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Structural Characteristics of Dongxia Coal Mine Face Based on Radio and Channel Wave Seismic Exploration

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ABSTRACT

Geological anomalies in underground coal seams pose serious risks to mining safety and productivity. This study applies an integrated geophysical approach—combining radio wave imaging and channel wave seismic methods—to investigate the structural integrity of the 31123-1 working face at Dongxia Coal Mine, China. Radio wave results indicated stable field intensities and low absorption coefficients, suggesting overall seam continuity with minor localized anomalies. Subsequent channel wave surveys confirmed the absence of faults or collapse features and identified a broad synclinal structure as the only significant anomaly. The findings demonstrate that integrating electromagnetic and seismic techniques enhances structural resolution and provides a reliable basis for safe and efficient mine planning in complex geological settings.

KEYWORDS

Radio Wave; Channel Wave; Structural Characteristics; Coal Mine.

1. INTRODUCTION

In the field of underground coal mining, geological hazards such as faults, collapse columns, hidden voids, and erosional zones continue to pose significant threats to production continuity and personnel safety [1-3]. These structures, often hidden within the coal seam or adjacent rock layers, may lead to catastrophic events including water inrush, gas outbursts, or roof collapses if not accurately predicted and managed in advance [4]. Consequently, improving the resolution and reliability of geophysical exploration techniques has become a central concern in mining geoscience and safety engineering [5-6]. Traditional surface-based seismic methods or sparse drilling strategies frequently fail to detect small-scale yet critical anomalies in time, particularly when coal seams lie beneath thick overburden or exhibit complex structural features. Under such circumstances, seismic methods that operate within the coal seam itself—such as Channel Wave Seismic (CWS) exploration—offer unique advantages due to their targeted sensitivity, long propagation distance, and high resolution within the seam.

Meanwhile, Radio Wave Imaging (RWI), a complementary geophysical method utilizing electromagnetic signals, has also been extensively applied in underground coal mines for preliminary structural screening and rapid anomaly detection due to its relatively simple operational deployment and fast data acquisition capabilities [7]. Radio wave methods exploit the dielectric contrasts between coal seams and surrounding rock strata; signals attenuate significantly in water-rich or broken zones (Figure 1A), thereby enabling the identification of potential geological hazards through anomalies in electromagnetic absorption characteristics [8]. Although RWI provides quick, reliable preliminary results, its effectiveness in characterizing smaller-scale structures or subtle geological discontinuities can be limited by factors such as electromagnetic interference, attenuation variability, and insufficient spatial resolution, particularly when anomalies exhibit subtle or negligible dielectric contrasts [9-10].

Channel waves, also referred to as guided seismic waves or seam waves, are a class of elastic waves that propagate laterally within low-velocity coal seams, which act as natural seismic waveguides bounded by higher-velocity roof and floor strata [11-12]. This unique propagation phenomenon arises from the principle of total internal reflection (Figure 1B): when seismic energy is excited within the coal seam, a portion of it becomes trapped and reflected repeatedly at the interfaces between coal and its surrounding rock, producing a guided wave that can travel several hundred meters with limited attenuation [13-14]. Two primary types of channel waves have been identified—Love-type and Rayleigh-type—distinguished by their polarization and propagation characteristics, with the former involving shear-horizontal motion and the latter comprising coupled compressional and shear-vertical motion [15-16]. These waves are typically dispersive, meaning that different frequency components propagate at different velocities, a property which can be exploited for thickness estimation and lithological interpretation of coal seams [17-18].

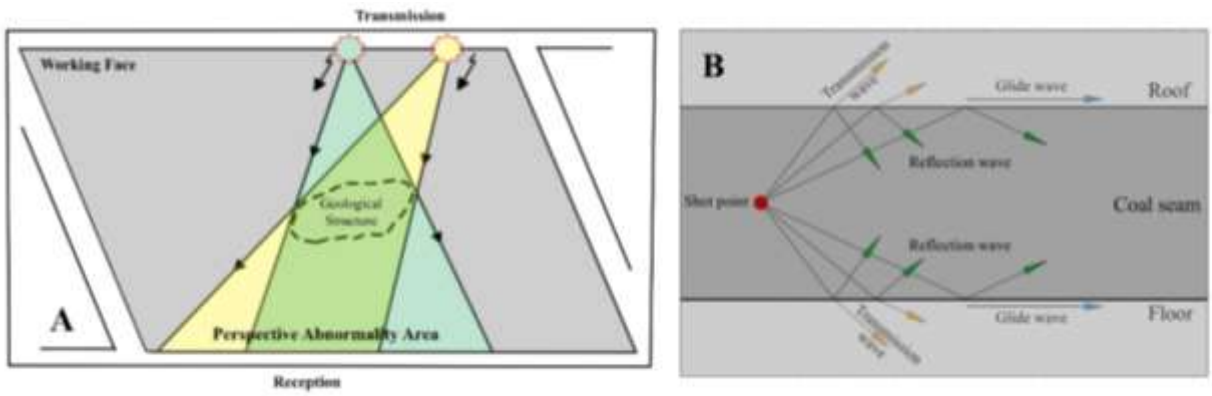

Figure 1. Schematic diagram of radio wave (A) and channel wave (B) formation mechanism

Because channel waves are inherently confined to the coal seam and highly sensitive to internal heterogeneities or discontinuities, they are particularly well-suited for applications in geological structure identification, fault detection, and anomaly mapping ahead of mining faces. The technique has proven capable of detecting features such as faults with minimal vertical offset, erosion zones, collapse columns, and mined-out areas, often with a degree of spatial resolution unattainable by surface-based seismic surveys or borehole logging [19-20]. For instance, reflected channel wave signals can identify the spatial extent and nature of internal anomalies, while transmitted signals—particularly when interpreted using travel-time tomography or energy attenuation models—can provide detailed images of seam continuity and thickness variations [21-23].

To highlight the advantages and limitations of each method, Table 1 summarizes the comparative analysis of radio waves and seismic waves in mining applications. Given their respective advantages and limitations, a logical strategy is to sequentially integrate RWI and CWS methods, first leveraging RWI's rapid and broad-scale electromagnetic imaging capabilities to preliminarily screen potential geological hazards, followed by detailed and targeted CWS exploration for confirming and characterizing identified anomalies or investigating subtle structures undetectable by electromagnetic methods alone [10]. Recent studies have highlighted the significant benefits of combining electromagnetic and seismic approaches, demonstrating enhanced reliability in geological anomaly detection and improved accuracy in structural characterization, thereby reducing geological uncertainties ahead of coal mine development and production faces [24-26].

Table 1. Comparative Analysis of Radio Waves and Seismic Waves in Mining Applications

Technology	Advantages	Limitations
Radio Waves	**Strong Penetration Ability:** Penetrate coal seams and surrounding rock at low frequencies, enabling through-ground transmission. Suitable for through-rock communication and geological imaging with large coverage.	**Susceptible to Interference:** Affected by metal infrastructure, electromagnetic noise (e.g., machinery, cables, solar activity). Requires filtering/shielding measures.
	Communication Capability: High bandwidth supports high-speed data transmission (sensor data, voice, video). Widely used for underground IoT and personnel communication.	**Sensitive to Medium Parameters:** Energy absorbed by conductive media (e.g., water-saturated layers, metal veins), leading to signal loss. Less effective in water-rich or metal-dense regions.
	Mature Technology: Established systems (e.g., Wi-Fi, low-frequency transmitters) simplify deployment and maintenance.	**Frequency Dependency:** Low frequencies enable penetration but limit communication rates and require large antennas. High frequencies offer faster data rates but are line-of-sight and blocked by obstacles.
Seismic Waves	**High Sensitivity to Geological Anomalies:** Detect subtle changes (e.g., faults, fractures, stress shifts) with amplified responses. Ideal for mapping hidden structures and monitoring rock mechanics.	**Not Suitable for Direct Communication:** Cannot transmit complex data; limited to detection/monitoring roles.
	Low Attenuation and Long-Distance Propagation: Confined within coal seams due to velocity contrast, propagating hundreds to thousands of meters. Enables remote geological exploration.	**High Dependence on Medium Continuity:** Fail in fragmented or discontinuous coal layers. Limited utility in thin or interrupted seams.
	Independent of Electrical Transmission: Operate via mechanical vibrations, eliminating electrical risks in hazardous environments (e.g., explosion-prone areas).	**Difficult Data Interpretation:** Complex signals (dispersion, multipath reflections) require specialized processing. Real-time monitoring challenges compared to radio waves.

In practice, at the Dongxia Coal Mine's 31123-1 working face, an initial application of the RWI method was performed, indicating a general continuity of the coal seam with no clearly detectable structural anomalies from electromagnetic attenuation imaging results. However, given the potential existence of subtle or minor-scale discontinuities beyond RWI's resolution limits, further detailed exploration employing CWS methods was subsequently conducted. This subsequent seismic investigation successfully identified geological features—including synclinal structures and minor-scale heterogeneities—not detectable by the initial electromagnetic assessment, thereby confirming the enhanced diagnostic capability provided by integrating these two exploration technologies.

The present study aims to address the methodological gap identified in earlier investigations by explicitly demonstrating the value of integrating RWI and CWS techniques, using the 31123-1 working face of the Dongxia Coal Mine located in the Huating coalfield of Gansu Province, China, as a detailed case study. The geological setting is characterized by a relatively thick coal seam intersected by synclinal structures and subtle internal complexities that could pose potential risks during mining operations if not thoroughly investigated. By first deploying electromagnetic exploration and subsequently applying detailed seismic analysis—covering transmission, reflection, and glide-wave attributes—this study systematically evaluates seam continuity, delineates subtle geological anomalies, and enhances geological confidence ahead of mining activities. The findings are expected to provide practical insights into effective integrated exploration frameworks for similar geological contexts, facilitating improved safety and productivity in underground coal mining operations.

2. GEOLOGICAL SETTING AND STUDY AREA

2.1. Study Site Description

The present study was conducted at the 31123-1 working face of the Dongxia Coal Mine, which is part of the Huating Coalfield in Gansu Province, Northwest China. Geographically, the mine is located in Donghua Town, Huating City, with geographic coordinates ranging from 106°39′14″E to 106°40′46″E and 35°11′39″N to 35°13′16″N (Figure 2). The mine's development area covers approximately 2.69 km², extending 2.66 km from north to south and 0.97 km from east to west.

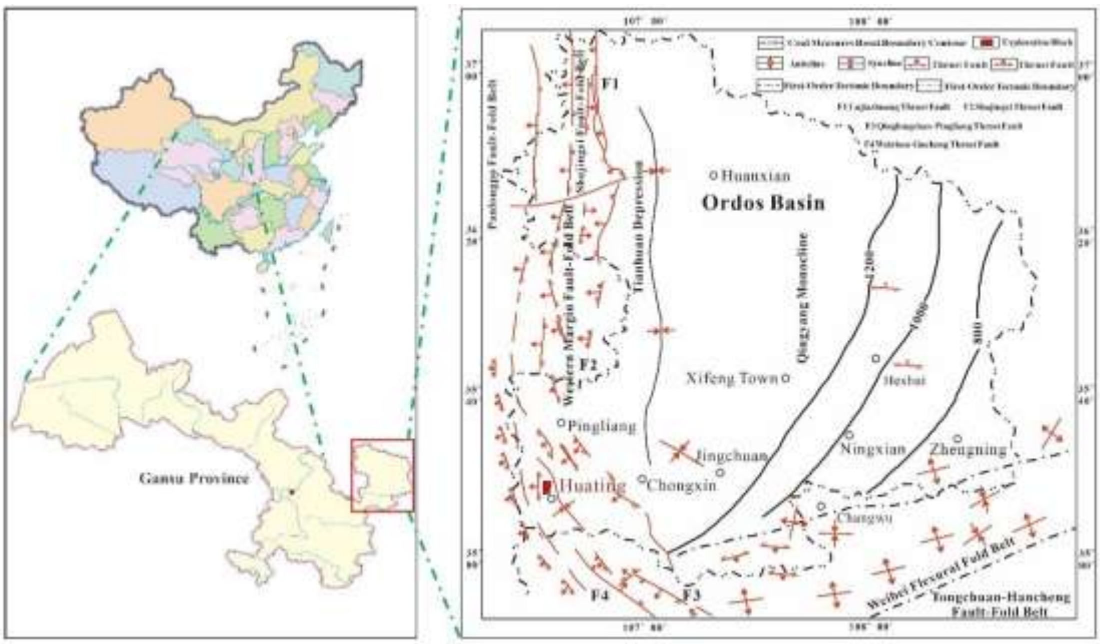

Figure 2. Study area and structural outline map

The 31123-1 working face is situated between the +865 m and +810 m elevations and is arranged along the No. 6-1 coal seam. The working face spans a total length of 1039 m, comprising a southern section of 348 m and a northern section of 691 m. The upper region of the working face lies beneath the goaf of the previously mined 37121-1 working face (between +940 m and +875 m), while the lower section remains unaffected by prior excavation activities. To investigate structural anomalies in this working face, including minor faults and deformation zones along the synclinal axis, CWS surveys were carried out in both the tailentry and headentry of the 31123-1 face.

Initially, the entire study region underwent comprehensive exploration using RWI. Two primary exploration zones were subsequently defined for detailed seismic exploration within this study:(1) the first extending 910 m outward from the headentry's cut-eye and covering a 200 m wide region on the eastern side; (2) the second extending 600 m outward from the working face along the main cut-eye.

2.2. Geological and Geophysical Characteristics

The geological setting of the Dongxia Coal Mine is characterized by a well-developed Mesozoic sedimentary sequence. The primary coal-bearing formation is the Middle Jurassic Yan'an Formation (J_2y), comprising interbedded sandstone, siltstone, mudstone, and coal. The coal seam of interest-No. 6-is stratigraphically positioned in the upper portion of the Yan'an Formation. It has a relatively complex internal architecture, consisting of multiple sub-seams including 6-1, 6-2 (upper, middle, lower), 6-3, and 6-4. Among these, the No. 6-1 seam is the most stable and widely mined.

At the 31123-1 working face, the 6-1 seam exhibits a thickness ranging from 6.5 to 7.5 meters, with an average coal thickness across the broader seam of approximately 34.01 meters. The coal quality is dominated by semi-bright coal, interspersed with bright and dull coal, and includes two carbonaceous mudstone partings (0.3 m and 0.5 m thick, respectively). Structurally, the coal seam demonstrates moderate development of joints and cleats, limited structural coherence, and a compressive strength within the range of 2–3 on the Mohs scale.

The roof and floor conditions surrounding the 6-1 seam also play a significant role in seismic wave behavior. The immediate roof consists of carbonaceous mudstone and argillaceous siltstone, with compressive strength values between 20.1 MPa (direct roof) and 66.8 MPa (main roof), while the floor is composed of fine-grained sandstone with relatively high strength (up to 59.7 MPa). The distinct mechanical contrasts between the coal seam and its surrounding rocks form high wave impedance interfaces, which favor the generation and confinement of channel waves within the seam. Table 2 summarizes the lithological and mechanical properties of the bounding strata.

Table 2. Lithological and Mechanical Properties of Seam Roof and Floor

Layer	Rock Type	Compressive Strength (MPa)	Tensile Strength (MPa)	Thickness (m)	Description
Main Roof	Fine sandstone	66.8	5.16	>5	White-gray, massive sandstone
Immediate Roof	Carbonaceous mudstone	20.1	1.10	0.35–2.11	Soft, brittle, gray to black mudstone
Floor	Fine sandstone	59.7	3.81	8.3–17.5	Compact, homogeneous gray sandstone

From a structural perspective (Figure 2), the coal-bearing strata in the 31123-1 working face area exhibit a simple monoclinic dip structure, with strike directions between 258° and 265° and dip angles ranging from 22° to 43°. Initial geological mapping and previous mining operations had not revealed any prominent faults, folds, or collapse features, although a broad, asymmetric syncline structure had been inferred from historical geological and borehole data. This inferred structure, running predominantly through the lower eastern section of the working face, provided significant impetus for further high-resolution exploration.

In summary, the geological and geophysical characteristics of the 31123-1 working face—including the seam's consistent thickness, distinctive lithological contrasts, initial lack of prominent anomalies from electromagnetic exploration, and inferred subtle structural complexities-collectively provide a robust basis for integrated and advanced geophysical exploration. The sequential approach adopted in this study—first utilizing RWI for initial broad-scale structural assessment, followed by targeted CWS surveys-represents a strategically coherent exploration methodology. It leverages the complementary strengths of each technique to comprehensively characterize geological conditions, minimize uncertainty, and effectively support safe and productive coal mine operations.

3. MATERIALS AND METHODS

3.1. Data Acquisition and Field Implementation

The rock mechanical property testing procedures were conducted in accordance with the Chinese National Standard (Standard for Test Methods of Engineering Rock Masses, GB/T 50266-2013), with the tensile strength determined by Brazilian splitting tests and the compressive strength measured through uniaxial compression tests.

Initially, comprehensive RWI exploration was conducted at the 31123-1 working face of the Dongxia Coal Mine, employing a YDT88 electromagnetic wave detection system (Huahong Intelligent Technology Co., Ltd., Fuzhou, Fujian Province, China). The field operation adhered strictly to established coal mine electromagnetic exploration standards（MT/T 898-2000）. The testing frequency was carefully selected as 365 kHz based on prior comparative trials, achieving optimal balance between penetration depth and resolution capabilities within the coal seam environment. Field acquisition involved systematic electromagnetic scanning through fixed-point measurement positions arranged along the mine roadways adjacent to the target coal seam. Each measurement position consisted of vertically aligned transmitting and receiving antennas embedded directly within boreholes drilled perpendicular to the seam axis.

Electromagnetic wave tomography is conducted between two roadways or boreholes within a coal seam. Assuming the midpoint O of the radiation source (antenna axis) as the origin, and considering the coal seam to be approximately homogeneous and isotropic, the electromagnetic field intensity HP at an observation point P, located at a distance r from point O, can be expressed as:

$$H_P = H_0 \frac{e^{-\beta r}}{r} f(\theta)$$

Where: H0 - the initial field strength in the coal seam surrounding the antenna under a given transmission power, with units of dB;

β - the absorption coefficient of the coal seam for electromagnetic waves, dB/m;

r - the straight-line distance from point O to point P, in meters;

f(θ) - the directionality factor, defined as the angle between the dipole axis and the direction of the observation point, generally approximated using f(θ)=sin(θ).

When the radiation conditions remain constant over time, H0 is considered a constant, and the absorption coefficient β becomes the primary parameter influencing the magnitude of the field intensity. A larger value of β corresponds to more significant attenuation of the field. The absorption coefficient is directly related to the electromagnetic wave frequency and the electrical properties of the coal seam, such as its resistivity: within a homogeneous coal seam, higher frequencies result in larger absorption coefficients and shorter penetration distances; similarly, lower resistivity leads to higher absorption and stronger attenuation.

Following the preliminary electromagnetic survey, detailed CWS exploration was performed, specifically targeting the same two exploration zones defined previously: one extending outward from the headentry cut-eye and another along the main cut-eye. The seismic design combined transmission and reflection configurations aimed at detecting geological anomalies, including subtle faults, seam discontinuities, and roof/floor irregularities. In total, over two hundred seismic shot points and geophone stations were deployed at uniform intervals along the working face entries, with boreholes drilled horizontally perpendicular to the roadway to ensure optimal seismic energy transmission into the seam. Each shot borehole, approximately 2.0 meters in depth, was loaded with standardized 150 g emulsion explosive charges initiated by first-delay electric detonators. Explosives were carefully positioned at borehole bottoms and sealed with clay tamping to achieve maximal energy coupling. Detonator consistency across all measurements was strictly maintained to minimize timing deviations, ensuring data comparability.

The seismic acquisition strictly followed the guidelines stipulated by the Chinese Coal Seam CWS Exploration Method (NB/T 51035-2015). A comprehensive quality assurance process was conducted, with dedicated field engineers managing borehole drilling, explosive loading, synchronization, and geophone coupling. Real-time quality control procedures—including immediate waveform checks and redundant firing of questionable channels—were consistently implemented to ensure high-quality seismic wave recordings with optimal signal-to-noise ratios. Field records underwent preliminary screening using on-site visualization tools to rapidly identify and rectify any problematic data segments, enhancing the reliability of the dataset for subsequent processing.

3.2. Radio Wave Data Processing and Interpretation

Following the completion of electromagnetic wave data acquisition across the 31123-1 working face—spanning two longitudinal survey lines at 10-meter point spacing and fully covering the extent of the working face—radio wave data processing and interpretation were conducted to extract meaningful structural indicators from the received signal profiles. Each measurement cycle at a given transmission point consisted of a standardized 6-minute operating sequence, comprising 4 minutes of active emission, 4 minutes of concurrent signal reception at multiple distributed receivers, and a 2-minute transition period for reconfiguring the transmission station. This protocol was designed to ensure stable signal acquisition, high repeatability, and uniform electromagnetic field conditions across the entire survey area.

During data acquisition, the survey team employed a maximum transmission distance strategy within the instrument's operational range. Specifically, each fixed transmission point was paired with as many spatially distributed reception points as permitted by the attenuation limits of the medium, thereby increasing the diversity of ray paths and incident angles within the measurement region. This acquisition geometry ensured that the resulting electromagnetic dataset provided broad angular coverage and enhanced sensitivity to spatial variations in seam properties and potential structural anomalies.

The core of the radio wave interpretation workflow involved the computation of the electromagnetic absorption coefficient for each ray path, derived from the relationship between initial and received field intensities over known distances. During processing, robust anti-interference algorithms were employed—particularly those involving iterative inversion of the Jacobian matrix—to mitigate the influence of random noise and environmental electromagnetic fluctuations on signal integrity. This algorithmic approach enabled enhanced stability during inversion, even in sections with weaker signal strength or inconsistent attenuation profiles.

To further strengthen interpretation reliability, multiple complementary processing methods were applied in parallel and used for mutual validation. Among these, a linear regression-based fitting method was employed to iteratively regress the fixed-point attenuation curves within the working face. This approach enabled accurate statistical modeling of absorption behavior across the seam, allowing for the extraction of two key diagnostic parameters: the initial radiation field strength (H0) at each transmission point, and the normal attenuation coefficient of the coal seam under undisturbed conditions. These parameters served as benchmarks for detecting local deviations in attenuation behavior potentially associated with structural disturbances, such as seam thinning, fracturing, or lithological discontinuities.

3.3. Channel Wave Data Processing and Interpretation

Seismic data processing utilized the KDZ3114 Seismic Data Processing and Interpretation System (Huahong Intelligent Technology Co., Ltd., Fuzhou, Fujian Province, China), specialized for coal seam guided-wave seismic analysis. Processing workflows involved preliminary trial processing to optimize parameters followed by comprehensive batch processing for full dataset evaluation, emphasizing high-resolution imaging and quantitative anomaly characterization.

Preprocessing commenced with the removal of defective or noisy seismic traces identified through initial data screening, alongside reordering of the dataset to facilitate subsequent processing steps. Detonator delay corrections were systematically applied to standardize the timing across all shot gathers, thus ensuring temporal consistency and accurate first-arrival measurements. To counteract amplitude attenuation effects inherent to seismic propagation, two-dimensional spreading corrections were implemented, preserving amplitude consistency between near-offset and far-offset seismic traces. Additionally, targeted broadband bandpass filtering effectively isolated the frequency bands characteristic of channel waves—particularly fundamental Love and Rayleigh modes—from extraneous low-frequency refractions and ambient noise, significantly enhancing channel wave signal clarity.

Channel wave identification and extraction employed advanced frequency-wavenumber (F-K) filtering techniques designed to exploit the distinct dispersive properties and phase velocity ranges of guided seismic waves. The separation of slow-propagating channel wave signals from faster refracted P- and S-wave energy enabled accurate isolation of guided-wave waveforms. Extracted channel wave wavelets underwent further detailed analysis, yielding critical wavefield attributes such as energy envelopes, phase velocities, and dominant frequency components. For datasets acquired in reflection mode, Kirchhoff diffraction stacking migration—a method based on the Huygens principle—was systematically applied, effectively relocating reflection events to accurate subsurface spatial positions and significantly improving interpretative reliability for structural boundaries and discontinuities.

A principal element of the seismic interpretation involved quantifying energy attenuation coefficients across the surveyed profile, as areas exhibiting increased attenuation were indicative of geological disruptions, seam irregularities, or subtle structural anomalies. Complementing this, travel-time based velocity inversions provided detailed velocity models and refined spatial delineation of subsurface features. The interpretation methodology adopted a multi-attribute integration strategy, simultaneously considering attenuation anomalies, velocity perturbations, and waveform morphology in conjunction with geological logs and roadway observations. The coherent integration of these seismic attributes allowed robust cross-validation of the geological interpretations, substantially enhancing the accuracy and reliability of the identified structural anomalies.

4. RESULTS

The geophysical exploration at the 31123-1 working face of Dongxia Coal Mine consisted of two complementary methodologies conducted sequentially, beginning with RWI, followed by detailed CWS exploration. This combined geophysical approach was intended to comprehensively characterize the coal seam structure and validate the integrity of geological conditions prior to mining operations.

4.1. Radio Wave Survey

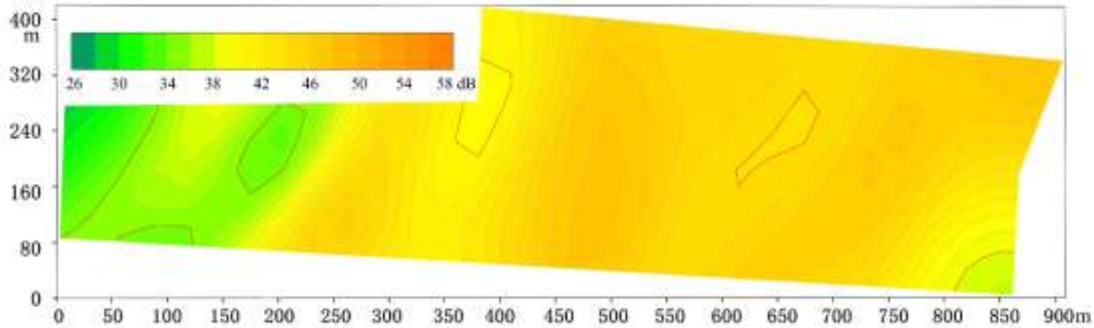

Figure 3. Radio Wave Field Intensity Map of the Working Face

The RWI survey provided a preliminary assessment of the working face's structural integrity. Analysis of the acquired electromagnetic field intensity data indicated stable radiation field strengths across most of the tested area, generally ranging from 26 to 58 dB. Attenuation coefficients (β) derived from iterative Jacobian matrix inversion exhibited uniformly low values, suggesting overall electromagnetic homogeneity and minimal disruption within the coal seam environment. Specifically, the computed attenuation coefficients ranged between approximately 0.02 and 0.07 dB/m across most parts of the 31123-1 working face, indicative of consistent seam continuity and favorable electrical properties.

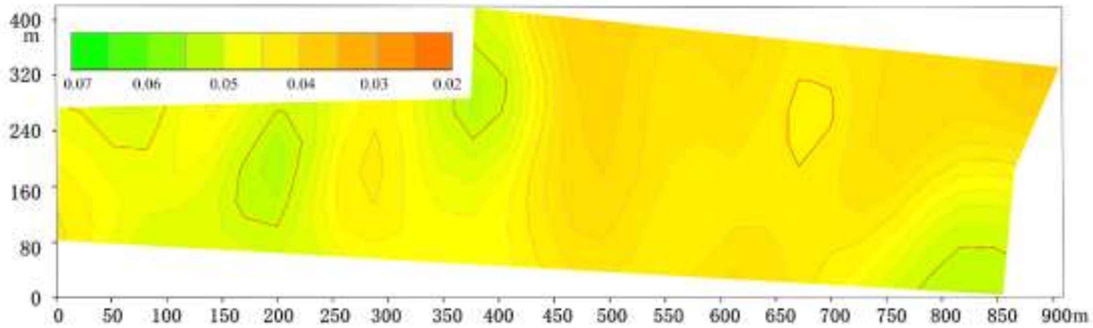

Figure 4. Absorption Coefficient Imaging Map from Radio Wave Tomography of the Working Face

Combined with geological data analysis, the six anomalous zones outlined in red in Figure 3 and the five anomalous zones highlighted in red in Figure 4 are attributed to the influence of concealed geological structures developed within the working face. However, certain localized areas displayed minor electromagnetic attenuation anomalies characterized by slightly elevated absorption coefficients and relatively reduced field intensities. These anomalous zones, although limited in scale and intensity, prompted further detailed investigation due to their potential indication of subtle structural variations or lithological heterogeneities. Nevertheless, no major disruptions or significant structural abnormalities—such as faults, erosional features, or severe seam thinning—were conclusively identified from the electromagnetic attenuation imaging results. Hence, the overall electromagnetic survey indicated predominantly stable seam conditions but justified the need for subsequent higher-resolution CWS exploration.

4.2. Transmission Survey

The through-seam transmission survey was subsequently conducted across the 6-1 coal seam between the headentry and opposite roadway, targeting the continuity and homogeneity of the seam along the working face axis. The channel wave signals exhibited high signal-to-noise ratios and clear waveform features, with minimal scattering or mode distortion throughout the transmission paths.

The analysis of channel wave travel times and energy envelopes revealed no significant time delays, velocity drops, or attenuation anomalies across the survey path (Figure 5). The waveform amplitudes remained stable over long propagation distances (>600 m), and the frequency content showed consistent dispersion patterns indicative of an uninterrupted coal waveguide. The transmission velocity field showed a uniform distribution, suggesting a laterally continuous and mechanically homogeneous seam structure.

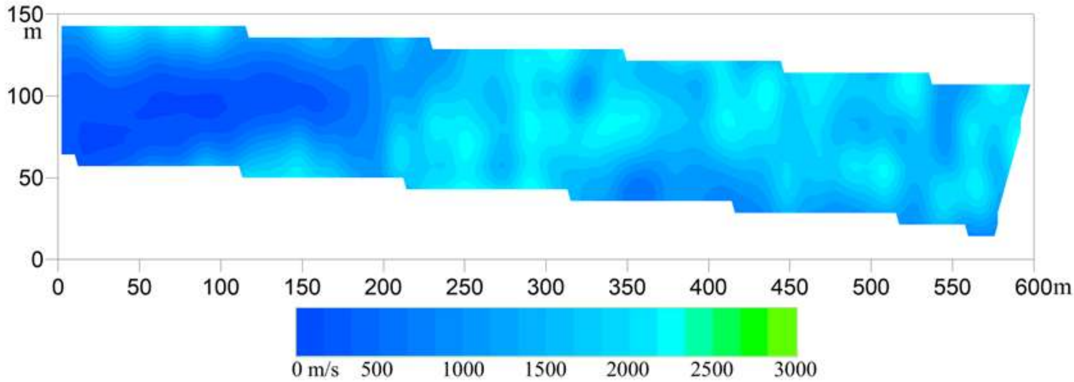

Figure 5. Transmitted channel wave velocity profile of the working face

Moreover, the attenuation coefficient inversion did not reveal any zones of elevated energy loss or abrupt impedance transitions, further corroborating the absence of faults, erosional gaps, or lithological replacements. Taken together, these results indicate that the 6-1 coal seam in the surveyed working face is structurally intact and suitable for uninterrupted longwall mining operations.

4.3. Tailentry Reflection Survey

The single-roadway reflection survey along the tailentry was designed to detect structural features ahead of mining using near-offset channel wave reflections. The processed seismic sections showed no identifiable reflectors, such as fault planes, parting zones, or collapse columns, within the detection range of approximately 300 m (Figure 6).

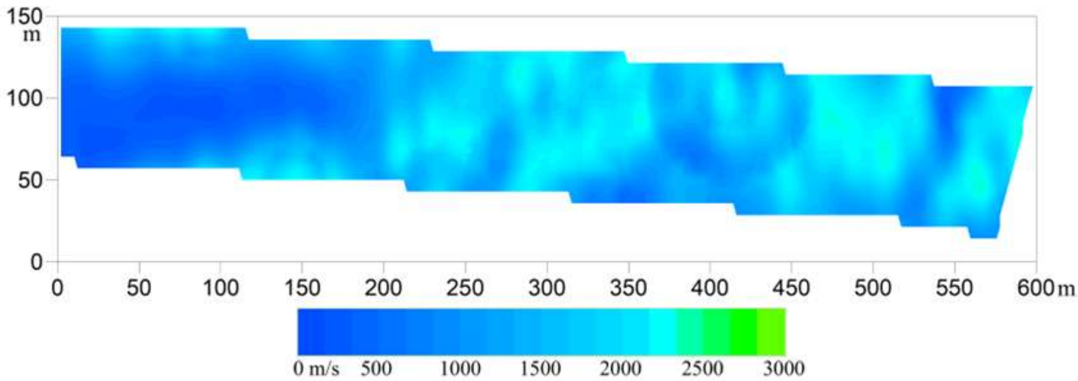

Figure 6. Reflected channel wave velocity profile of the tailentry

The observed waveform continuity and uniform amplitude decay suggest the absence of sharp lateral impedance contrasts. Additionally, no secondary arrivals or diffractions were detected that would typically indicate abrupt terminations or offsets within the coal seam. These results confirm that the upper section of the 31123-1 working face does not contain any significant geological anomalies within the anticipated mining path.

4.4. Headentry Inner-Side Reflection Survey

The inner-side reflection survey in the headentry exhibited similar results to the tailentry. The channel wave first arrivals were clearly defined (Figure 7), with consistent energy and dispersion signatures. Throughout the survey length, no discrete reflection events or energy disruptions were observed.

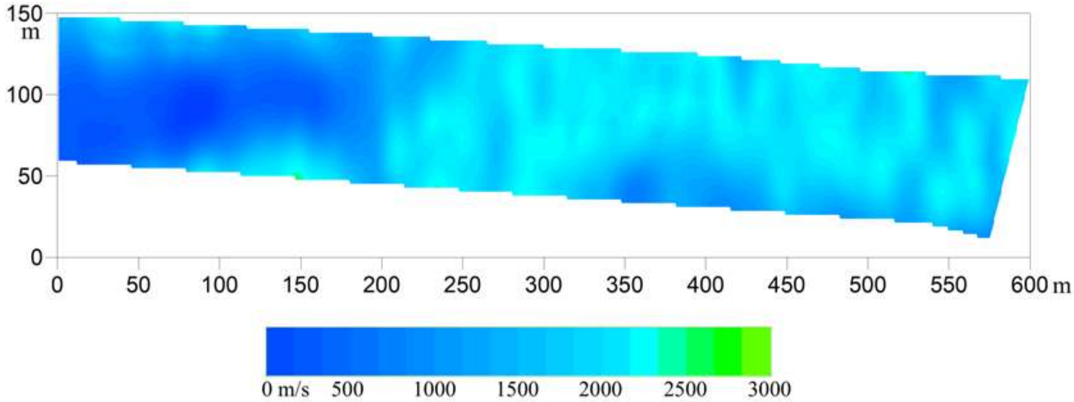

Figure 7. Reflected channel wave velocity profile of the headentry

In the seismic sections, the amplitude decay was smooth, and the dominant frequency remained stable across shot points. This further supports the interpretation that the coal seam within the headentry is free from major structural disturbances such as faults or severe thinning zones. The inner roadway can thus be considered structurally safe for tunneling and auxiliary roadway development.

4.5. Identification of Anomalous Zone

The outer-side reflection survey of the headentry revealed the only significant anomaly across the entire 31123-1 working face. Between approximately 150 m and 910 m along the survey line, seismic records exhibited a consistent pattern of reduced channel wave energy, attenuated amplitude, and elongated waveform durations, particularly in the vertical (Z) and horizontal (X) components. This zone, designated as CBYC1 (Figure 8), extended laterally over 760 m and vertically between 60 m and 150 m in depth.

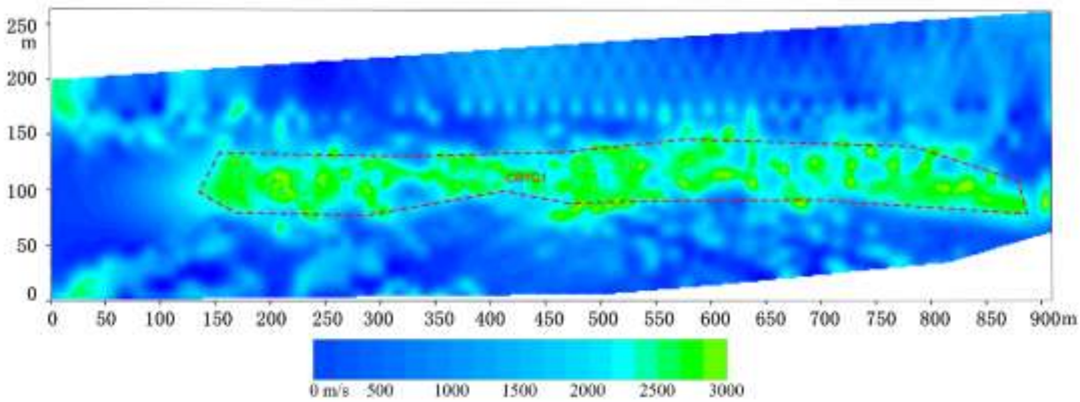

Figure 8. Reflected channel wave velocity profile of the outer side of the headentry

Despite the attenuated energy, no obvious fault reflections or abrupt wave terminations were observed. The waveform distortion was gradual and symmetric, lacking polarity reversals or travel time offsets typically associated with fault planes. Furthermore, velocity inversion results showed a gentle spatial velocity gradient, consistent with a broad, asymmetric synclinal structure.

Geological correlation confirmed that this anomaly aligns with the axis of a known regional syncline, and that the waveform distortion is attributable to gradual changes in coal seam dip and geometry, rather than a destructive structural feature. As such, CBYC1 is interpreted as a non-hazardous synclinal anomaly, not requiring major engineering mitigation prior to mining.

4.6. Comprehensive Interpretation

Integrating the findings from both electromagnetic and seismic exploration methodologies, a coherent geological interpretation emerges for the 31123-1 working face. While initial RWI provided reassuring evidence of generally stable seam conditions—characterized by uniform electromagnetic field intensities and consistently low absorption coefficients—minor local attenuation anomalies identified by radio wave surveys warranted further scrutiny. The subsequent, detailed CWS investigation confirmed that the local anomalies mainly resulted from gradual geological changes, notably the gentle synclinal deformation (CBYC1), rather than disruptive faults or erosional features.

Collectively, these comprehensive geophysical results confirm the geological continuity and structural integrity of the 31123-1 working face, validating the suitability of the site for safe, uninterrupted coal extraction operations. Moreover, the complementary nature and systematic integration of electromagnetic and seismic methodologies demonstrated in this exploration campaign underscore their combined efficacy in robustly characterizing geological structures, minimizing mining risks, and enhancing the accuracy of coal seam assessments ahead of mining operations.

5. DISCUSSION

The integrated results from both the electromagnetic RWI and CWS exploration conducted at the Dongxia Coal Mine's 31123-1 working face provide comprehensive insights into the effectiveness of combined geophysical approaches for geological anomaly detection in structurally complex coal seams. The initial electromagnetic survey offered a broad-scale evaluation of seam integrity, identifying stable field intensity distributions and generally low absorption coefficients, which indicated that the coal seam is predominantly homogeneous and free from major disruptive anomalies across the surveyed area. However, local electromagnetic attenuation anomalies were detected, suggesting potential subtle geological influences that warranted additional high-resolution seismic investigation.

The subsequent CWS exploration delivered important clarifications on these initially identified electromagnetic anomalies. The absence of abrupt wavefield disruptions—such as amplitude polarity reversals, discontinuities in first arrivals, or high-frequency diffraction patterns—in the seismic data confirmed the structurally intact and seismically homogeneous nature of the coal seam throughout the majority of the working face. Specifically, the high signal-to-noise ratios, stable waveform amplitudes, and consistent dispersion characteristics observed in both the transmission and reflection data sets further reinforced the interpretation of a continuous, undisturbed waveguide, consistent with previous studies that emphasized the reliability of guided wave methods for structural integrity assessment [27].

A notable finding emerged with the detailed seismic analysis of the CBYC1 anomalous zone, initially hinted at by localized electromagnetic attenuation variations but conclusively characterized through seismic attribute integration. Although the channel wave energy attenuation patterns and elongated waveforms in this zone superficially resembled those typically associated with structural disruptions such as faults or collapse columns, the absence of distinct reflection signatures and the symmetric nature of amplitude decay strongly supported its reinterpretation as a gentle, asymmetric synclinal structure. Geological correlations based on borehole data and seam geometry analyses further validated this interpretation. This nuanced insight illustrates the critical advantage of integrated waveform and velocity attribute analyses provided by the seismic method, enabling precise differentiation between structurally hazardous discontinuities and benign geological anomalies, thus significantly enhancing diagnostic confidence and reducing the potential for misinterpretation.

From a methodological perspective, this study clearly demonstrates the complementary strengths of integrating RWI with detailed seismic exploration. The initial radio wave assessment effectively delineated regions requiring closer scrutiny, thus guiding subsequent targeted seismic surveys. Transmission surveys within seismic exploration excelled at evaluating broad seam continuity and homogeneity, whereas reflection surveys provided critical depth-resolved imaging of localized anomalies. The comprehensive approach of combining both electromagnetic and seismic methods, supported by advanced attenuation coefficient inversions, dispersion compensation, and reflection migration techniques, was instrumental in clarifying weak or ambiguous anomaly signatures, especially in the presence of structurally subtle features such as synclines, where energy attenuation effects can be gradual and challenging to interpret solely through electromagnetic or seismic methods independently [28].

Despite these methodological strengths, certain limitations remain. Both electromagnetic and seismic responses can be sensitive to variations in seam thickness and quality. In thinner or significantly heterogeneous coal seams, channel wave signals might become insufficiently confined, resulting in weaker signals and reduced interpretive reliability. Similarly, electromagnetic imaging effectiveness can diminish under conditions of extreme electrical conductivity variability. In such scenarios, supplementary methods such as microseismic monitoring or geoelectric tomography may be necessary. Additionally, assumptions of isotropy in velocity and attenuation inversions could oversimplify real-world anisotropic effects related to cleat orientations, stress fields, or coal seam heterogeneity, especially in tectonically active regions.

In summary, the integrated geophysical exploration strategy combining RWI with CWS methods effectively verified the structural integrity and geological continuity of the 31123-1 working face, while also offering deeper insights into subtle geological features and their implications for mining safety and operations. The present case study not only validates the practical applicability of combined electromagnetic and seismic techniques in complex coalfields but also contributes to a deeper understanding of the relationship between wavefield anomalies and subtle structural variations within stratified coal seam environments.

6. CONCLUSIONS

This study employed a comprehensive and integrated geophysical exploration approach—consisting of initial radio wave electromagnetic imaging followed by detailed CWS exploration—to systematically evaluate the structural integrity and geological continuity of the 31123-1 working face at Dongxia Coal Mine, situated within the structurally intricate Huating Coalfield of Gansu Province. The key conclusions derived from the combined exploration methods are as follows:

(1) The electromagnetic survey provided an effective preliminary assessment of the 31123-1 working face, revealing stable electromagnetic field intensities and predominantly low absorption coefficients across the working face, with no significant anomalies indicative of major structural disruptions, thereby establishing a baseline of seam continuity and justifying further high-resolution seismic investigation.

(2) The subsequent CWS exploration confirmed the structural integrity and seismic homogeneity of the No. 6-1 coal seam; both transmission and reflection surveys—conducted along the tailentry and headentry inner-side—exhibited excellent waveform stability, low attenuation, and consistent

dispersion characteristics, with no evidence of faults, erosional gaps, or lithological discontinuities, thereby validating the suitability of the working face for safe and continuous longwall mining operations.

(3) A single notable anomalous zone (CBYC1), initially suggested by electromagnetic data, was conclusively characterized through detailed seismic analysis. Integrated waveform and velocity attribute interpretation, combined with geological correlation, identified this anomaly as a gentle asymmetric synclinal structure rather than a disruptive geological feature, confirming it poses no significant risk to mining operations.

Overall, this study clearly demonstrates the enhanced diagnostic effectiveness achieved through the integration of electromagnetic and seismic exploration techniques. The combined approach significantly improved the reliability of geological anomaly detection and structural characterization, reducing interpretative uncertainties and providing robust guidance for safe mining practice. Future research directions should include improving channel wave resolution in ultra-thick or highly heterogeneous seams, employing multi-component seismic datasets for detailed anisotropy analyses, and leveraging machine-learning techniques for automated anomaly classification and real-time monitoring in complex geological environments.

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DATA AVAILABILITY STATEMENT

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest related to this work. We do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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