

Application of OVT-Domain Five-Dimensional Interpolation to Improve Shallow Imaging in Coalbed Methane Exploration

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Abstract

To address the problem of degraded shallow imaging quality caused by source–receiver offset variations in coalbed methane (CBM) exploration in Shanxi Province, this study applies the five-dimensional interpolation technique in the OVT (Offset Vector Tile) domain. By regularizing seismic data, this method effectively mitigates the uneven distribution of offsets induced by large source–receiver deviations due to surface obstacles. Shanxi Province is characterized by well-developed coal-bearing strata and abundant CBM resources. In recent years, as seismic exploration has penetrated deeper, the subsurface structures have become increasingly complex, leading to greater challenges for exploitation and more stringent requirements for shallow imaging quality. However, source–receiver deviations reduce the fold coverage of shallow target layers, severely compromising imaging results. By employing the OVT-domain five-dimensional interpolation technique to improve the uniformity of source–receiver distribution and enhance fold coverage, the quality of shallow imaging can be significantly improved.

Keywords

OVT domain; five-dimensional interpolation; coalbed methane exploration; data regularization.

1. Introduction

Against the backdrop of increasing difficulties in conventional oil and gas extraction and the tightening requirements for ecological and environmental protection, coalbed methane (CBM), as a low-carbon and clean unconventional hydrocarbon resource, has become a strategically important energy source for ensuring the transition of the energy structure and achieving the “dual-carbon” goal^[1,2]. The Qinshui Basin is the core area for high-rank CBM exploration and development in China, and its northeastern Shanxi block, characterized by stable and minable high-quality coal seams, possesses considerable exploration value and significant development potential^[3,4].

Exploration in this block primarily targets two key coal-bearing formations. The first is the No. 15 coal seam of the Carboniferous Taiyuan Formation, which exhibits stable thickness (4.35–7.08m) and high gas content (14–32m³/t based on measurements), making it the principal CBM-bearing seam in the area. The second is the No. 3 coal seam of the Permian Shanxi Formation, which is relatively thin (0–1.37m, averaging 0.90m) but widely distributed, thus constituting another important exploration target.

However, the block is characterized by complex surface conditions. Situated on the western flank of the central Taihang Mountains, it exhibits typical eroded mid-mountain landforms with pronounced topographic relief (maximum elevation difference of 279 m). Bedrock is extensively exposed, with loess deposits restricted to valley bottoms. Poor transportation infrastructure further hampers field operations, making it difficult for large seismic acquisition equipment to reach some areas. As a result, source and receiver stations often need to be

relocated to avoid villages, gullies, and steep slopes, ultimately leading to a highly irregular acquisition geometry.

This irregular geometry introduces three critical problems: (1) OVT-domain gathers are severely undersampled, particularly in near-offset data essential for shallow imaging, which account for less than 20% of the total; (2) fold coverage is extremely uneven, with the designed 64-fold coverage achieved in only 45% of the central block where villages are densely distributed, and with the No. 3 seam covered by as few as 20 folds—far below the requirement for reservoir characterization; and (3) the distribution of offsets and azimuths is highly irregular, with azimuthal variations within individual OVT tiles reaching up to 40°, resulting in "arc-like" noise during prestack migration that disrupts reflection signal recognition.

To resolve these issues, the OVT-domain five-dimensional interpolation technique provides an effective solution. By jointly utilizing five dimensions—InLine, CrossLine, Offset, Azimuth, and Time—and employing advanced algorithms, this method reconstructs missing seismic data and enforces regularization. Consequently, it enhances data continuity and uniformity, thereby providing a robust foundation for subsequent processing steps such as prestack time migration, structural interpretation, and reservoir inversion. Based on a 3D seismic dataset from a block in Shanxi Province, this paper systematically demonstrates the workflow and parameter optimization of the five-dimensional interpolation technique and evaluates its effectiveness in improving shallow imaging quality and reservoir interpretation accuracy. The study aims to offer a practical reference for CBM seismic exploration in similarly complex terrains

2. Methodology and Technical Workflow

2.1. Fundamental Principle of Five-Dimensional Interpolation

The five-dimensional interpolation technique in the OVT (Offset Vector Tile) domain is founded on the principle of data sparsity, assuming that seismic data are sparsely distributed in the five-dimensional frequency–wavenumber domain^[5]. Missing data can therefore be reconstructed through an irregular Fourier transform. The core of this method is the Orthogonal Matching Pursuit (OMP) algorithm, which iteratively selects the Fourier coefficients with the largest contribution in the frequency domain, progressively approximating the characteristics of the original data^[6].

Let the irregular time-domain seismic data be defined as $f(x_j)$ ($j = 0, 1, \dots, N_x - 1, N_x$), where N_x is the number of seismic traces. Its irregular Fourier transform can be expressed as^[7]:

$$f(x_j) \approx \sum_i \bar{f}(I) e^{\frac{2\pi i I x_j}{x_{max}}} \quad (1)$$

where $\bar{f}(I)$ denotes the Fourier coefficient, I is the wavenumber index, and x_{max} is set to four times the maximum offset to ensure full coverage of the wavenumber spectrum. The iterative process proceeds as follows:

1. Initialization: Set the initial residual as $R^0(x_j) = f(x_j)$;
2. Compute the Fourier transform of the residual $\tilde{R}^m(I)$, and select the wavenumber index P_m corresponding to the maximum coefficient P_m ;
3. Coefficient update: Update the Fourier coefficients based on the least-squares criterion, minimizing the objective function:

$$\emptyset(m+1) = \sum_j \left[f \left(x_j - \sum_{i=0}^m \bar{f}(P_i) e^{\frac{2\pi i P_i x_j}{x_{max}}} \right) \right]^2. \quad (2)$$

4. residual update: Compute the new residual $R^{m+1}(x_j)$ and iterate until the residual error falls below a predefined threshold.

2.2. Technical Workflow

Considering the irregular acquisition geometry of the study area and the demand for high-resolution coal seam imaging, the five-dimensional interpolation workflow comprises four major steps:

1. Data preprocessing: Apply 3D refraction static corrections to eliminate near-surface topographic effects; attenuate surface waves using adaptive filtering with a reference velocity of 800 m/s; and suppress abnormal amplitudes with the STA/LTA threshold method, thereby ensuring data reliability.

2. OVT gather sorting: Based on the acquisition system with 200 m line spacing and 40 m receiver spacing, partition the dataset into 144 OVTs using a sorting criterion of twice the source–receiver spacing, while controlling intra-tile offset deviations within 10%.

3. Parameter optimization: Define offset binning at 20 m intervals, azimuth binning at 10° intervals, and apply 50 Fourier iterations. The wavenumber range is set to $k_x \in [-\frac{k_N}{2}, \frac{k_N}{2}]$, $k_y \in [-\frac{k_N}{2}, \frac{k_N}{2}]$, ensuring high precision in data reconstruction.

4. Quality control: Enforce strict evaluation standards, including a root-mean-square amplitude deviation < 0.1 , fold-coverage coefficient of variation < 0.15 , and absence of arc-like noise in migrated sections, to guarantee data quality for subsequent processing and interpretation.

3. Study Area and Practical Application

3.1. General Geological and Acquisition Setting

The study area is located in the northeastern Qinshui Basin and is characterized by eroded mid-mountain geomorphology, with strong topographic relief and poor accessibility. Consequently, an irregular acquisition geometry was adopted for seismic data collection. The No. 15 coal seam of the Carboniferous Taiyuan Formation, with stable thickness and favorable gas content, and the No. 3 coal seam of the Permian Shanxi Formation, with broad areal distribution, constitute the principal targets for CBM exploration in this block. However, the irregular acquisition has resulted in missing OVT-domain data, uneven fold coverage, and disordered offset and azimuth distributions, all of which restrict the quality of migration imaging. To address these issues, a 3.9 km² 3D seismic dataset from the southern part of the block was selected for regularization testing to verify the effectiveness of five-dimensional interpolation in improving OVT-domain migration imaging.

3.2. Analysis of OVT Gathers

Due to obstacles such as villages and rivers, acquisition geometry was frequently adjusted, leading to locally missing offsets and uneven coverage. After five-dimensional interpolation, the offset distribution was significantly improved. In individual OVT tiles, near-, mid-, and far-offset data became more complementary, and the coverage rate of offset information in previously missing regions exceeded 92%. This provided a more complete dataset for azimuthal anisotropy analysis (Figure 1).

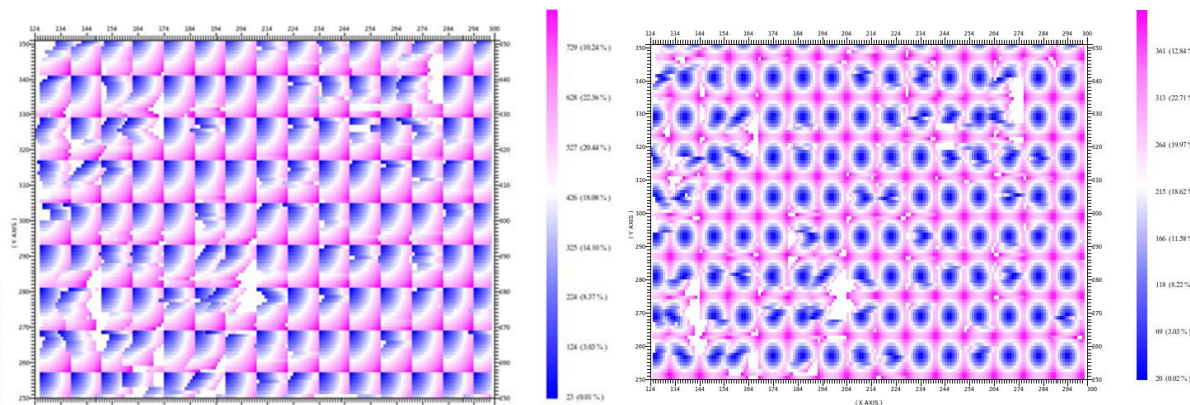
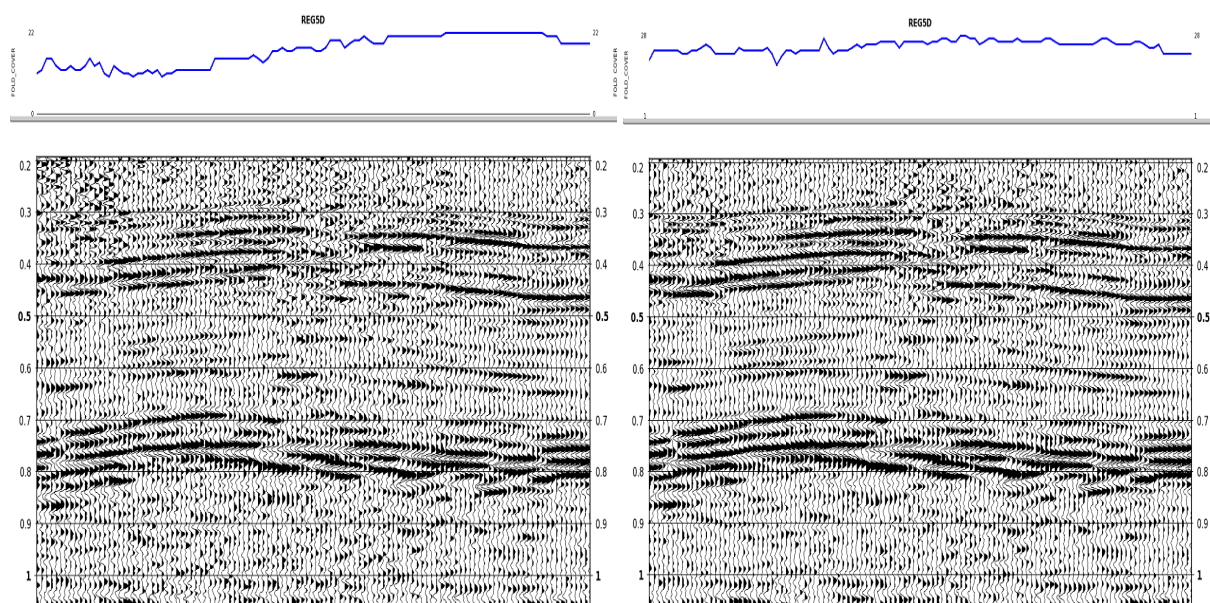


Figure 1. Comparison of offset distribution before and after interpolation.

As shown in Figure 1, the offset distribution within individual OVT tiles became more uniform, with the standard deviation of offsets reduced from 85 m to 32 m, while the azimuth range contracted to within $\pm 15^\circ$. This enhancement in data consistency reduced the incidence of arc-like noise during subsequent prestack time migration by more than 60%.

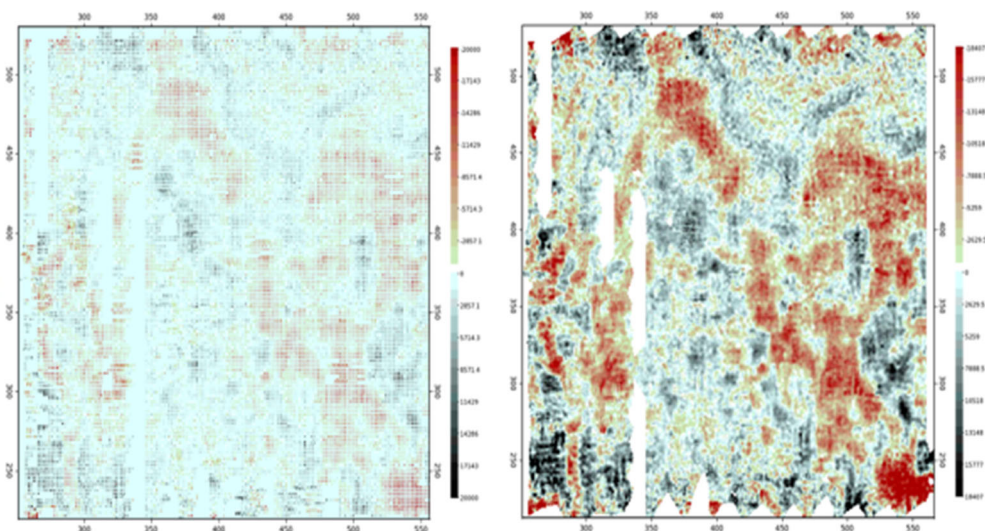
3.3. Stacked Section Analysis

For the main producible seams—the No. 15 seam of the Taiyuan Formation and the No. 3 seam of the Shanxi Formation—the stacked sections (Figure 2) exhibit markedly improved lateral continuity of coal seam reflection events after interpolation. The traceable length of the No. 15 seam reflection axis increased from 1.2 km to 2.8 km, and the signal-to-noise ratio of the thin No. 3 seam (0.5–1.0 m) improved by 35%, effectively resolving the indistinct reflections present in the raw data. Well tie calibration indicates that the depth error of coal seams relative to key wells (e.g., HL-U-18-V and HL-U-25-V) was reduced to within 3%, meeting the precision requirements of CBM exploration. At the same time, OVT-domain interpolation effectively filled missing offsets caused by surface obstacles, thereby improving data integrity.



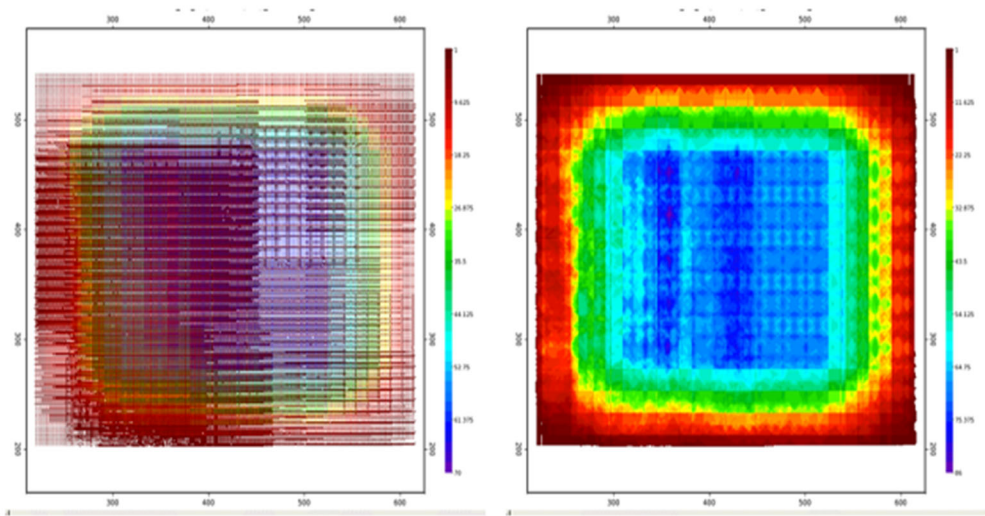
(a) OVT-domain migration before interpolation; (b) OVT-domain migration after interpolation
Figure 2. Comparison of OVT-domain seismic data before and after interpolation.

The application of this technique effectively mitigated deficiencies in the raw data. Before interpolation, time sections exhibited conspicuous data gaps and pronounced acquisition footprints due to irregular geometry. After interpolation, missing traces were accurately reconstructed, the degree of regularization was greatly improved, acquisition footprints were significantly reduced, and data continuity as well as signal-to-noise ratio were markedly enhanced. As shown in Figure 3, numerous gaps in offset coverage prior to interpolation could induce arc-like artifacts during prestack migration. After interpolation, these gaps were largely eliminated, data distribution became more uniform, and migration noise was substantially reduced.



(a) Before interpolation in the OVT domain (b)After interpolation in the OVT domain
Figure 3. Comparison of seismic slices before and after interpolation.

Regarding fold coverage optimization, prior to interpolation some local areas exhibited inadequate fold coverage due to obstacles, with strong spatial variability that hindered effective stacking of target reflections. After interpolation, fold coverage across the entire block became more uniform (Figure 4).



(a) The number of overlays before interpolation in the OVT domain (b)The number of overlays after interpolation in the OVT domain
Figure 4. Comparison of fold coverage before and after interpolation.

In this study area, the five-dimensional interpolation technique successfully compensated for regions of low fold coverage. Validation through control-line stacking confirmed that the processed dataset exhibited no fold irregularities or trace gaps. The signal-to-noise ratio of seismic data was further enhanced, ensuring effective stacking of target reflections.

The improved uniformity and consistency of OVT-domain gathers after interpolation made them more suitable for subsequent prestack time migration. The migration results demonstrate clearer coal seam reflections and stronger lateral continuity of reflection events. The No. 15 and No. 3 seams were delineated with higher precision, providing a reliable basis for seam depth estimation and CBM reservoir distribution prediction. Furthermore, the regularized OVT gathers preserved complete offset and azimuth information, creating favorable conditions for subsequent studies of azimuthal anisotropy, fracture prediction, and prestack inversion, thereby facilitating more accurate identification of CBM-rich zones.

4. Conclusions

Based on the actual exploration data from a coalbed methane block in Shanxi Province, source-receiver offset information with superior quality was preferentially selected, and the OVT-domain five-dimensional interpolation technique was applied for data processing. The stacked sections obtained after interpolation were subsequently analyzed. The results demonstrate that five-dimensional interpolation significantly increased the amount of offset data within OVT tiles, greatly improving the completeness of offset information. Moreover, coal seam reflection characteristics in the stacked sections became more prominent, and the imaging quality of shallow target layers was substantially enhanced.

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