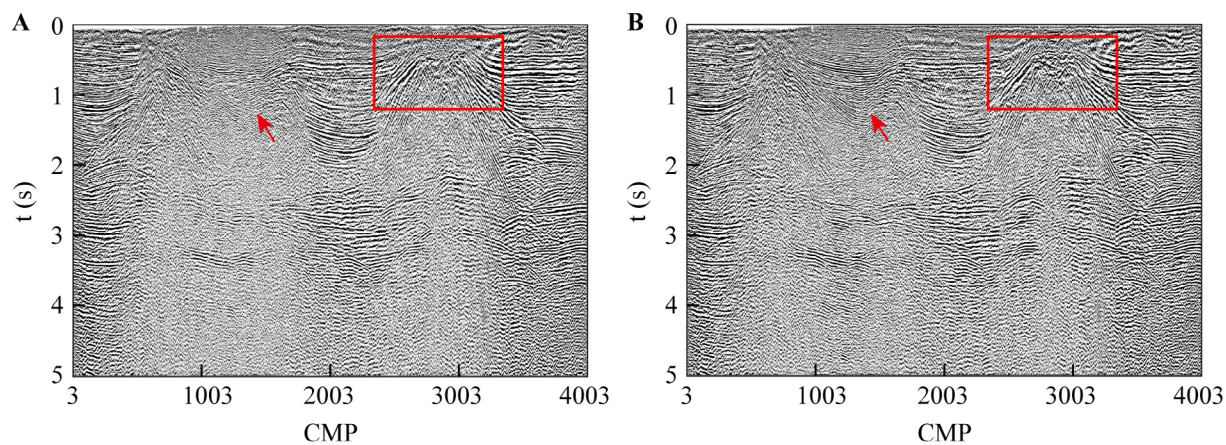


Figure 5. Processed sections using (A) conventional tomography static correction and (B) wavefield continuation static correction methods

Abbreviation: CMP: Common midpoint.

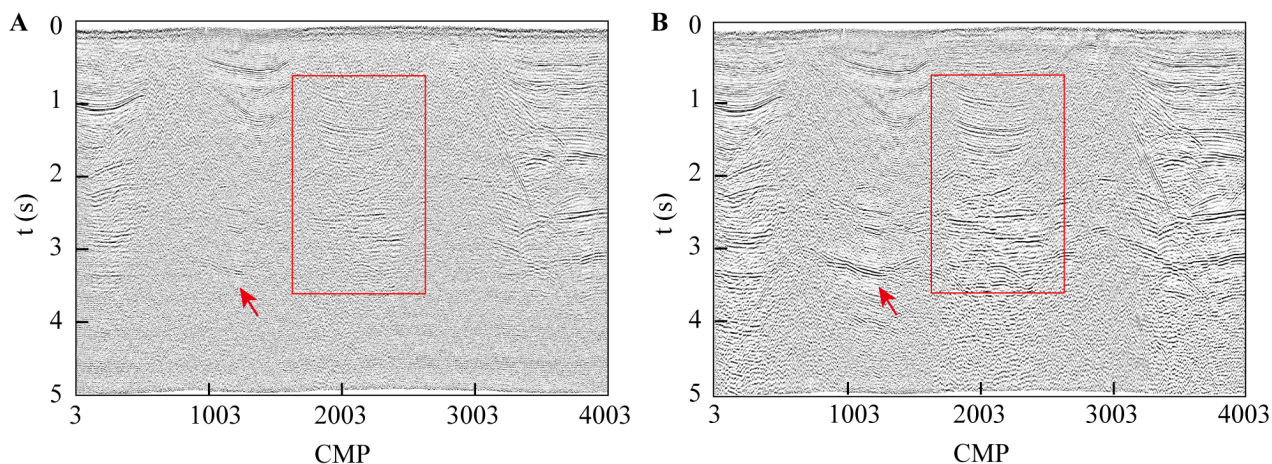


Figure 6. Processed sections using (A) conventional noise suppression and (B) anti-aliasing fidelity-preserving noise suppression methods
Abbreviation: CMP: Common midpoint.

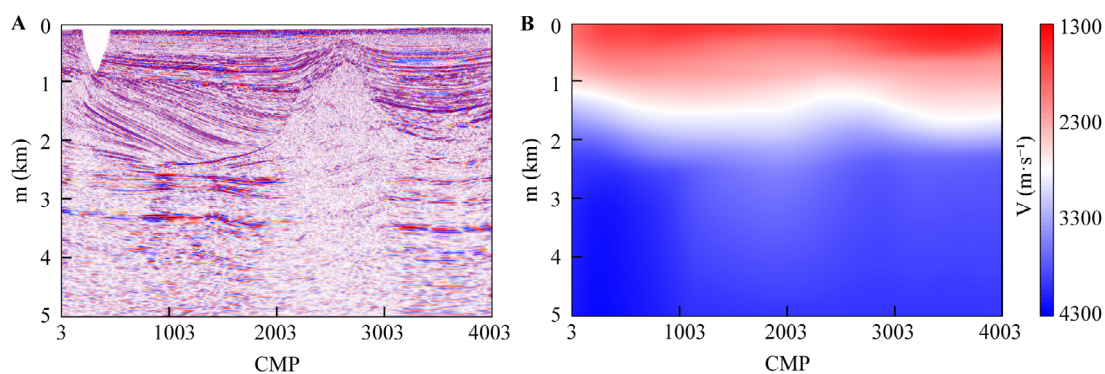


Figure 7. Processed section (A) and corresponding velocity model (B) from the application of multi-line jointly constrained tomography velocity modeling technology in an area
Abbreviation: CMP: Common midpoint.

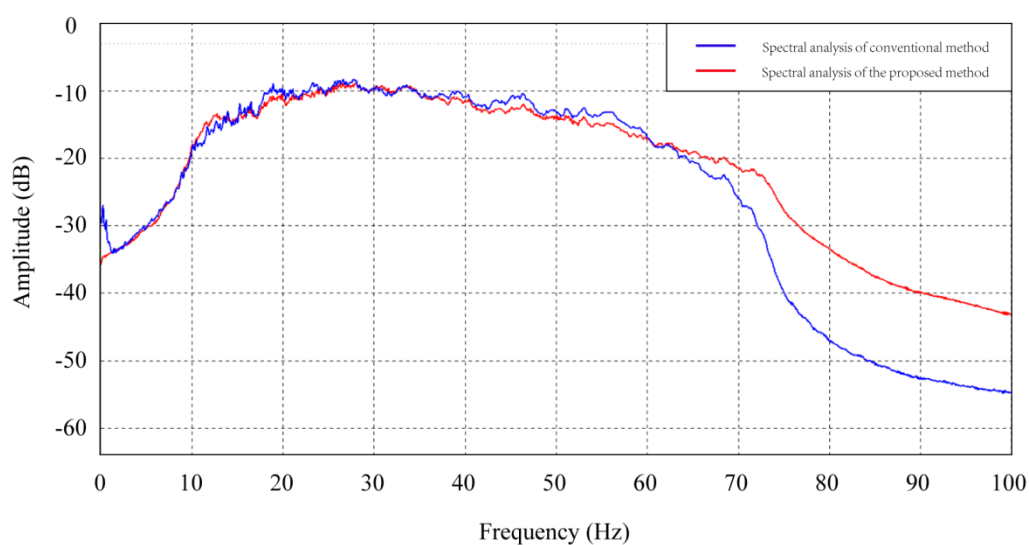


Figure 8. Amplitude spectra of the denoised data: conventional method vs. proposed method in the salt dome region of Kazakhstan

4.1. Technological synergy and systemic logic

This system adheres to a core logic of “physical reconstruction → mathematical purification → data synergy.” The static correction based on wave-equation continuation accomplishes a paradigm shift from empirical correction to physical reconstruction, establishing a high-fidelity data foundation. Denoising via the synchrosqueezed curvelet transform achieves a leap from “noise suppression” to “precision signal extraction,” ensuring the integrity of signals, particularly weak ones. The multi-line jointly constrained tomographic modeling leverages the inherent spatial relationships within the data itself, upgrading from “single-line independent inversion” to “networked collaborative constraint.” These three components are interlinked, with the output of one stage serving as high-quality input to the next. This creates a positive, closed-loop process in which errors are progressively suppressed, and information fidelity is propagated, thereby systematically overcoming the coupled challenges of “dually complex” imaging.

4.2. Advantages, limitations, and future prospects

The comprehensive advantages of this method were validated through its applications: it delivered high imaging precision, significantly improving SNR, event continuity, and structural positioning accuracy; it fundamentally resolved the spatial closure problem inherent to 2D survey network imaging; it demonstrated good generalizability and robustness across complex areas of different origins, such as compressional foothill belts and ductile salt domes; and its implementation based on existing 2D seismic lines offered notable practicality. However, this study also acknowledges certain limitations: the computational cost of wave-equation continuation is relatively high; under our current parallel implementation (using 200 CPU cores), processing a 50 km 2D line (4 GB of data) takes approximately eight hours. For large-scale 3D surveys with hundreds of lines, computation time can reach weeks, posing a challenge for industrial adoption. Constraints based on ray traveltimes have limited resolution for small-scale anomalies (e.g., small fault blocks, fractures, and cavities); and the influence of anisotropy has not been considered. Future work should focus on: developing more efficient algorithms (e.g., phase-screen methods) to reduce computational costs; transitioning towards full-waveform joint inversion to enhance resolution; and incorporating anisotropy parameters (e.g., vertical or tilted transverse isotropy medium assumptions) into the inversion framework, which would require replacing the current acoustic wave equation (Equation 1) with an appropriate anisotropic wave equation, aiming to achieve more accurate “geological transparency” modeling.

5. Conclusion

Focusing on the challenges of seismic imaging in complex foothill belts, this study, through methodological innovation and integration, drew the following key conclusions:

- (i) An effective high-precision imaging technical system was established. Integrating innovative techniques—wave-equation static correction, anti-aliasing fidelity-preserving denoising, and multi-line joint tomographic velocity modeling—constituted a systematic solution for addressing geological conditions characterized by “dual complexity.”
- (ii) The imaging quality of real seismic data was significantly improved. The application in the western Liaoning Jinyang Basin demonstrated that this technical suite fundamentally enhances data quality. The resulting imaging profiles exhibited clear structural frameworks, accurate fault positioning, and well-defined event characteristics, thereby resolving long-standing imaging blurriness in this region. Spectral analysis of this case study (Figure 3) confirmed that the proposed method preserved low-frequency signals, which were essential for accurate velocity inversion and depth imaging.
- (iii) The general applicability and robustness of the methodological principles were validated. The application in a salt dome region of Kazakhstan proved the good adaptability of this methodological system to complex exploration areas of different origins (e.g., foothill belts and salt tectonic regions), indicating broad prospects for its wider application. Spectral analysis from this region (Figure 8) further supported the consistency of low-frequency signal preservation across diverse geological settings.
- (iv) A clear technical development pathway was outlined. This integrated framework established a foundation for future technological evolution. Subsequent work can involve deeper integration with techniques such as FWI and anisotropy modeling, aiming to achieve a transition from precise structural imaging to the quantitative prediction of reservoir parameters.

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Conflict of interest

The authors declare no conflicts of interest.

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Availability of data

Data are available from the corresponding author upon reasonable request.

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