

Article

Accurate Delimitation of Mine Goaves Using Multi-Attribute Comprehensive Identification and Data Fusion Technologies in 3D Seismic Exploration

Junjie Zhou ¹, Yanhui Wu ^{2,*}, Qingchao Zhang ¹, Zhen Nie ³, Tao Ding ^{3,*}  and Guowei Zhu ⁴

¹ School of Earth Science and Engineering, Hebei University of Engineering, Handan 056038, China; ansanzhou7684@163.com (J.Z.); yinyinsiu@gmail.com (Q.Z.)

² School of Mining and Geomatics Engineering, Hebei University of Engineering, Handan 056038, China

³ MNR Key Laboratory of Saline Lake Resources and Environments, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China; nieezhen518@163.com

⁴ College of Geoscience and Surveying Engineering, China University of Mining and Technology, Beijing 100083, China; zgw@cumt.edu.cn

* Correspondence: wuyh_198210@163.com (Y.W.); dtcumt@163.com (T.D.); Tel.: +86-10-6899-2231 (T.D.)

Abstract: Existing goaves (e.g., shafts and roadways) in mines represent important hidden dangers during the production of underlying coal seams. In this view, the accurate identification, analysis, and delimitation of the scope of goaves have become important in the 3D seismic exploration of mines. In particular, an accurate identification of the boundary swing position of goaves for 3D seismic data volumes within a certain depth interval is key and difficult at the same time. Here, a wide-band and wide-azimuth observation system was used to obtain high-resolution 3D seismic data. The complex structure of a mine was analyzed, and a seismic double processing system was applied to verify the fine processing effect of a goaf and improve the resolution of the 3D seismic data. Based on the seismic attribute identification characteristics of the goaf structure, we decided to adopt multi-attribute comprehensive identification and data fusion technologies to accurately determine the position of the goaf and of its boundary. Combining this information with the mine roadway engineering layout, we verified the accurateness and correctness of the goaf boundary location. Our study provides a good example of the accurate identification of the 3D seismic data of a roadway goaf.

Keywords: goaf; 3D seismic exploration; recognition; dual processing system



Citation: Zhou, J.; Wu, Y.; Zhang, Q.; Nie, Z.; Ding, T.; Zhu, G. Accurate Delimitation of Mine Goaves Using Multi-Attribute Comprehensive Identification and Data Fusion Technologies in 3D Seismic Exploration. *Appl. Sci.* **2024**, *14*, 5012. <https://doi.org/10.3390/app14125012>

Academic Editor: Nicholas Vassiliou Sarlis

Received: 10 May 2024

Revised: 30 May 2024

Accepted: 1 June 2024

Published: 8 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Goaf structures represent hidden geological factors in mining. The fine detection and identification of goaf boundaries, locations, and water-richness is key to ensure safe, efficient, and intelligent mining activities [1,2], as well as a comprehensive management of goaves [3,4]. 3D seismic exploration can be applied to coal mines as a fine exploration technology [5–7]. In the presence of goaves, however, the accuracy with which any underlying coal strata are recognized diminishes [8]. Especially in the case of coal seam goafs located at a relatively high depth and relatively thin coal seams, coal mining has been carried out by roadway mining. After a goaf is formed, water and gas accumulate inside it and a fracture zone develops around it. This setting hinders the fine identification of structures through 3D seismic exploration. Improving the vertical and horizontal resolution of 3D seismic exploration techniques is therefore key to identify any goaf structures and their boundaries at large mining depths [9]. For field data acquisition, an advanced acquisition system and high-resolution excitation and receiving equipment need to be adopted, so to ensure high-quality and high-resolution field seismic data. Data processing is always based on high-resolution and high-fidelity processing technologies. The combination of all-round

and multi-means processing technologies is the key to accurately determine the position of goaf boundaries [10,11].

The scale of the goaves in a coal mine will influence the stress and strain on the roof and on the floor of the coal seam and, consequently, the characteristics of the failure, collapse, and deformation zones. Physical parameters tend to vary in different sections of the mine, following a certain gradient [12–15], hindering the identification of goaf structures through 3D seismic exploration techniques. Although many scholars have carried out laboratory and simulation studies on the physical parameters of goaves, there are still deficiencies in the detection and identification of goaves in coal roadways within a certain depth interval, especially concerning the vertical and lateral resolutions and the detection of their boundaries. Notably, the disturbances caused by mining activities create a collapse zone around each goaf, leading to a variety of fracture distributions. These fracture zones have an impact on the propagation of seismic waves [16]. High-resolution 3D seismic exploration techniques are required in such settings, especially to avoid or reduce the blind-area problem: a special observation system needs to be used for field data acquisition [17,18].

In this study, we focused on the roadway formed during mining activities in the Xinyuan Mine (Yangquan, China) and adopted a high-resolution 3D seismic fine exploration technology involving multiple dimensions and components. In the data acquisition stage, we aimed at obtaining high-resolution and high-quality data by selecting the right engineering layout, acquisition equipment, and acquisition parameters. In particular, a high-quality seismic data volume was obtained by using a dual seismic data processing system software and applying multi-method comprehensive static correction, multi-domain multi-method combination denoising, pre-stack time migration, 5D interpolation, OVT (Offset Vector Tile) domain regularization, and other targeted data processing. To accurately identify the boundary position of a small goaf, a seismic spectrum decomposition technology was used and the seismic signal response characteristics of a certain time window for different frequencies (in relation to different main frequencies) were obtained. When considering the same layers, the spectral decomposition slices of different frequencies maintained a high overall consistency but showed quite different energy intensities. From low to high frequencies, the energy ranges became more concentrated, and anomalies became more obvious. In the tectonically complex parts, high-frequency seismic signals were rapidly attenuated: strong low-frequency and weak high-frequency energies were observed. Based on the spectral decomposition characteristics, the boundary position of the goaf was finely identified. By combining these results with those of a slice analysis of the seismic attributes (performed through the variance body technique), the location of the goaf was determined. The accuracy of the goaf boundary position was high, demonstrating the accuracy of our approach.

2. Geological Setting

The sixth area of the Xinyuan Mine in Shanxi Province (China) will soon be mined. Over most of the surface of this mining area, Quaternary loose loess occurs. According to previous drilling data and field surveys, the thickness of the loess is 0–30 m and the loess beam is relatively thick (Figure 1). Notably, the loess valley is relatively thin, and the seismic reflection wave has a small propagation velocity in the loose loess layer. Moreover, this layer is characterized by a very strong energy absorption and the attenuation of the seismic reflection wave: this results in a fast attenuation of the target layer's reflected wave energy and in a serious loss of high-frequency components [19,20], which is unfavorable for high-resolution seismic exploration. Under the loess layer there is a red paleosol layer: according to previous studies, high-quality single-shot records can be obtained by exciting it.

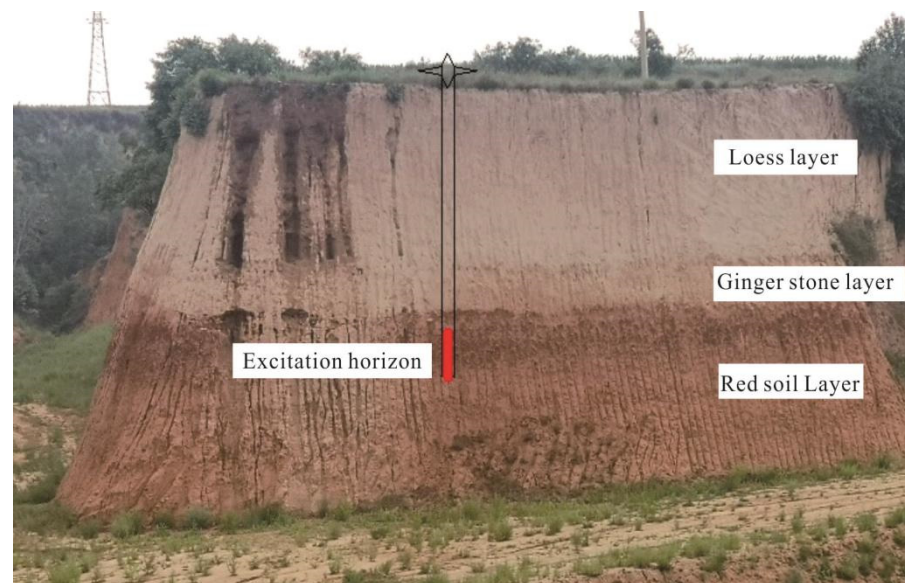


Figure 1. Photo showing the artificial seismic excitation horizon (highlighted in red).

Overall, the lateral lithology of the shallow layer in the study area changes greatly (Figure 2) and, therefore, the excitation horizon is not easy to identify. At the same time, the terrain undulates greatly, making any static correction difficult to achieve during data processing; the shallow seismic geological conditions in the study area are complex.

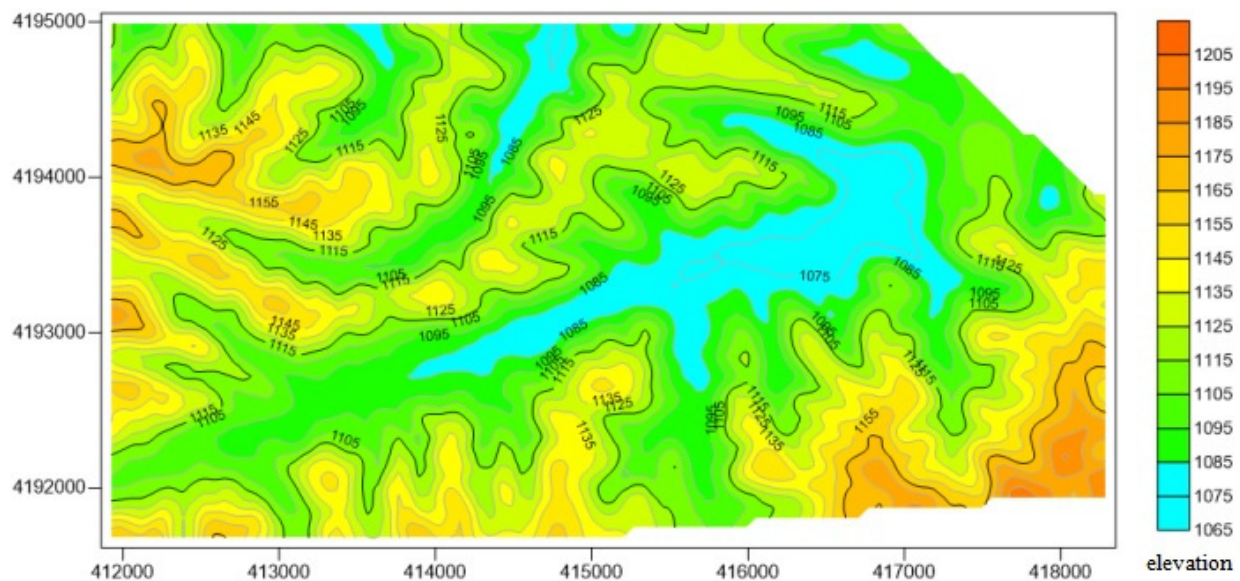


Figure 2. The value of the land surface elevation in Xinyuan mining exploration area.

3. The 3D Seismic Fine Identification Technology

3.1. Design Observation System

A variety of excitation and reception combination techniques were used to define the complex structure of the loess plateau, characterized by dramatic surface undulations, gullies, and large lateral variations in surface structure [21–23]. For the shallow loess coverage area, we adopted the excitation mode for the interval between the shallow hole and the bedrock surface, and the excitation mode for the interval between the single well and the red clay layer in the thick loess area. A high-sensitivity digital geophone was used, applying a wide azimuth angle, a high number of superposition times (>30), and a small-bin observation system (Figure 3). The color legend in Figure 3 represents the fold

(the number of times the data is stacked) in the 10-line 5-shot seismic observation system. The maximum fold is 30 times, shown as the central area of the square.

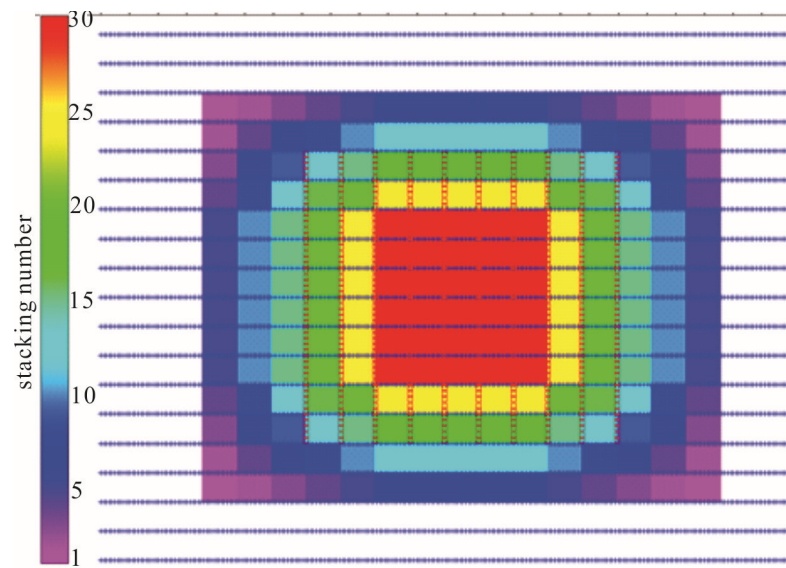


Figure 3. Distribution diagram showing the stacking times of a 10-line and 5-shot observation system.

Design parameters: a beam-shaped observation system with 10 lines and 5 shots at midpoint. Each receiving line consists of 144 receivers. The distance between the receiving lines is 100 m, and the spacing between the receiving channels is 10 m. The lateral spacing between the shots is 20 m, and the longitudinal spacing is 120 m. The CDP grid is 5×10 m. There are 30 coverage cycles in total, with 5 lateral cycles and 6 longitudinal cycles. The aspect ratio is 0.78. Overall, it belongs to a dataset with comprehensive coverage and high coverage frequency, suitable for detailed analysis in mining areas.

Within the study area, there are a total of 26 seismic lines constructed, covering an exploration area of 6.00 km^2 . The area covered by a complete 30-fold coverage is 6.03 km^2 . In total, there are 4235 physical points, with 4150 physical points covered by the construction of seismic lines. Additionally, there are three experimental sites, totaling 15 physical points.

3.2. Fine Static Correction Processing Technology

3.2.1. Static Correction

In order to improve the quality and resolution of the seismic records collected through field analysis, we applied a double processing system. Considering the complex structure of the loess plateau, including dramatic surface undulation, gullies, ravines, and large lateral changes in the surface structure, we decided to perform a laminar static correction of the CGG processing system (Figure 4). A short-wavelength static correction was achieved through a fine stacked acceleration analysis, the iteration of the surface consistency residual static correction, and a global search for the optimal residual static correction.

The remaining static correction components were mainly obtained by applying a residual static correction of the surface consistent reflection wave and a comprehensive global optimization residual static correction (Figure 5). The global optimization residual static correction was based on three methods: the maximum energy method, simulated annealing, and the genetic algorithm [24–26]. The basic idea is to enhance the genetic algorithm with simulated annealing and the maximum energy method for static correction calculations. Simulated annealing generates new solutions by creating several candidate values for each parameter using probability distribution functions. These candidate values form the initial state of each individual in the genetic algorithm population. The maximum energy method iteratively improves optimization, using local solutions from the final

iterations as initial candidates for the genetic algorithm. By combining the maximum energy method and simulated annealing, the initial population for the genetic algorithm is optimized based on the objective function. This approach ensures a smaller, more targeted population while maintaining diversity, enhancing search efficiency [27]. The genetic algorithm evolves solutions through selection, crossover, and mutation, ensuring diversity and broad search capability. To address the lack of a focused search, the evolutionary solutions are further refined using the local and random search capabilities of the maximum energy method and simulated annealing. This combined approach improves convergence ability and velocity, outperforming individual methods.

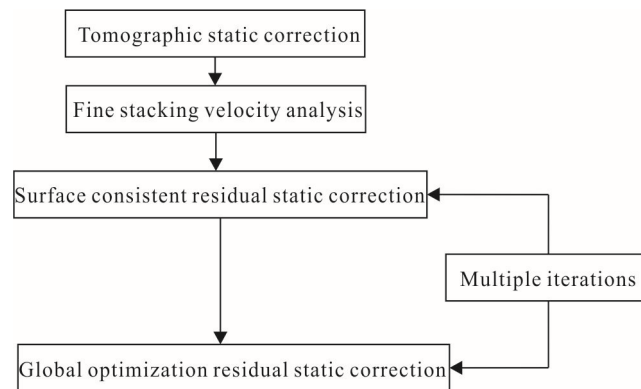


Figure 4. Main phases of the static correction processing.

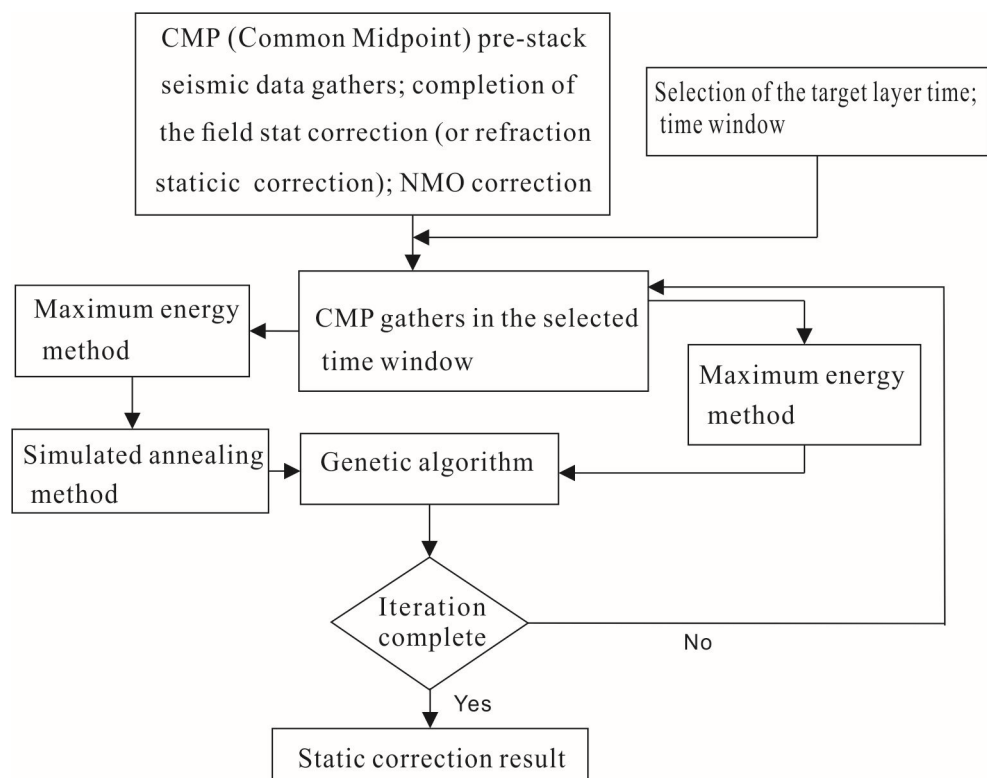


Figure 5. Global optimization residual static correction process.

In order to accurately determine the velocity of extraction and improve the accuracy of velocity interpretation, the stacking velocity gathers, and the stacking profiles were used for quality control. Moreover, we made sure that the velocity field would conform to the geological law by using the geological law itself to guide the velocity analysis. After several iterations, the best velocity model was obtained (Figure 6).

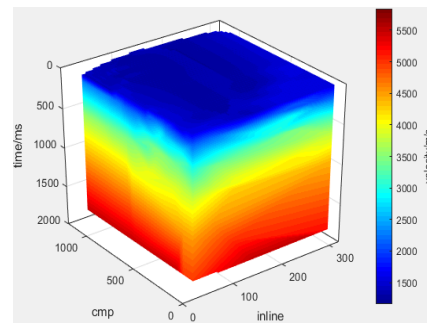


Figure 6. The selected 3D p -wave velocity model.

3.2.2. OVT Domain Interpolation Processing

In the presence of complex terrains and buildings, variable observation systems lead to irregular seismic data acquisition: the distribution of offset and azimuth data, as well as the overall data coverage, tend to be uneven, affecting the quality of seismic imaging and resulting in false anomalies when thick seismic data are conventionally processed. In order to eliminate the difference between actual and ideal spatial sampling attributes, the seismic data were regularized in the OVT domain, ensuring that the seismic migration would not be affected by irregular spatial sampling [28,29]. After processing a Kirchhoff migration in the OVT domain, the COV (Common Offset Vector) gathers in the OVT domain were transformed back to the time–space domain by inverse transformation, obtaining the CRP (Common Reflection Point) gathers after anisotropic processing.

The Fourier interpolation algorithm based on orthogonal matching pursuit (OMP) is a relatively effective interpolation method developed in recent years. This method primarily employs Fourier transform as its basis functions. It iteratively selects the largest coefficients from the Fourier transform coefficients and places them into a sparse spectrum. Then, it subtracts these selected coefficients from the input data iteratively until the residual becomes negligible. Finally, it performs an inverse Fourier transform on the resulting sparse spectrum to obtain the interpolated results at the desired locations.

The implementation steps are as follows: conduct a discrete Fourier transform (DFT) along the time axis of the input seismic data to acquire the Fourier spectrum in the frequency domain. Compute the energy curves at various angles for the Fourier spectrum and utilize these energy curves as weighting factors applied to the entire Fourier spectrum [30–32]. Identify the Fourier spectrum component with the highest energy after weighting (effective signal) and integrate this component into the original Fourier spectrum without weighting. Perform an inverse Fourier transform on the Fourier spectrum component obtained in the preceding step and output the result to the corresponding original input positions. Subtract the iterative result from the previous step from the original input data to proceed with the next iteration. These steps delineate the procedure for the Fourier interpolation algorithm employing orthogonal matching pursuit (OMP) for seismic data [33,34].

Given the seismic data input represented by $f(x_j)$, where $j = 0, \dots, N_x - 1$, and N_x denotes the total number of seismic traces, with $0 \leq x_j \leq x_{\max}$ representing the spatial coordinate corresponding to the j th trace. The Fourier expansion of the input data $f(x_j)$ is expressed as:

$$f(x_j) \approx \sum_l \tilde{f}(l) \exp\left(\frac{i2\pi l x_j}{x_{\max}}\right) \quad (1)$$

The inverse Fourier transform is:

$$\tilde{f}(l) \approx \sum_{j=0}^{N_x-1} f(x_j) \exp\left(\frac{-i2\pi l x_j}{x_{\max}}\right) \quad (2)$$

where k_l represents the spatial wavenumber, and $k_l = 2 \times \pi \times l / x_{\max}$, for $l = -N_k/2, \dots, N_k/2$, where N_k is the total number of frequencies. Increasing $x_{\max}$ not only increases

the number of traces involved in the calculation but also enhances the sampling in the wavenumber domain, thereby improving interpolation accuracy. Building upon Equation (1), with each addition of a frequency component in the frequency-wavenumber domain, after m steps, the residual quantity can be expressed as:

$$R^m(x_j) = f(x_j) - \sum_{l=0}^{m-1} \tilde{f}(P_l) \exp\left(\frac{i2\pi P_l x_j}{x_{\max}}\right) \quad (3)$$

P_l is the index corresponding to the coefficients selected in the l -th step. Setting $m = 0$, $R_0(x_j) = f(x_j)$; iteration is carried out via Equation (4):

$$\tilde{R}^m(l) = \sum_{j=0}^{N_x-1} R^m(x_j) \exp\left(\frac{i2\pi l x_j}{x_{\max}}\right) \quad (4)$$

By computing Equation (4), find the index P_m corresponding to the maximum coefficient. Construct the least squares function Equation (5) to calculate the residual $R_{m+1}(x_j)$. Iteration ceases when R_{m+1} becomes sufficiently small. Equation (5) is given by:

$$\varphi(m+1) = \sum_j \left[f(x_j) - \sum_{l=0}^{m-1} \tilde{f}(P_l) \exp\left(\frac{i2\pi P_l x_j}{x_{\max}}\right) \right]^2 \quad (5)$$

3.3. Spectrum Decomposition

Spectral decomposition consists in the continuous time–frequency analysis of a single seismic trace, with the objective of obtaining the corresponding time–frequency spectrum. In this way, a 1D seismic signal can be decomposed in a time–frequency plane, on which part of the seismic signal can be continuously analyzed and compared.

For the spectral decomposition of a specific signal, the noise introduced for different time window types will vary.

We opt for the S-transform (ST) to conduct spectral decomposition due to its capability to produce high-resolution spectral decomposition images, as demonstrated in previous studies [35]. This method proves advantageous in noise removal and analysis of thin interbeds. The S-transform of a function $h(t)$ can be expressed as:

$$S_f(\tau, f) = \int_{-\infty}^{\infty} h(t) w(t - \tau, f) \exp(-i2\pi ft) dt \quad (6)$$

$$w(t) = \frac{|f|}{\sqrt{2\pi}} \exp\left(-\frac{f^2 t^2}{2}\right) \quad (7)$$

Therefore, the following result can be obtained:

$$S_f(\tau, f) = \int_{-\infty}^{\infty} h(t) \frac{|f|}{\sqrt{2\pi}} \exp\left[-\frac{f^2(\tau - t)^2}{2}\right] \exp(-i2\pi ft) dt \quad (8)$$

where f is frequency, t is time, τ is the time on control the gauss window position on the timeline.

However, even for the same time window type, the noise introduced for different time window widths will also vary quite a lot (Figure 7). Notably, a Gaussian time window will be used. Figure 7 shows that, in the case of a narrow time window, the spectrum will be lower and flatter, and the frequency range of influence will be larger than in the case of a wide time window. In the first case, not only the low frequency band will be affected, but the middle and high frequency bands will be impacted even more. Notably, in the case of a wide time window the spectrum will be steeper, and the influence frequency range will be

smaller (mainly concentrated in the low frequency band). With the enlargement of the time window, the corresponding spectrum will change its shape from straight to steep.

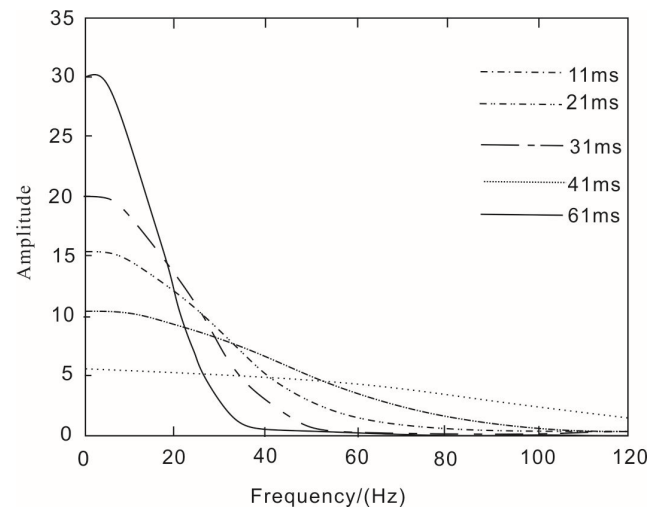


Figure 7. Spectra corresponding to time windows with different widths.

Regarding spectral decomposition, its effect does not only depend on the selected time window, but also on the characteristics of the seismic signals. The influence of a certain time window on seismic signals with different dominant frequencies will vary (Figure 8). Moreover, for a certain window width, the higher the main frequency of the seismic signal, the closer will the spectrum be to its true value. In the case of seismic signals with different dominant frequencies, the selection of a time window for the spectral decomposition processing should be adjusted accordingly.

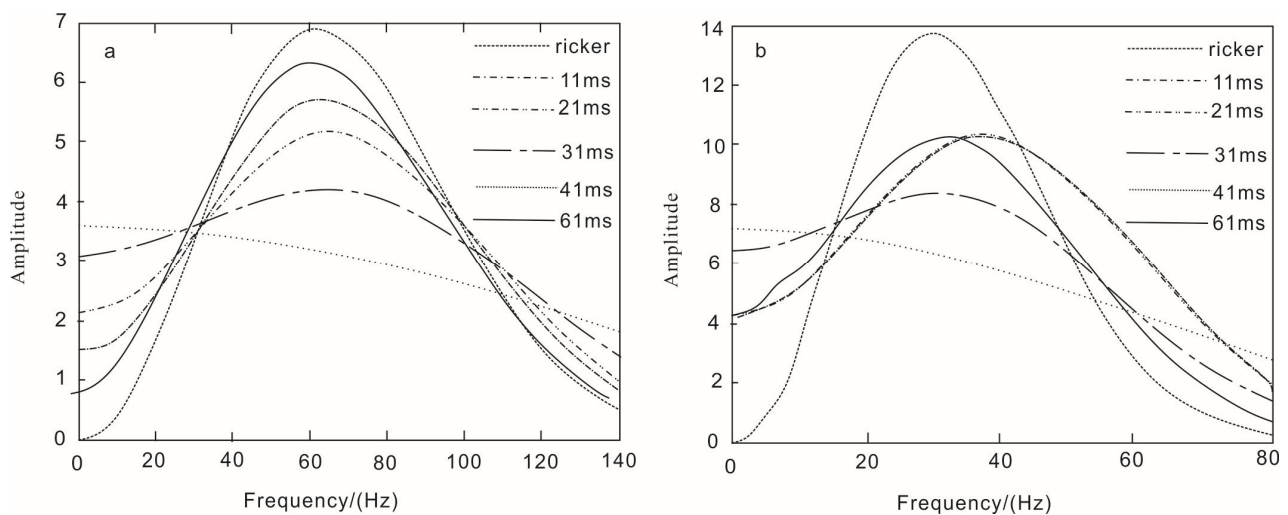


Figure 8. Spectra of seismic signals with different main frequencies (**a**—60 Hz; **b**—30 Hz) after the overtime window.

4. Results and Discussion

4.1. Sensitivity Testing

Four experimental survey lines (Figure 9) were laid out, each with the same length and identical shot and receiver point locations. Each survey line used the same type of geophones for data acquisition, with a receiver line spacing of 10 m. The solid black lines represent the receiver lines, each 1440 m long, with a geophone placed every 10 m. The red line represents the shot point alignment line, with a shot-receiver distance of 10 m. All four lines simultaneously recorded seismic signals, resulting in single-shot records and

the corresponding signal-to-noise ratios (Figure 10). The digital geophones used were SmartSolo node geophones with a frequency response range of 0 to 413 Hz. The remaining lines used dynamic coil geophones with dominant frequencies of 60 Hz, 10 Hz, and 7 Hz, respectively.

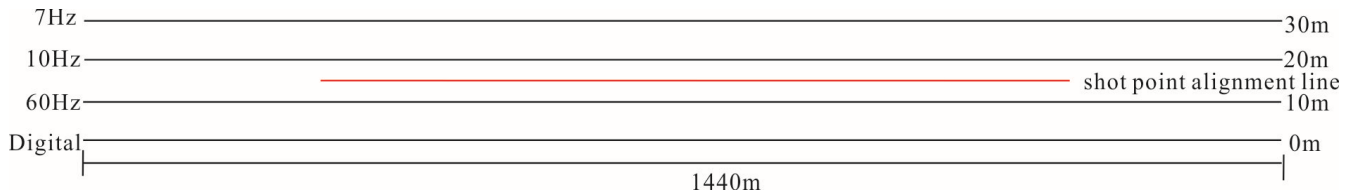


Figure 9. Experimental line layout schematic diagram of different type detector.

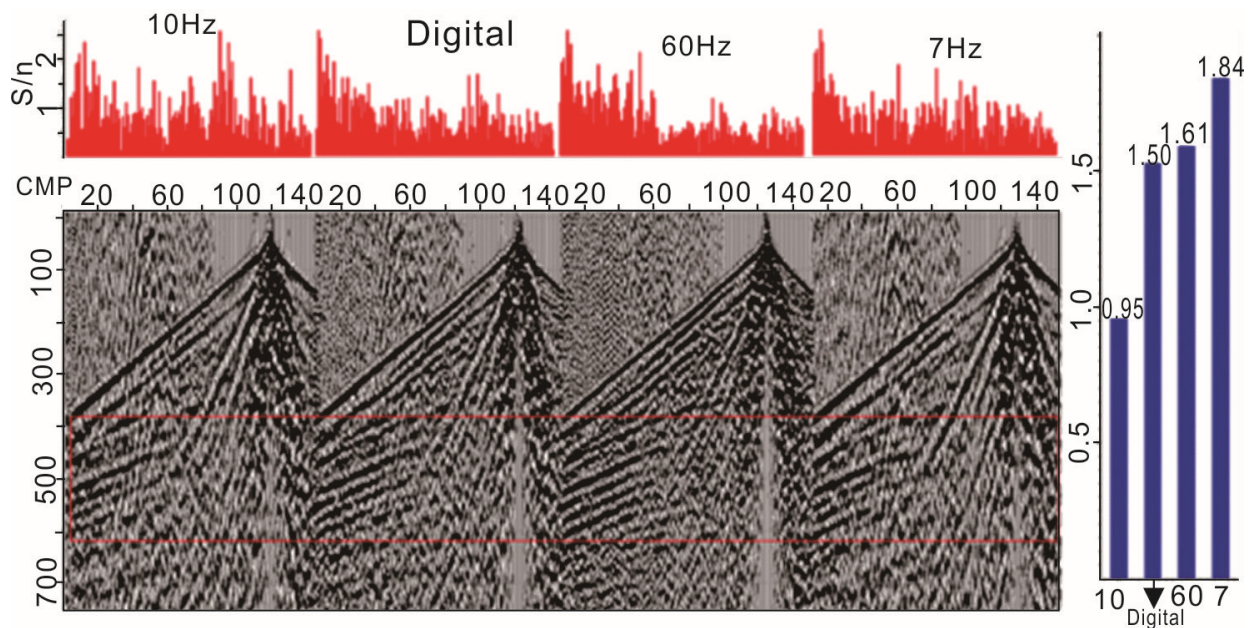


Figure 10. Comparison between the data acquired by a digital geophone and a moving coil geophone with different main frequencies.

The sensitivities of 60 Hz, 10 Hz, and 7 Hz digital geophones used in this area were analyzed (Figure 10). The data collected using the 7 Hz geophone showed a good continuity of the target layer, a strong reflected wave energy, and a high signal-to-noise ratio. In areas characterized by high signal-to-noise ratio, near-surface absorption, and the attenuation of general areas, digital detectors with high-frequency bandwidths showed obvious advantages. However, in areas characterized by high near-surface absorption, the attenuation of intense areas, and low signal-to-noise ratio, low-frequency detectors were more advantageous.

4.2. The 5D +OVT Interpolation

This, in turn, affects the accuracy with which goaves and their boundaries can be identified. Here (Figure 11), a 5D interpolation was performed on conventional seismic data to improve the spatial sampling rate, the coverage times, and the signal-to-noise ratio. The distribution of shot points in the mining area after the 5D interpolation obviously reduced the “empty window” in the seismic profile, which was caused by an uneven distribution of the ground shot points, especially for the shallower coal seams (Figure 12).

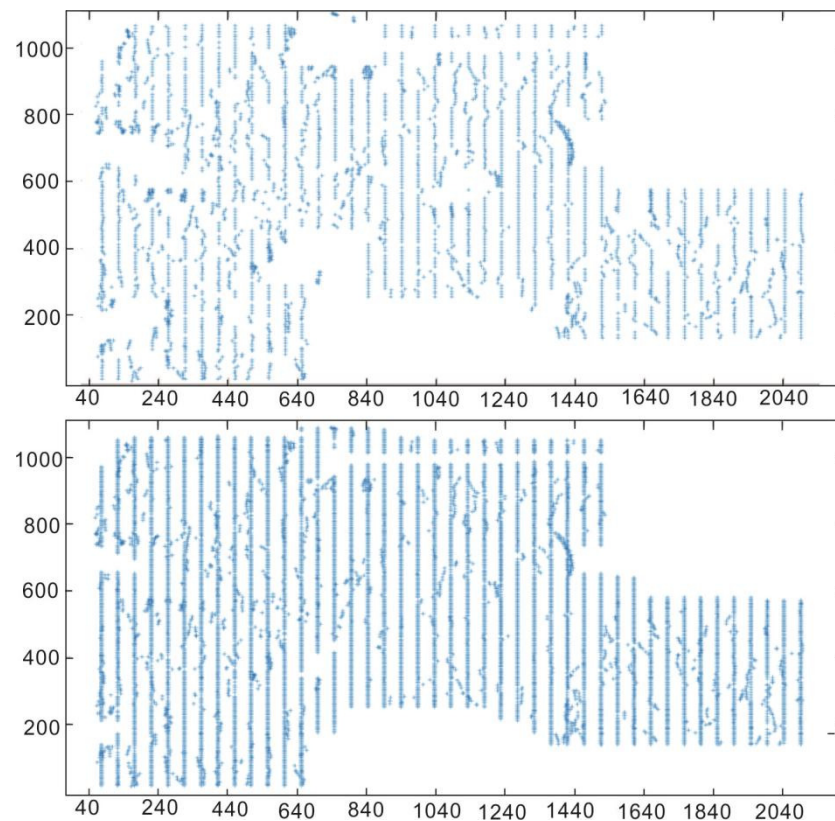


Figure 11. 5D interpolation of the front (**top**) and back (**bottom**) shot point distribution.

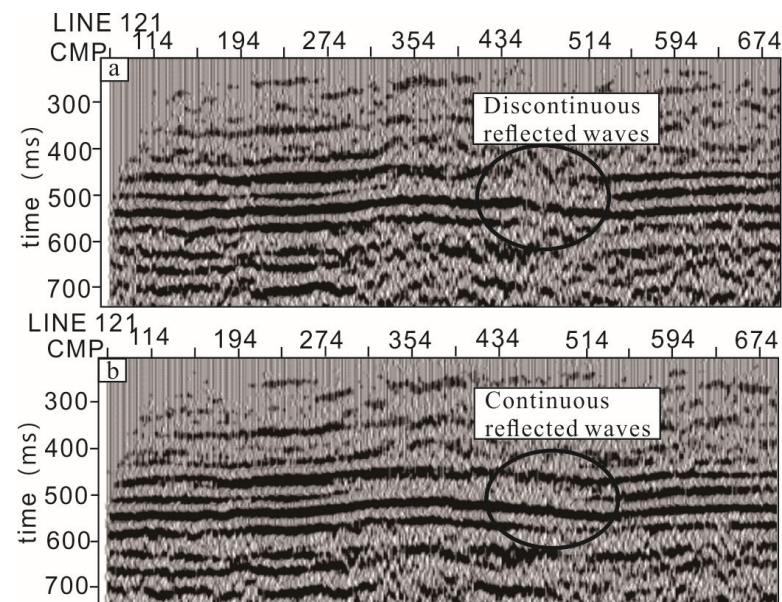


Figure 12. Comparison between the stacking time sections obtained before (a) and after (b) 5D interpolation.

The OVT technology not only enhances the illumination intensity of complex underground structures but also enables the extraction of reservoir properties related to azimuthal anisotropy. Initially, missing data within a single OVT tile are located, followed by the utilization of five-dimensional regularization techniques. Following the matching pursuit Fourier algorithm, all missing data are interpolated and reconstructed, ultimately achieving a uniform spatial distribution of data within a single OVT tile, ideal for single

coverage. The frequency resolution of the obtained seismic data was relatively low, whereas the identification of the goaf boundary required a high-frequency resolution. A section obtained through conventional processing and another obtained through 5D interpolation + OVT lifting (Figure 13) were compared, noting obvious differences. The arrow in Figure 13 indicates the known 31,009 goaf boundary. Compared with that obtained from the conventional treatment, the goaf boundary detected after the OVT treatment was clearer and its position was more easily identified; moreover, the profile resolution increased after frequency lifting.

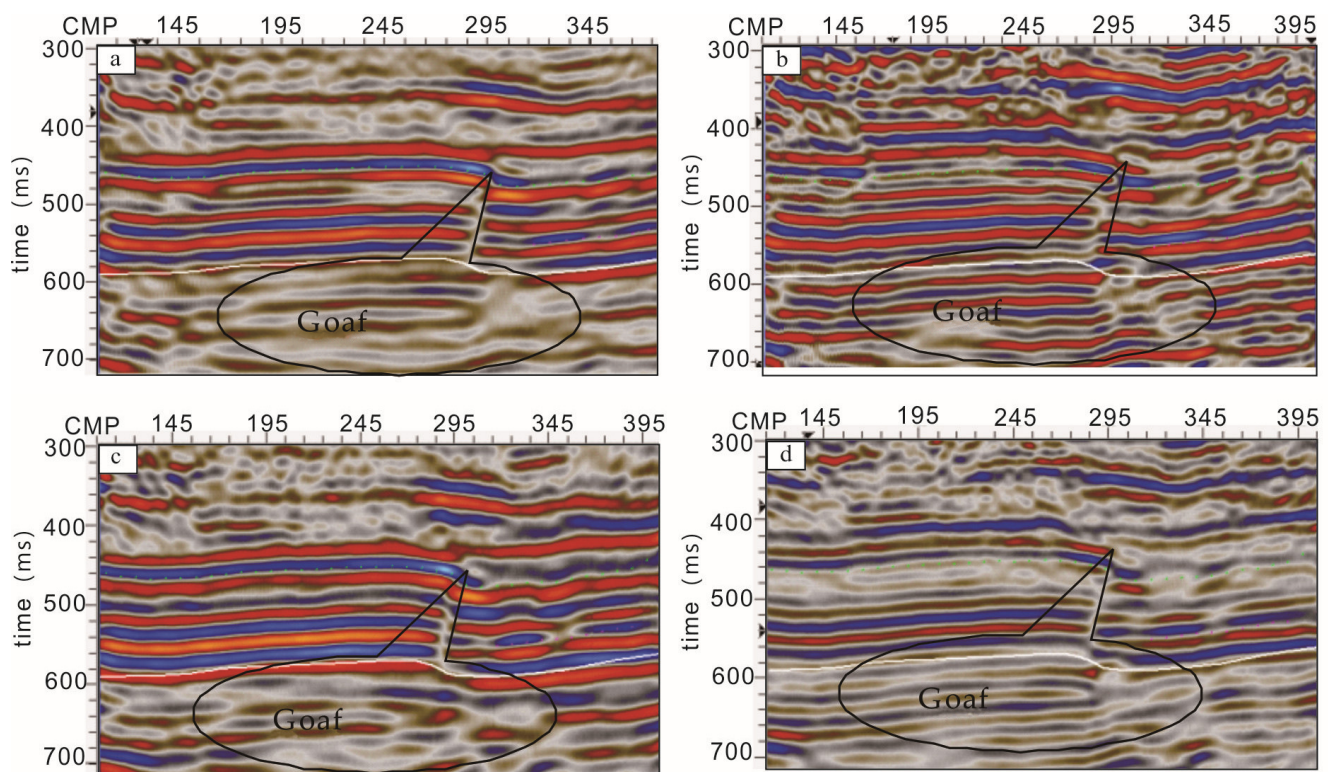


Figure 13. Goaf boundary in the conventional profile (a), in the conventional frequency lifting profile (b), in the OVT treatment profile (c), and in the OVT treatment frequency lifting profile (d).

4.3. Spectrum Decomposition Comparison

For the 15–50 Hz range, the seismic data volume was decomposed by spectral decomposition [36–38], using a 5Hz step size. The spectral decomposition data volumes for different frequencies were obtained, together with the corresponding attribute slices along the layer spectral decomposition (Figure 14). For the same layers, the spectral decomposition slices of different frequencies were highly consistent overall but showed different energy intensities. From low to high frequencies, the energy range became more concentrated, and the anomaly became more obvious. The low energy part of the slice map, visible after high frequency spectrum decomposition, represents the abnormal body. Figure 14 shows obvious anomalies for the goaf in the 45 Hz and 15 Hz areas of the coal seam #3.

We digitized and standardized the logging data and synthesized the seismic records by integrating the logging data with the seismic data. This process was used to calibrate the target #3 and #15 coal seams. High-quality seismic data from Well 163 was selected to analyze the seismic wavelet statistics and synthesize the seismic records (Figure 15). The #3 and #15 coal seam intervals correspond to the negative phase positions at 420 ms and 480 ms on the seismic trace, respectively.

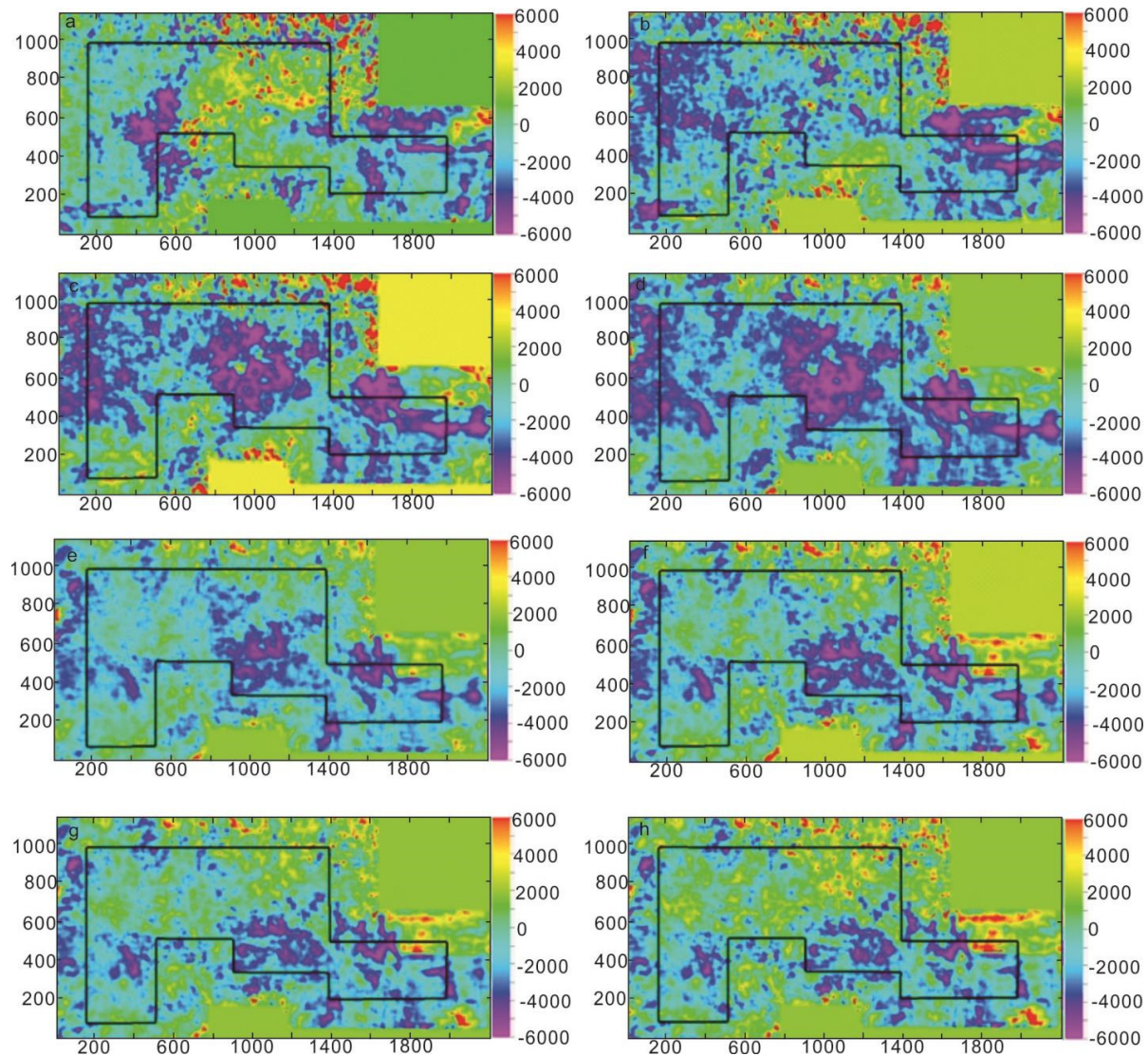


Figure 14. Installing amplitude slicing along the spectra obtained for coal seam #3 (a–15 Hz, b–20 Hz, c–25 Hz, d–30 Hz, e–35 Hz, f–40 Hz, g–45 Hz, h–50 Hz).

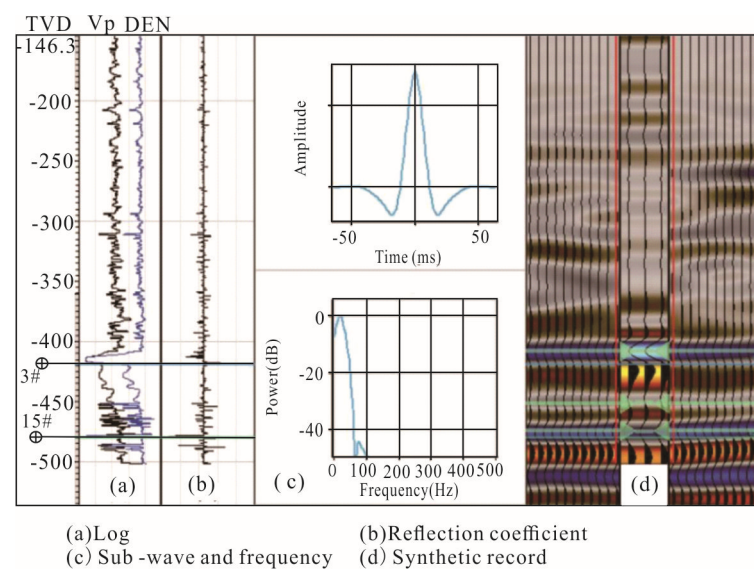


Figure 15. Synthetic Seismic Record and Horizon Correlation for Well 163.

By converting the well logs with pseudo-velocity curves into a velocity-depth relationship, we obtained the time-depth relationship for the study area. Due to the significant differences in rock properties (density and p-wave velocity) between the coal seams and the surrounding strata, the interfaces at the top and bottom of the coal seams were identified as locations where the reflection coefficient reaches its maximum absolute value (Figure 16).

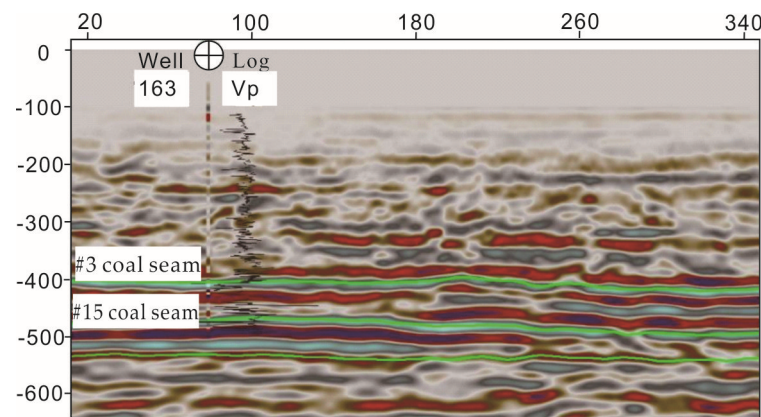


Figure 16. Characteristics of Major Coal Seams on the Seismic Profile.

During the time-depth conversion, we used the average velocity calculated from the well side tracks to correct the average velocity field. This correction enhances the accuracy of the velocity field, thereby improving the overall precision of the time-depth conversion.

The typical seismic profile of the sixth mining area (Figure 17), from top to bottom, shows the reflection wave of coal seam #3, the reflection wave of coal seam #15, and the top interface of Ordovician limestone. The reflection waves of coal seams #3 and #15 are evident in the profile, and the continuity of the whole area is good; moreover, the reflection wave of the Ordovician limestone top interface is strong and continuous in the whole area. Coal seam #3 was mined out on the right side of the seismic profile, resulting in a goaf. At the boundary between normal coal and the goaf, the in-phase axis of coal seam #3 obviously changes from strong to weak, and there is an obvious time difference. The energies reflected by coal seam #15 and by the Ordovician limestone top interface are not much different, but the horizon time is obviously larger. In the 45-Hz spectral decomposition profile (Figure 17b), there is an obvious energy loss zone between the goaf and the normal coal seam, which directly indicates the location of the goaf boundary.

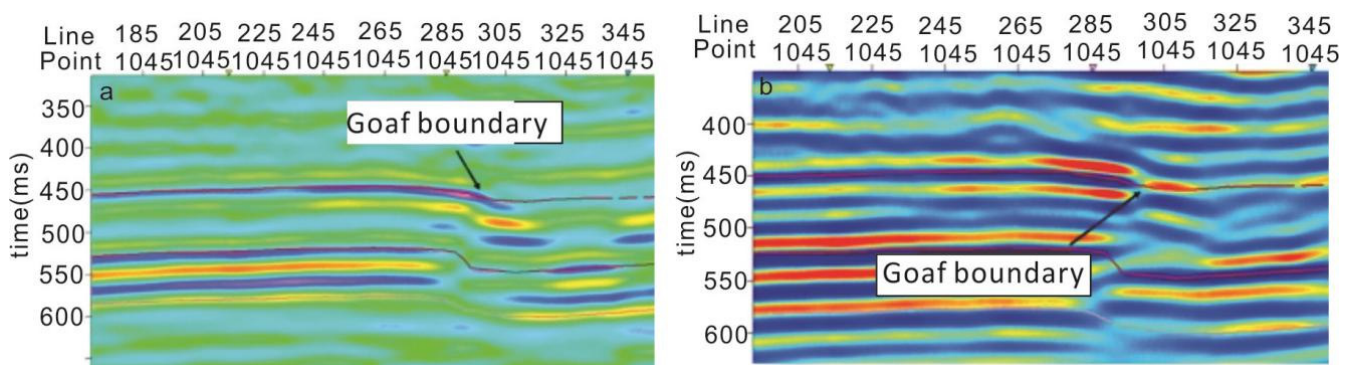


Figure 17. Features of the goaf in a conventional time section (a) and in a spectral decomposition profile (b).

To analyze the boundary of the goaf in the roadway, drilling depth, seismic data processing for dynamic correction velocity calculation of layer velocities and average velocities are employed to form a velocity field in spatial positions. After time-depth conversion, the coal seam roof and the ground elevation are obtained, forming a planar distribution. Along

the seismic time profile of coal seam #3, 45 Hz and 15 Hz spectral decomposition instantaneous amplitude slices are extracted. The goaf and mining engineering drawings are overlaid on the slice image, and low-frequency strong energy strips, which were generated at the boundary of the extraction zone, can be clearly seen in Figure 18.

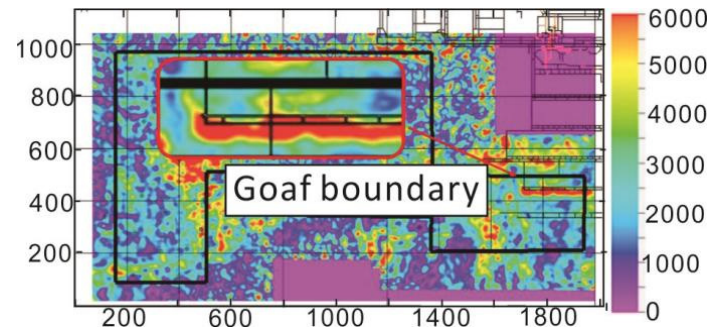


Figure 18. Characteristics of the goaf boundary and tunnel projection of the spectral decomposition slice.

4.4. The Results of Goaf Boundary

Instantaneous 45-Hz and 15-Hz spectral decomposition slices were extracted along coal seam #3. Low-frequency strong energy bands, generated by the goaf boundary, can be clearly seen in Figure 19. The goaf and the mining engineering maps were superimposed on each other, finding that the seismic attributes were in good agreement with the actual excavation goaf. The small blue box in Figure 19 highlights the measurement location of the error between the seismic attributes and the boundary of the actual excavated (hollow) area. The red color in the diagram represents a strong energy and derives from the presence of protective coal pillars. Notably, the error between the red strip measurements and the edge of the coal pillars' protective effect next to the hollow area is of ~ 3.9 m.

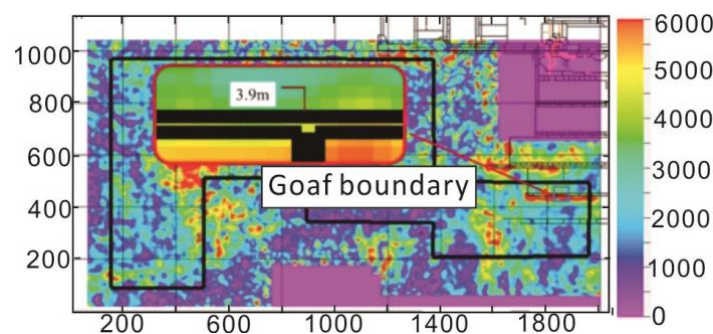


Figure 19. Diagram resulting from the comparison between the 15-Hz spectral decomposition slice goaf boundary and the tunnel projection for coal seam #3.

Figure 20 clearly shows high-frequency weak energy bands generated by the goaf boundary. By comparing the detected goaf location with the mining engineering map, we found that the seismic attributes were in good agreement with the actual excavation goaf. The small red box in Figure 20 shows the measurement position of the error between the seismic attribute and the actual excavation goaf boundary. The purple strip represents weak energy and is in correspondence with a protective coal pillar. The error between the measured purple strip and the edge of the protective coal pillar next to the goaf is of ~ 5.9 m.

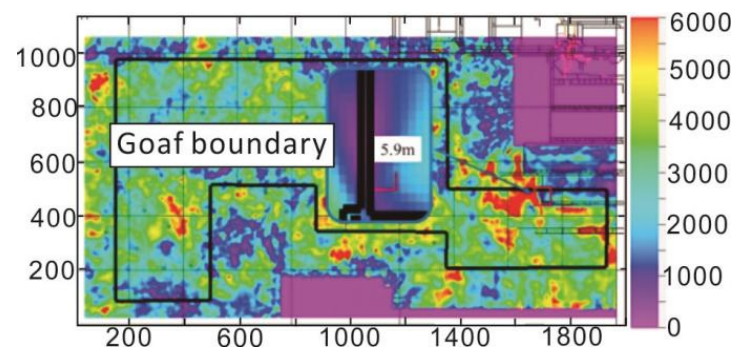


Figure 20. Diagram resulting from the comparison between the 45-Hz spectral decomposition slice goaf boundary and tunnel projection for coal seam #3.

4.5. Discussion

(1) When dealing with complex structures and topography such as loess plateaus, the targeted techniques employed by the CGG processing system, including tomographic static correction, effectively address the long-wavelength static correction issue. Through refined stacking velocity analysis and residual static correction iterations consistent with surface conditions, the shorter wavelength static correction problem is effectively tackled. Additionally, utilizing stacked velocity gathers and profiles for quality control ensures accurate velocity extraction. Guidance from geological variations aids velocity analysis, ensuring the velocity field conforms to geological principles, thereby enhancing velocity interpretation precision. After multiple iterations, the optimal velocity model is obtained, enabling seismic record processing to more accurately reflect subsurface structures, thus providing a reliable foundation for subsequent detailed interpretation of mined-out areas.

(2) This paper employs 5D interpolation techniques to interpolate conventional seismic data, enhancing the spatial sampling rate and coverage to improve seismic imaging quality. 5D interpolation effectively reduces the occurrence of “windowing” phenomena in seismic profiles, especially in shallow coal seams. This method’s advantage lies in enhancing the signal-to-noise ratio of the seismic data, resulting in the clearer imaging of subsurface structures and aiding accurate identification of mined-out areas and their boundaries. Regularization processing of seismic data in the OVT domain is performed to eliminate disparities between actual and ideal spatial sampling attributes, crucial for ensuring seismic migration remains unaffected by spatially irregular sampling, thereby enhancing imaging accuracy and resolution of subsurface structures. Through 5D interpolation and OVT domain processing, seismic data quality and sampling rates are effectively improved, resulting in clearer and more accurate subsurface imaging.

(3) Consistency and feature variations of spectral decomposition slices: different frequency spectral decomposition slices exhibit high overall consistency. The 45Hz spectral decomposition profile shows a distinct energy loss band between mined-out areas and normal coal seams, directly indicating mined-out area boundaries. Spectral decomposition slice characteristics of the mined-out area boundaries are consistent with those of actual excavated mined-out areas but exhibit different energy strengths.

5. Conclusions

The integration of GeoEast and CGG dual processing systems optimized the processing workflow and facilitated the selection of the most suitable processing parameters, resulting in a high signal-to-noise ratio and the high-resolution processing of seismic data and obtaining a high-quality 3D seismic data volume. Addressing the challenge of uneven shot-receiver point distribution during data acquisition, we applied both 5D interpolation and OVT regularization processing technologies, effectively overcoming any adverse effects of irregular acquisition. This comprehensive approach provided highly consistent pre-stack migration gathers and stacked data volumes, strengthening the recognition characteristics of the goaf boundary and enhancing the accuracy and resolution of our interpretations. By

combining data volumes of different types (i.e., conventional, conventional high-frequency, OVT processing, and OVT processing high-frequency), we conducted interactive interpretation and seismic attribute analysis, enabling fine identification of the goaf through combined attribute analysis technology. Through comparisons of different sections and the application of 3D seismic data volume spectrum decomposition technology, we improved the position recognition accuracy of different layers in the goaf, demonstrating high accuracy in determining the overall boundary position of the goaf with a detection accuracy exceeding 75%.

Author Contributions: Conceptualization, G.Z. and T.D.; methodology, Y.W.; software, J.Z.; validation, J.Z., T.D. and Y.W.; formal analysis, Y.W.; investigation, G.Z. and Q.Z.; resources, Y.W. and T.D.; data curation, J.Z.; writing—original draft preparation, J.Z.; writing—review and editing, J.Z., T.D. and Y.W.; visualization, Q.Z.; supervision, G.Z.; project administration, T.D. and Y.W.; funding acquisition, Z.N. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully thank the National Key Research and Development Program of China (2022YFC2904005), the Hebei Science and Technology and Development Research Project (D2022402040) and the Innovation Fund Project of Hebei University of Engineering (SJ2401002064) for financial support.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zhou, X.; Wang, S.; Sun, Y.; Yang, X.; Yin, J.; Wang, L.; Du, W. Application of Comprehensive Geophysical Prospecting Method in Fine Detection of Goaf. *Chem. Technol. Fuels Oils* **2023**, *59*, 1089–1096. [\[CrossRef\]](#)
2. Peng, S. Mining-induced stress redistribution and roof hazardous characteristics of the channel-filled sandstone roof: A physical modeling study. In *Rock Mechanics Tools and Technique*; A A Balkema: Rotterdam, The Netherlands, 1996; pp. 423–429.
3. Morris, A.; Silver, D.; Ferguson, D.; Thayer, S. Towards topological exploration of abandoned mines. In Proceedings of the 2005 IEEE International Conference on Robotics and Automation, Barcelona, Spain, 18–22 April 2005; pp. 2117–2123.
4. Banks, S.; Banks, D. Abandoned mines drainage: Impact assessment and mitigation of discharges from coal mines in the UK. *Eng. Geol.* **2001**, *60*, 31–37. [\[CrossRef\]](#)
5. Jia, N.; Li, Z. Porosity Estimation of a Porous Goaf Area Based on Seismic Wave Attenuation. *Pure Appl. Geophys.* **2021**, *178*, 1845–1858. [\[CrossRef\]](#)
6. Liu, C.; Li, G.; Yu, C. Methods for the Geophysical Exploration and Sustainable Utilisation of Coalbed Methane Resources in Abandoned Mines of Shanxi, China. *Sustainability* **2024**, *16*, 2677. [\[CrossRef\]](#)
7. Huang, X.; Li, X.; Li, H.; Duan, S.; Yang, Y.; Du, H.; Xiao, W. Study on the Movement of Overlying Rock Strata and Surface Movement in Mine Goaf under Different Treatment Methods Based on PS-InSAR Technology. *Appl. Sci.* **2024**, *14*, 2651. [\[CrossRef\]](#)
8. Zhao, W.; Cao, A.; Zhang, N.; Lv, G.; Li, G.; Peng, Y.; Gu, Q. Mechanism and Prevention of Main Roadway Roof Shock in Strong-Bump Coal Seam with Asymmetric Goaf. *Appl. Sci.* **2024**, *14*, 2264. [\[CrossRef\]](#)
9. Wang, N.; Wang, Z.; Sun, Q.; Hui, J. Coal Mine Goaf Interpretation: Survey, Passive Electromagnetic Methods and Case Study. *Minerals* **2023**, *13*, 422. [\[CrossRef\]](#)
10. Deng, B.; Liu, S.; Wang, C.; Jiang, Y.; Wang, H. Numerical investigation on passing through goaf in coal mine failure zone. *Appl. Mech. Mater.* **2013**, *275*, 1518–1524. [\[CrossRef\]](#)
11. Lin, P.; Peng, S.; Zhao, J.; Cui, X.; Du, W. Accurate diffraction imaging for detecting small-scale geologic discontinuities. *Geophysics* **2018**, *83*, 447–457. [\[CrossRef\]](#)
12. Chlebowska, D.; Burtan, Z. Geophysical and Analytical Determination of Over stressed Zones in Exploited Coal Seam: A Case Study. *Acta Geophys.* **2021**, *69*, 701–710. [\[CrossRef\]](#)
13. Ju, Y.; Luxbacher, K.; Li, X.; Wang, G.; Yan, Z.; Wei, M.; Yu, L. Micro-structural evolution and their effects on physical properties in different types of tectonically deformed coals. *Int. J. Coal Sci. Technol.* **2014**, *1*, 264–275. [\[CrossRef\]](#)
14. Wang, K.; Peng, S.; LU, Y.; Cui, X. The velocity-stress finite-difference method with a rotated staggered grid applied to seismic wave propagation in a fractured medium. *Geophysics* **2020**, *85*, T89–T100. [\[CrossRef\]](#)
15. Gui, H.; Lin, M. Types of water hazards in China coalmines and regional characteristics. *Nat. Hazards* **2016**, *84*, 1501–1512. [\[CrossRef\]](#)
16. Zhang, X.; Ma, J.; Li, L. Monitoring of Coal-Mine Goaf Based on 4D Seismic Technology. *Appl. Geophys.* **2020**, *17*, 54–66. [\[CrossRef\]](#)

17. Han, J.; Gu, B.; Zhu, G.; Liu, Z. High-Precision Depth Domain Migration Method in Imaging of 3D Seismic Data in Coalfield. *Remote Sens.* **2022**, *14*, 2850. [\[CrossRef\]](#)
18. Yang, J.; Huang, J.; Wang, X.; Li, Z. An amplitude-preserved adaptive focused beam seismic migration method. *Pet. Sci.* **2015**, *12*, 417–427. [\[CrossRef\]](#)
19. Boué, P.; Roux, P.; Campillo, M.; de Cacqueray, B. Double beamforming processing in a seismic prospecting context. *Geophys. J. Soc. Explor. Geophys.* **2013**, *78*, 101–108. [\[CrossRef\]](#)
20. Bolondi, G.; Loinger, E.; Rocca, F. Offset continuation of seismic sections. *Geophys. Prospect.* **1982**, *30*, 813–828. [\[CrossRef\]](#)
21. Priyank, J.; Robert, H.; Michael, G. Pitfalls in three-dimensional seismic interpretation: Footprints of an irregular source–receiver layout. *AAPG Bull.* **2017**, *101*, 1747–1758.
22. Li, D.; Qi, L. Full wave seismic exploration technology. *Pet. Explor. Dev.* **2022**, *49*, 586–595. [\[CrossRef\]](#)
23. Fomel, S. Seismic reflection data interpolation with differential offset and shot continuation. *Geophysics* **2003**, *68*, 733–744. [\[CrossRef\]](#)
24. Rotman, D.H. Automatic estimation of large residual–statics correction. *Geophysics* **1986**, *51*, 332–346. [\[CrossRef\]](#)
25. Kirkpatrick, S.; Gelatt, C.D.; Vecchi, A.M.P. Optimization by simulated annealing. *Science* **1983**, *220*, 671–680. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Wu, Y.; Wang, W.; Zhu, G.; Wang, P. Application of seismic multiattribute machine learning to determine coal strata thickness. *J. Geophys. Eng.* **2021**, *18*, 834–844. [\[CrossRef\]](#)
27. Marano, G.C.; Rosso, M.M.; Aloisio, A.; Cirrincione, G. Generative adversarial networks review in earthquake-related engineering fields. *Bull. Earthq. Eng.* **2023**, *22*, 3511–3562. [\[CrossRef\]](#)
28. Zhang, L.; Li, A.; Yang, J.; Li, S.; Yao, Y.; Xiao, F.; Huang, Y. Five-dimensional interpolation in the OVT domain for wide-azimuth seismic data. *J. Geophys. Eng.* **2021**, *18*, 529–538. [\[CrossRef\]](#)
29. Brian, B.; Tim, S. Multi-azimuth and wide-azimuth seismic: Shallow to deep water, exploration to production. *Lead. Edge* **2007**, *26*, 450–458.
30. Gulunay, N. Seismic trace interpolation in the Fourier transform domain. *Geophysics* **2003**, *68*, 355–369. [\[CrossRef\]](#)
31. Liu, C.; Wei, X.; Zhu, S.; Ji, Y. Application of spectral decomposition in carbonate v. *Acta Geol. Sin.* **2008**, *82*, 429–431.
32. Daniel, T. Five-dimensional interpolation: Recovering from acquisition constraints. *Geophysics* **2009**, *74*, 123–132.
33. Zhu, Z.; Wu, G.; Gu, Y.; Huang, J.; Chen, Z.; Lu, H. Time-varying discrete cosine transform based on shaping regularization and its application in seismic data analysis. *J. Geophys. Eng.* **2024**, *21*, 496–506. [\[CrossRef\]](#)
34. Vermeer, G.J.O. Creating image gathers in the absence of proper common–offset gathers. *Explor. Geophys.* **1998**, *29*, 636–642. [\[CrossRef\]](#)
35. Luo, C.; Li, X.; Huang, G. Hydrocarbon identification by application of improved sparse constrained inverse spectral decomposition to frequency-dependent AVO inversion. *J. Geophys. Eng.* **2018**, *15*, 1446–1459. [\[CrossRef\]](#)
36. Mousavi, J.; Radad, M.; Monfared, M.; Kahoo, R. Fault Enhancement in Seismic Images by Introducing a Novel Strategy Integrating Attributes and Image Analysis Techniques. *Pure Appl. Geophys.* **2022**, *179*, 1645–1660. [\[CrossRef\]](#)
37. Khayer, K.; Hosseini, F.E.; Roshandel, K.A.; Soleimani, M.M.; Ahmadyfard, A. Integration of feature extraction, attribute combination and image segmentation for object delineation on seismic images. *Acta Geophys.* **2023**, *71*, 275–292. [\[CrossRef\]](#)
38. Farrokhnia, F.; Kahoo, A.R.; Soleimani, M. Automatic salt dome detection in seismic data by combination of attribute analysis on CRS images and IGU map delineation. *J. Appl. Geophys.* **2018**, *159*, 395–407. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.