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Research Article

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Posted Date: October 5th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10380400/v1>

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Multiscale heterogeneity controls ultrasonic wave propagation in tectonically deformed coal: Insights from CT imaging and numerical wavefield modelling

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Abstract

To elucidate how multiscale heterogeneous structures control ultrasonic wave propagation in tectonically deformed coal, primary coal and cataclastic coal collected from the No. 15–17 coal seam of the Shoushan No. 1 Mine in Pingdingshan, China, were investigated using a combination of ultrasonic testing, X-ray computed tomography (CT), digital core reconstruction, and finite-element wavefield simulation. The pore-fracture characteristics and acoustic responses of different coal structures were systematically analyzed. The results show that the average P-wave and S-wave velocities of primary coal are 2038.33 and 1123.50 m/s, respectively, whereas those of cataclastic coal decrease to 1571.67 and 879.33 m/s, representing

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reductions of 22.89% and 21.73%, respectively. CT-based reconstruction reveals that the mineral content of both coal types is comparable, accounting for approximately 6%–8% of the total volume. In contrast, the porosity of cataclastic coal (2%–3%) is markedly higher than that of primary coal (1%–2%), accompanied by a broader pore-size distribution and a higher proportion of large-scale pores and fractures ($>150\text{ }\mu\text{m}$). Acoustic analysis indicates that the dominant frequency of primary coal is concentrated at 75–85 kHz, with the main time–frequency energy distributed between 100 and 250 μs . In comparison, cataclastic coal exhibits more pronounced low-frequency and multi-peak spectral characteristics, with the main energy zone shifting to 150–350 μs , indicating enhanced scattering attenuation and prolonged coda waves. Finite-element simulations further demonstrate that mineral inclusions induce only localized wavefield perturbations with negligible influence on the first-arrival time, whereas pore-fracture networks significantly alter wave propagation paths. In fractured models, the first-arrival time is delayed from 55 to 58 μs (approximately 5.45%), accompanied by the formation of multiple discrete energy clusters within 80–200 μs . These findings indicate that the pore-fracture system is the dominant factor controlling ultrasonic wave propagation, wave velocity attenuation, spectral broadening, and coda-wave complexity in tectonically deformed coal, whereas mineral inclusions mainly exert localized perturbation effects. This study provides a theoretical basis for the acoustic characterization of tectonically deformed coal and the evaluation of coal damage.

Keywords: Tectonically deformed coal; Pore-fracture system; Ultrasonic wave propagation; CT reconstruction; Wavefield simulation

1. Introduction

Under long-term tectonic stress, coal seams undergo compression, shearing, and fragmentation (Zhang, Yao & Wang, 2022), causing the original coal structure to progressively evolve into various types of tectonically deformed coal, including cataclastic (Cao, et al., 2003), granular, and mylonitic coal (Yu, et al., 2020). Extensive studies have demonstrated that tectonic deformation not only alters the mechanical properties and permeability of coal but also significantly affects coalbed methane occurrence, migration, and the development of dynamic disasters, making it one of the key controlling factors in coal and gas outbursts (Ju, et al., 2012). During tectonic deformation, the initiation, propagation, and coalescence of pores and fractures are accompanied by the redistribution of mineral inclusions and the progressive degradation of coal matrix continuity (Wen, et al., 2026). Consequently, the coal evolves into a multiscale heterogeneous medium consisting of the coal matrix, mineral inclusions, and an interconnected pore-fracture system (Wang, et al., 2019). This complex structure not only governs the macroscopic physical and mechanical properties of coal but also directly controls the propagation behavior of elastic waves within the medium (Masson & Virieux, 2023). Ultrasonic testing has been widely employed in geotechnical engineering (Martínez-Martínez, Benavente & García-del-Cura, 2012), hydrocarbon reservoir characterization, and coal damage assessment because of its non-destructive nature, rapid measurement, operational simplicity, and high sensitivity to internal structural heterogeneity (Ling, et al., 2021). Previous studies have shown that ultrasonic wave velocity, amplitude attenuation, spectral characteristics, and waveform distortion can effectively characterize variations in the internal structure of coal and rock (Xu, et al., 2026). Song et al. (Song, Chen & Zhang, 2023) reported that both P-wave and S-wave

63 velocities of tectonically deformed coal are significantly lower than those of primary coal, with
64 wave velocities decreasing progressively as the degree of tectonic deformation increases. She
65 et al. (She, et al., 2025) demonstrated that the development of pores and fractures reduces elastic
66 wave velocity and enhances wave dispersion, primarily because an increased proportion of
67 compliant pores leads to greater energy dissipation during wave propagation. Du et al. (Du, et
68 al., 2024) further found that fracture development significantly decreases acoustic wave
69 velocity while intensifying wave scattering and energy attenuation. Although previous studies
70 have highlighted the important role of pore-fracture structures in governing the acoustic
71 response of coal, most have focused on the relationships between acoustic parameters and
72 individual structural descriptors, such as porosity, fracture density, or damage variables. A
73 systematic understanding of how different components of the multiscale heterogeneous
74 structure jointly govern ultrasonic wave propagation remains lacking.

75 In recent years, advances in high-resolution X-ray computed tomography (CT) have
76 provided a powerful tool for characterizing the microstructure of coal (Huang, et al., 2025).
77 Digital core models reconstructed from CT images can faithfully preserve the internal pore-
78 fracture architecture and the spatial distribution of mineral inclusions, enabling three-
79 dimensional visualization and quantitative characterization of the heterogeneous structure of
80 coal (Fan, et al., 2020). Previous studies have demonstrated that digital core technology offers
81 significant advantages in characterizing pore-fracture structures, evaluating pore connectivity
82 (Li, et al., 2012), and analyzing flow behavior in coal. Wu et al. (Wu, et al., 2023) quantitatively
83 investigated the influence of pore-fracture connectivity on seepage behavior based on CT
84 scanning and digital core reconstruction. Wang et al. (Wang, et al., 2025) further integrated

digital core models with multiphysics simulations to characterize fluid transport and stress responses within coal at the microscale (Hou, et al., 2012). However, existing studies on digital cores have primarily focused on seepage, gas adsorption, and mechanical behavior, whereas relatively little attention has been paid to the mechanisms governing ultrasonic wave propagation in coal controlled by multi-scale heterogeneous structures.

Meanwhile, advances in numerical methods, including the finite element method (FEM) (Dong, et al., 2021), finite difference method (FDM) (Seriani & Oliveira, 2008), and lattice Boltzmann method (LBM) (Van Pamel, et al., 2017), have made wavefield simulation based on realistic digital core models an effective approach for investigating ultrasonic wave propagation in complex heterogeneous media. Compared with homogeneous models or idealized fracture models (Yu, et al., 2026), realistic structural models can explicitly represent the spatial configuration of the coal matrix, mineral inclusions, and the pore-fracture system, enabling direct observation of wave reflection (Gregor & Moczo, 2020), transmission, scattering, and diffraction at different material interfaces. Consequently, they provide valuable insights into how heterogeneous structures govern wavefield evolution, propagation paths, and energy distribution (Xu, et al., 2024). However, previous studies have mainly focused on wave propagation in homogeneous or simplified heterogeneous media (Zhao & Cai, 2001), and a systematic understanding of ultrasonic wave propagation in tectonically deformed coal (Li, et al., 2020), where the coal matrix, mineral inclusions, and pore-fracture system interact simultaneously, remains lacking (Sakellariou, et al., 2004). In particular, tectonic deformation promotes both pore-fracture development and mineral redistribution, giving rise to complex multi-scale heterogeneous structures (Zhang, et al., 2022). The effects of these structures on

first-arrival propagation paths, wave scattering characteristics, spectral evolution, and coda-wave formation have yet to be fully clarified (Zheqiang, et al., 2020). Moreover, most ultrasonic studies have been limited to the analysis of macroscopic acoustic parameters (Xu, et al., 2026), such as wave velocity and amplitude, with relatively little effort devoted to elucidating the mechanisms responsible for acoustic response variations from the perspective of microscale heterogeneous structures (Pan & Connell, 2012).

To address these knowledge gaps, this study investigates primary coal and cataclastic coal collected from the No. 15–17 coal seam of the Shoushan No. 1 Mine using an integrated approach combining ultrasonic testing, high-resolution X-ray computed tomography, digital core reconstruction, and finite-element wavefield simulation. First, ultrasonic transmission tests were performed to compare wave velocity, time-domain waveforms, frequency spectra, and time-frequency responses of coals with different structural characteristics. Subsequently, CT scanning and digital core reconstruction were employed to quantitatively characterize the coal matrix, mineral inclusions, and pore-fracture system and correlate these structural features with acoustic responses. Finally, a finite-element model based on realistic two-dimensional CT slices was established to simulate ultrasonic wave propagation and reveal the roles of mineral inclusions and pore-fracture structures in governing propagation paths, interface reflection, transmission, scattering, and energy attenuation. In particular, this study aims to clarify the relative contributions of mineral inclusions and pore-fracture structures to ultrasonic wave propagation in tectonically deformed coal. The findings provide new insights into the ultrasonic response mechanisms of tectonically deformed coal and offer a theoretical basis for coal structure characterization and ultrasonic exploration in structurally complex coalfields.

2. Materials and methods

2.1 Coal sample collection and preparation

The Shoushan No. 1 Mine is located in the eastern Pingdingshan Coalfield, China, where the No. 15–17 coal seam serves as the primary mining seam. The regional tectonic framework has been strongly controlled by the Yanshanian tectonic movement, particularly the long-term activity of the Xiangjia strike-slip fault and associated fold deformation. Under prolonged tectonic stress, the coal seam has undergone varying degrees of compression, shearing, and fragmentation, resulting in substantial structural reorganization and the formation of different types of tectonically deformed coal. Tectonic deformation not only modifies the development of the pore-fracture system but also alters the spatial distribution of mineral inclusions and degrades the continuity of the coal matrix, giving rise to pronounced multi-scale structural heterogeneity. Previous studies have demonstrated that the structural evolution of coal is closely related to its deformation mechanisms. According to the degree and characteristics of tectonic deformation, coal can generally be classified into primary coal, cataclastic coal, granular coal, schistose coal, and mylonitic coal. Among these, primary coal largely preserves its original depositional structure, exhibiting a relatively intact coal matrix and a low degree of fracture development. In contrast, cataclastic coal is typically formed under brittle tectonic deformation and is characterized by the extensive development of tensile and shear fractures induced by tectonic stress, resulting in a marked reduction in structural integrity. Consequently, compared with primary coal, cataclastic coal exhibits significant differences in pore-fracture development, mineral occurrence, and structural heterogeneity.

According to underground geological observations and field investigations, primary coal

and cataclastic coal are the predominant coal types in the No. 15–17 coal seam of the Shoushan No. 1 Mine. These two coal types are highly representative of the structural evolution induced by tectonic deformation. To investigate the influence of heterogeneous structures on ultrasonic wave propagation, primary coal and cataclastic coal samples were collected from the No. 15–17-12150 working face of the Shoushan No. 1 Mine and prepared as standard specimens (Fig. 1). Considering the relatively weak and fragile nature of coal, conventional coring may induce secondary fractures and alter its original microstructure. To preserve the intrinsic structural characteristics as much as possible, large block samples collected underground were processed by wire electrical discharge machining (wire-EDM) to prepare standard cylindrical specimens with dimensions of $\Phi 50 \times 100$ mm. Six specimens were prepared for each coal type, yielding a total of 12 specimens for subsequent ultrasonic testing, CT scanning, digital core reconstruction, and wavefield simulation.



Fig. 1. Underground coal sample collection

2.2 Ultrasonic testing

To investigate the ultrasonic wave propagation characteristics of coals with different structural types, ultrasonic transmission tests were conducted using the pulse transmission

method. All experiments were performed under ambient conditions (25 °C and atmospheric pressure) using a TGM-U204 ultrasonic testing system (Hunan Tiangong Measurement and Control Technology Co., Ltd., China), as shown in Fig. 2. The system was equipped with a pair of piezoelectric transducers with a center frequency of 100 kHz for ultrasonic signal generation, reception, and full-waveform acquisition (Srivastava, et al., 2025). During testing, ultrasonic pulses generated by the transmitting transducer propagated through the coal specimen and were recorded by the receiving transducer. In addition to measuring the first-arrival time of P-waves for wave velocity calculation, the system simultaneously acquired complete ultrasonic waveforms for subsequent time-domain, frequency-domain, and time-frequency analyses (Di Martino, De Siena & Tisato, 2022). Prior to testing, the system was calibrated using a standard glass calibration rod, and the zero-time correction was set to 6 μ s. To ensure the repeatability and comparability of the measurements, the excitation voltage, sampling interval, sampling length, and amplifier attenuation were fixed at 500 V, 0.1 μ s, 16 K, and 10, respectively.

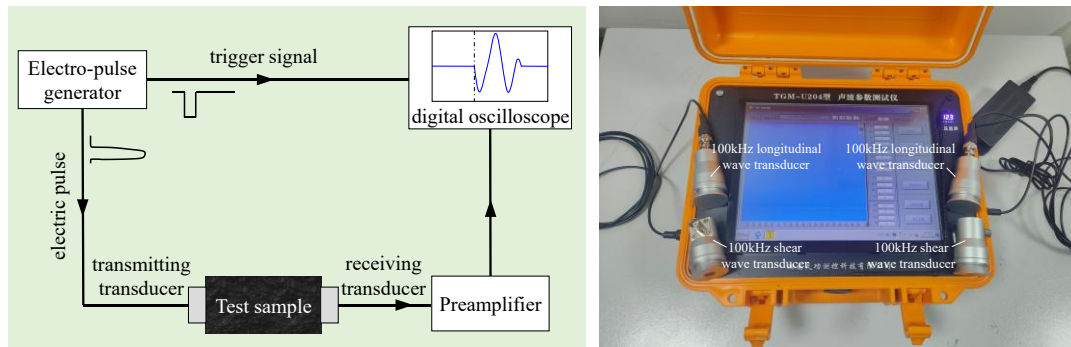


Fig. 2. Principle and equipment of acoustic wave parameter test

A thin layer of petroleum jelly was applied as a coupling agent to ensure effective acoustic coupling between the transducers and the specimen surfaces. The travel times of the P- and S-waves were determined from their first-arrival times, and the corresponding wave velocities were calculated using Eqs. (1) and (2). Each specimen was tested three times, and the average

value was used for subsequent analysis.

$$v_p = L / t_p \quad (1)$$

$$v_s = L / t_s \quad (2)$$

where L is the specimen length, km; t_p and t_s are the travel times of the P-wave and S-wave, s, respectively; and v_p and v_s are the P-wave and S-wave velocities, km/s, respectively.

Table 1 Wave velocity and density of the sample

Sample name	P-wave velocity(km/s)	S-wave velocity(km/s)	Density(kg/m ³)
Primary coal#1	2304	1326	1379.68
Primary coal#2	2155	1140	1475.94
Primary coal#3	1779	1002	1530.43
Primary coal#4	1859	1032	1346.07
Primary coal#5	2045	1108	1312.45
Primary coal#6	2088	1133	1328.24
Cataclastic coal#1	1475	777	1370.51
Cataclastic coal#2	1733	1012	1349.12
Cataclastic coal#3	1745	1006	1365.93
Cataclastic coal#4	1715	923	1366.44
Cataclastic coal#5	1144	661	1266.11
Cataclastic coal#6	1618	897	1291.06

The measured P-wave velocity, S-wave velocity, and density of each specimen are summarized in Table 1. Meanwhile, complete ultrasonic transmission waveforms were synchronously acquired during the tests. Based on the recorded waveforms, subsequent analyses were performed in the time, frequency, and time-frequency domains. Specifically, the original waveforms were used to characterize ultrasonic wave propagation, the frequency spectra were obtained using the fast Fourier transform (FFT), and the time-frequency characteristics were analyzed using the continuous wavelet transform (CWT) to characterize the temporal evolution of frequency components (Landinez, Rueda & Lora-Clavijo, 2021).

These analyses provide the basis for elucidating the acoustic response characteristics of coals with different structural types and the underlying structural controls.

2.3 Computed tomographic scan

High-resolution X-ray computed tomography (CT) scanning was performed using a NanoVoxel-2600 three-dimensional X-ray microscopy (3D-XRM) system (Tianjin SanYing Precision Instruments Co., Ltd., Tianjin, China), as shown in Fig. 3. The system consists of a main control unit, a micro-focus X-ray source, a high-resolution flat-panel detector, and an image-processing workstation (Fan, et al., 2024). The NanoVoxel-2600 is equipped with a micro-focus sealed transmission X-ray source operating at an accelerating voltage of 30–160 kV. During scanning, X-rays generated by high-energy electrons striking a metal target were collimated into a focused beam to penetrate the specimen (Li, et al., 2023). A rotational scanning mode was adopted, in which the specimen was mounted on a high-precision rotation stage and continuously rotated through 360°, while the X-ray source and detector remained stationary (Yu, et al., 2024). This configuration effectively minimizes mechanical errors and improves the stability and spatial resolution of the reconstructed images.



Fig. 3. NanoVoxel-2600 three-dimensional X-ray microscopy imaging system

A processing workflow consisting of noise reduction, image cropping, and image segmentation was adopted for the CT images. First, median filtering was applied to the raw images to suppress noise and improve the signal-to-noise ratio. Subsequently, regions affected by edge artifacts were removed, and only high-quality image regions were retained for further analysis. Based on the grayscale contrast among the coal matrix, mineral inclusions, and the pore-fracture system, an interactive thresholding method combined with a top-hat transformation was employed to achieve effective phase segmentation (Yao, 2016). Following image segmentation, a series of two-dimensional slices representing the coal matrix, mineral inclusions, and the pore-fracture system was obtained. Three-dimensional digital core models were then reconstructed in Avizo by slice stacking and spatial registration, enabling visualization of the heterogeneous internal structure of the coal. Quantitative analysis was performed using the Volume Fraction module in Avizo to determine the porosity and mineral content, thereby quantifying the volumetric fractions of pore and solid phases (coal matrix and mineral inclusions) in different coal samples. Representative regions of interest (ROIs) were subsequently extracted from the reconstructed models. The Label Analysis module was then employed to identify and quantify the pore-fracture system by extracting geometric parameters, including equivalent diameter, area, and volume, thereby providing a quantitative characterization of the pore-size distribution.

2.4 Digital core wavefield simulation method

Based on the two-dimensional XZ-plane CT slice extracted from the center of each specimen, image segmentation was performed to identify the coal matrix, mineral inclusions, and pore-fracture system. The segmented image was then used to construct a two-dimensional

structural model that preserves the realistic microscale heterogeneous characteristics of the coal (Nakagawa & Schoenberg, 2007). Subsequently, the model was imported into COMSOL Multiphysics to establish a CT-derived finite-element model for ultrasonic wavefield simulation, as shown in Fig. 4. To quantitatively evaluate the effects of different heterogeneous structural components on ultrasonic wave propagation, four comparative models were constructed. Model 1 consisted solely of the coal matrix and served as the homogeneous reference model. Model 2 incorporated mineral inclusions into the coal matrix to investigate their influence on local wavefield perturbations. Model 3 introduced the pore-fracture system into the coal matrix to evaluate the effects of fractures on wave propagation paths and energy attenuation. Model 4 included the coal matrix, mineral inclusions, and the pore-fracture system simultaneously, representing the realistic multiphase heterogeneous structure of coal. In all finite-element models, the coal matrix and mineral inclusions were assumed to be isotropic linear elastic materials, and elastic wave propagation was simulated using the Solid Mechanics module in COMSOL. Comparative analysis of the four models was performed to elucidate the respective roles of mineral inclusions and the pore-fracture system in controlling wave propagation paths, interface reflection and scattering, and wave energy attenuation.

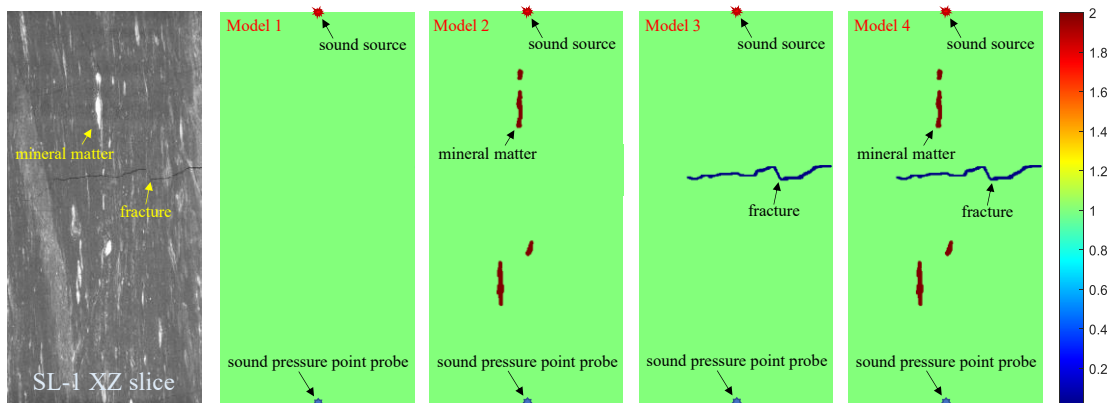


Fig. 4. Two-dimensional slicing and finite element model construction

When the sound wave propagates in the solid domain, the velocity-strain formula is used to solve the governing equation of the general linear elastic material. The wave equation is :

$$\rho \frac{\partial \mathbf{v}}{\partial t} - \nabla \cdot \mathbf{S} = \mathbf{F}_v \quad (3)$$

$$\frac{\partial \boldsymbol{\varepsilon}}{\partial t} - \frac{1}{2} [\nabla \mathbf{v} + (\nabla \mathbf{v})^T] = 0 \quad (4)$$

$$\mathbf{S} = \mathbf{C} : \boldsymbol{\varepsilon} \quad (5)$$

where $\mathbf{v}$ is the velocity vector, m/s; ρ is the material density, kg/m³; $\mathbf{S}$ is the second Piola–Kirchhoff stress tensor, N/m²; $\boldsymbol{\varepsilon}$ is the strain tensor; $\mathbf{C}$ is the elastic stiffness tensor; $\mathbf{F}_v$ is the body force per unit deformed volume N/m³; ∇ is the gradient operator; and ∇^2 is the Laplace operator.

Table 2 Parameters of model material

Material name	P-wave velocity(km/s)	S-wave velocity(km/s)	Density(kg/m ³)
Mineral	3000	1900	2350
Coal	1800	1000	1365

The material properties assigned to the coal matrix were determined from the average experimental values obtained by ultrasonic testing, with a P-wave velocity of 1800 m/s, an S-wave velocity of 1000 m/s, and a density of 1365 kg/m³ (Table 2). These values represent the average mechanical properties of the coal matrix in the investigated samples. The mineral phase was modeled as an equivalent elastic medium based on the typical properties of the dominant minerals occurring in coal. Quartz and clay minerals (e.g., kaolinite and illite) are generally the major mineral constituents of coal, with quartz exhibiting relatively high elastic stiffness and wave velocity. Therefore, the mineral phase was assigned a P-wave velocity of 3000 m/s, an S-wave velocity of 1900 m/s, and a density of 2350 kg/m³. These values fall within the reported

ranges for quartz-bearing silicate minerals and provide a reasonable representation of the acoustic impedance contrast between mineral inclusions and the coal matrix while avoiding unnecessary complexity associated with individual mineral species.

The model dimensions were set to 50×100 mm. The red, green, and blue regions represent mineral inclusions, the coal matrix, and internal fractures, respectively. The acoustic source was placed at the geometric center of the upper boundary of the model, where a sinusoidal acoustic excitation was applied. A point probe was positioned at the geometric center of the lower boundary to record the received acoustic signal. The acoustic source was excited by a sinusoidal pressure load, which is expressed as follows:

$$G(t) = 1 \times 10^6 e^{-((2t-2T_0)/T_0)^2} \times \sin(2\pi f_0 t) \quad (7)$$

where $G(t)$ denotes the sinusoidal pressure excitation, Pa; t is time, s; and (x_0, y_0) is the source location, with $x_0=25$ mm and $y_0=100$ mm. The peak pressure amplitude of the excitation is 1 MPa.

In the finite-element simulations, the point source located at (x_0, y_0) was implemented as an equivalent body force to enable its application within the computational domain. In theory, a point load can be expressed as a body force proportional to the Dirac delta function, i.e.,

$$F(t) = G(t) \cdot \delta(x - x_0, y - y_0) \quad (8)$$

where $F(t)$ is the equivalent body force, and $\delta(x, y)$ denotes the Dirac delta function approximated by a Gaussian function. The Gaussian approximation of the Dirac delta function is given by:

$$\delta(x - x_0) = \lim_{a \rightarrow \infty} \frac{1}{\sqrt{\pi a^2}} e^{-\left(\frac{x-x_0}{a}\right)^2} \quad (9)$$

This formulation represents the source excitation as a domain source expressed as the product

of a temporal function and a spatial function. The spatial distribution is described by a two-dimensional Gaussian function centered at (x_0, y_0) , which serves as a regularized approximation of the Dirac delta function.

3 Results and Discussion

3.1 Acoustic response characteristics

The time-domain ultrasonic waveforms of primary coal and cataclastic coal are presented in Fig. 5. For clarity, the specimen labels were abbreviated as PC (primary coal) and CC (cataclastic coal). Overall, the received waveforms exhibit pronounced complexity and non-stationary characteristics, with highly irregular waveforms and long-lasting coda waves. Distinct coda signals are still observable at approximately 600 μs , indicating that ultrasonic waves undergo significant scattering and multiple wave superposition during propagation through the coal.

A comparison between the two coal types shows that the first-arrival time of the PC specimens is consistently earlier than that of the CC specimens. Moreover, the waveforms of the PC specimens are more continuous and stable, whereas those of the CC specimens exhibit weaker amplitudes, stronger waveform distortion, and less distinct first arrivals, reflecting more severe attenuation during wave propagation. These differences are primarily attributed to the well-developed pore-fracture system and enhanced structural heterogeneity in cataclastic coal. During propagation, ultrasonic waves undergo multiple reflections, transmissions, diffractions, and scattering within the complex pore-fracture network, resulting in continuous energy dissipation, prolonged coda waves, waveform distortion, and accelerated attenuation of high-

frequency components. Consequently, the time-domain responses of cataclastic coal are characterized by prolonged coda waves, more complex waveform patterns, and stronger energy attenuation.

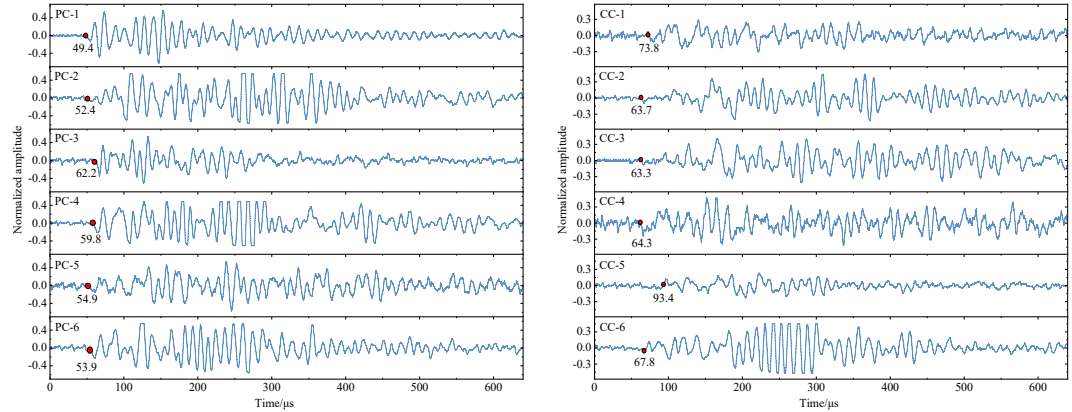


Fig. 5. Time-domain spectra of ultrasonic received waves

In contrast, the frequency-domain characteristics of the coal specimens exhibit pronounced differences (Figs. 6a and 6b). Both primary coal and cataclastic coal display broadband, multi-peaked spectra with relatively low spectral stability, and their spectral continuity is noticeably poorer than that typically observed in more homogeneous rock specimens. The dominant frequency of primary coal is mainly distributed between 75 and 85 kHz, although considerable variations exist among individual specimens. Some specimens still retain appreciable spectral energy near 100 kHz, suggesting that despite the presence of fractures, the coal matrix remains relatively continuous and supports the transmission of high-frequency components.

The spectra of cataclastic coal are considerably more complex. The dominant frequencies are more dispersed, with some specimens exhibiting a distinct shift toward lower frequencies, accompanied by an increased proportion of low-frequency energy and pronounced attenuation of high-frequency components. These characteristics indicate that the well-developed pore-

fracture network in cataclastic coal enhances wave scattering, reflection, and diffraction during propagation, leading to rapid dissipation of high-frequency energy while preserving relatively more low-frequency components. Moreover, the broader and more pronounced multi-peaked spectral features reflect the strong structural heterogeneity of cataclastic coal. The resulting increase in propagation-path complexity promotes frequency splitting and spectral broadening, giving rise to the observed broadband spectral characteristics.

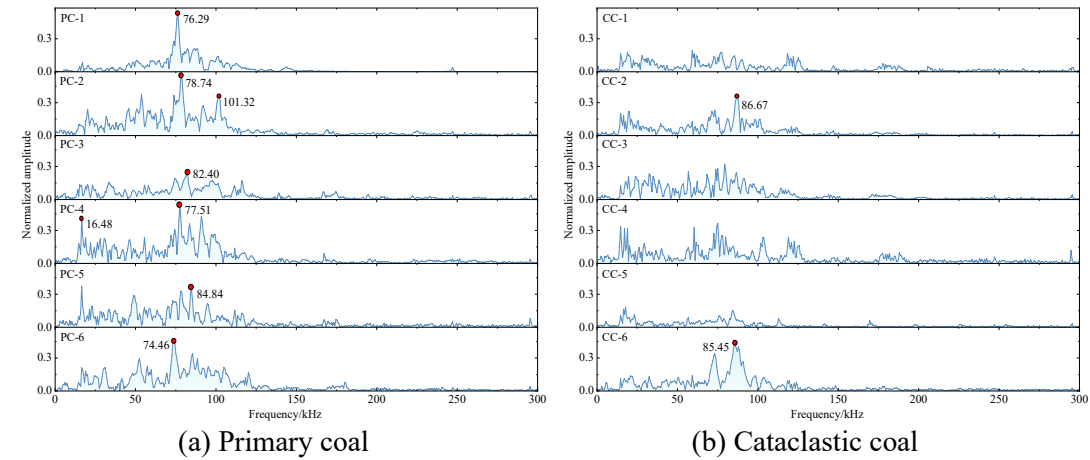


Fig. 6. Frequency domain spectrum of ultrasonic receiving waves

As shown in Fig. 7a, the time-frequency responses of the primary coal specimens exhibit pronounced characteristics of wave propagation in a heterogeneous medium. The dominant energy is mainly concentrated within the 70–100 kHz frequency band. Compared with typical sandstone and mudstone specimens, the frequency band is considerably broader, with abundant low- and high-frequency components, indicating strong wave dispersion and scattering within the coal. The high-energy region is primarily distributed between 100 and 250 μ s, which occurs later than that commonly observed in rock specimens, reflecting the relatively lower ultrasonic velocity in coal. In addition, considerable variations in the energy distribution are observed among different specimens, with both continuous energy bands and discrete multi-peaked energy clusters present, suggesting pronounced spatial heterogeneity associated with the coal

matrix, pores, and fractures. Furthermore, weak high-frequency responses above 200 kHz are still detectable in some specimens, while low-frequency coda signals persist within 300–400 μ s, indicating that multiple reflections, transmissions, diffractions, and scattering occur during wave propagation, resulting in prolonged coda waves and relatively slow energy attenuation.

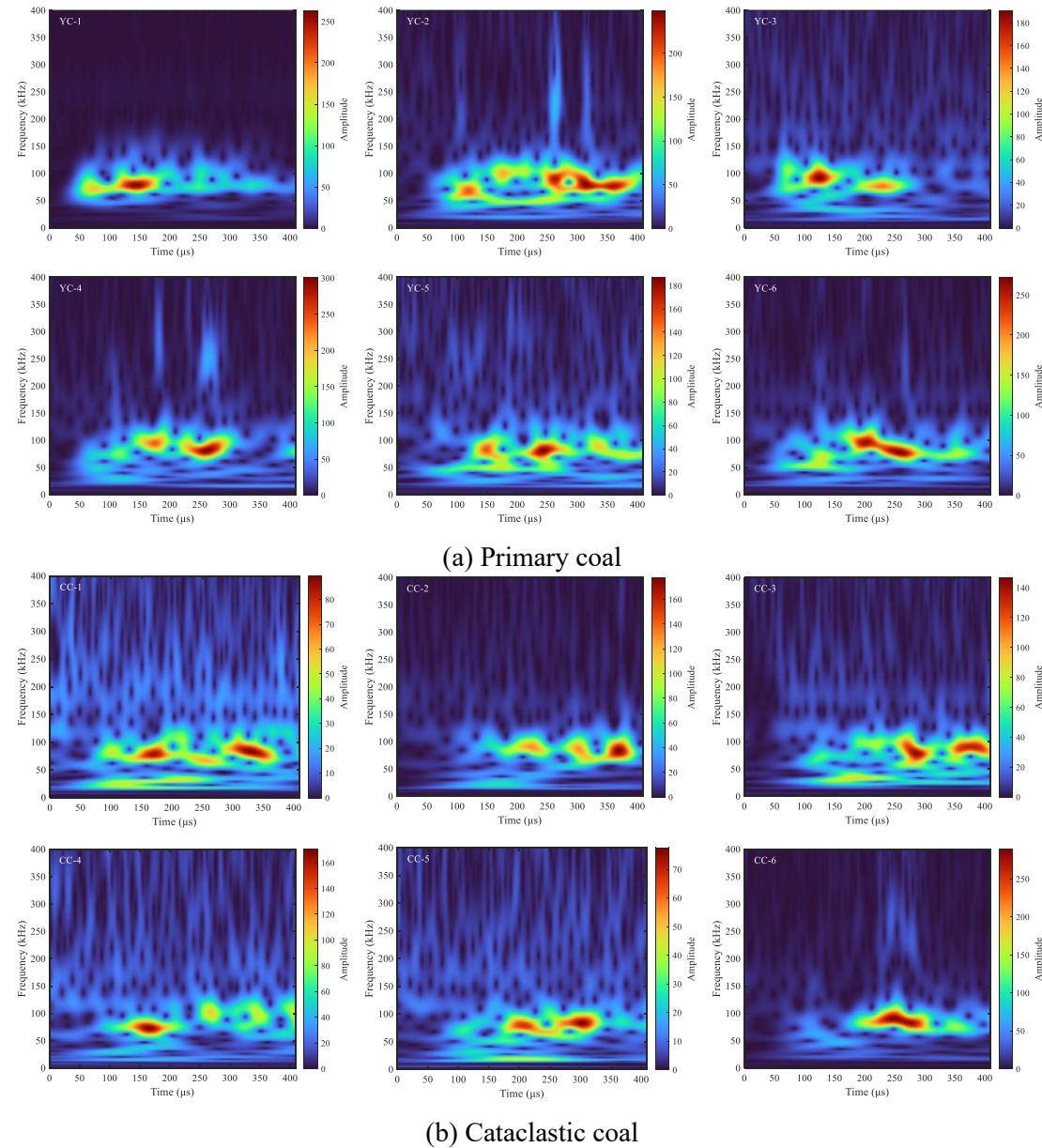


Fig. 7. Time-frequency spectra of ultrasonic received waves

As shown in Fig. 7b, the time-frequency responses of the cataclastic coal specimens are considerably more complex than those of the primary coal, exhibiting greater discontinuity and instability. Although the dominant energy is likewise concentrated within the 70–100 kHz range,

the frequency band becomes noticeably broader, accompanied by enhanced low-frequency background energy, indicating stronger scattering and dispersion induced by the well-developed pore-fracture network. The high-energy region is mainly distributed between 150 and 350 μ s, representing an overall delay relative to the primary coal and implying a further reduction in ultrasonic velocity. Moreover, the energy clusters become increasingly discontinuous and multi-peaked, while the dominant energy distribution is less stable, reflecting the markedly enhanced structural heterogeneity of the cataclastic coal. Distinct low-frequency coda responses persist over a longer propagation time, together with more pronounced background energy streaks, demonstrating that intensive multiple scattering and energy dissipation occur within the complex pore-fracture network, thereby leading to significantly stronger attenuation of high-frequency components.

3.2 Mineral and pore characteristics

Based on the CT image segmentation results and three-dimensional digital core reconstruction, the pore-fracture characteristics of primary coal (PC) and cataclastic coal (CC) were quantitatively characterized. Figure 8 presents the digital core reconstruction of representative PC-1 and CC-1 specimens together with the corresponding image-processing workflow. The reconstructed models reveal that both coal types exhibit typical multi-scale heterogeneous structures composed of the coal matrix, mineral inclusions, and the pore-fracture system. Mineral inclusions occur as discrete particles embedded within the coal matrix, whereas the pore-fracture system exhibits varying degrees of development and connectivity, constituting the principal structural component controlling the physical properties and ultrasonic wave propagation behavior of coal.

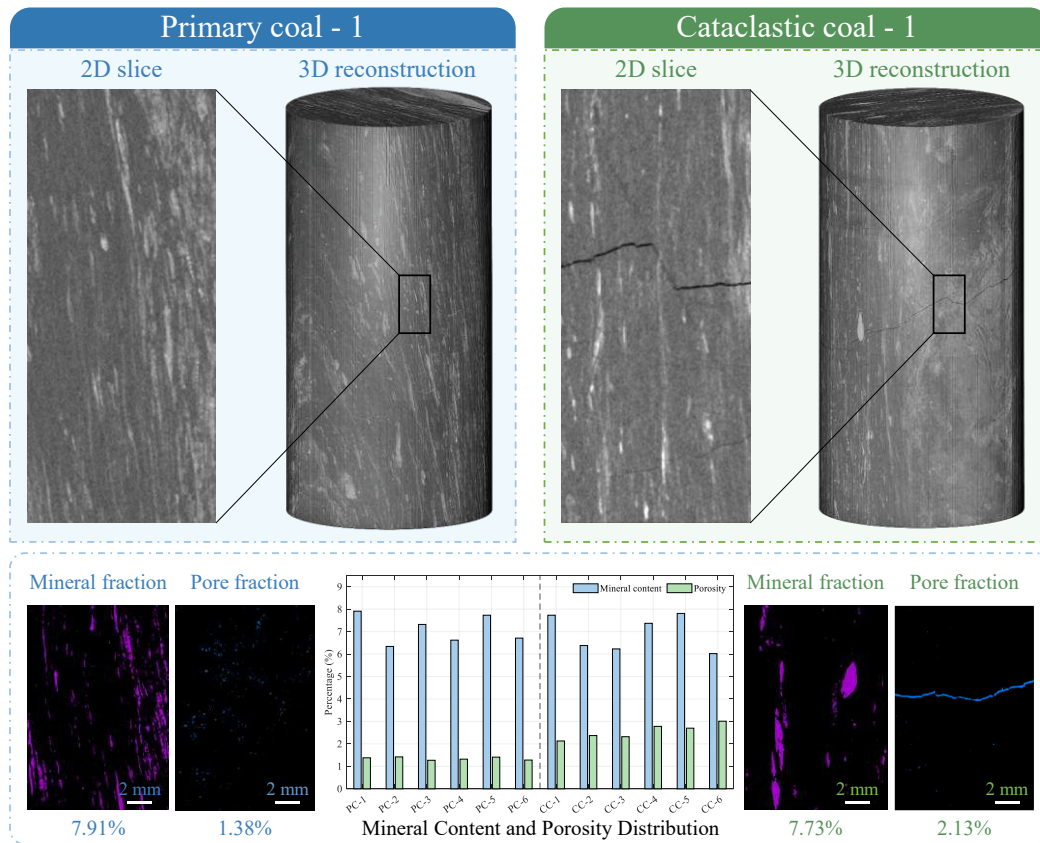


Fig. 8. CT reconstruction of different types of coal samples

The volumetric analysis shows that the mineral contents of the two coal types are comparable, with both ranging from approximately 6% to 8%, indicating that tectonic deformation has little influence on the overall mineral content. Instead, its effect is mainly reflected in the spatial distribution and occurrence of mineral inclusions. Owing to the relatively small acoustic impedance contrast between mineral inclusions and the coal matrix, only limited local reflection and scattering occur at mineral interfaces, resulting in a relatively minor influence on the overall wave propagation behavior. In contrast, a significant difference is observed in porosity. The porosity of cataclastic coal is consistently higher than that of primary coal, ranging from 2% to 3%, whereas that of primary coal is mainly distributed between 1% and 2%. This result indicates that tectonic deformation promotes the initiation, propagation, and interconnection of pores and fractures, leading to a substantial increase in pore volume. As

the principal low-acoustic-impedance phase within coal, the pore-fracture system significantly increases the complexity of wave propagation paths and enhances wave scattering, reflection, and energy dissipation. Consequently, the higher porosity of cataclastic coal not only reflects its stronger structural heterogeneity but also explains its lower wave velocity, greater attenuation, and more complex waveform characteristics observed in the ultrasonic experiments.

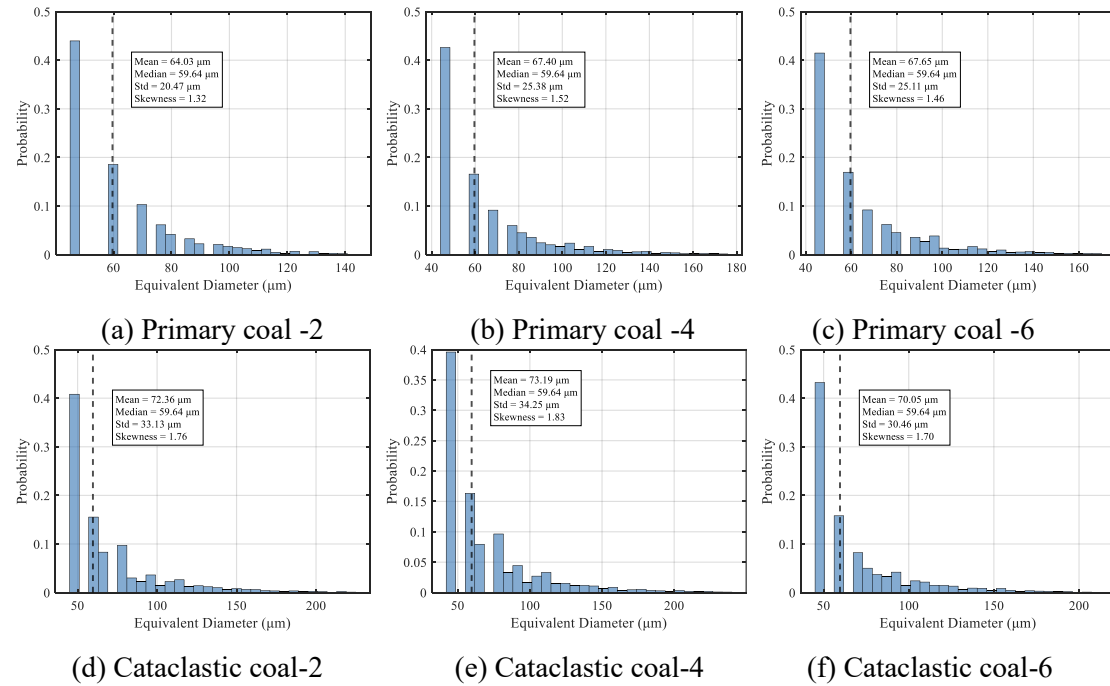


Fig. 9. Histogram of aperture distribution and its statistical characteristics

Figure 9 presents the pore-size distribution histograms and corresponding statistical parameters (mean, median, standard deviation, and skewness) for six representative specimens of primary coal and cataclastic coal. Both the distribution patterns and statistical results reveal pronounced differences in the pore-fracture structures of the two coal types. The pore sizes of the primary coal specimens (PC-2, PC-4, and PC-6) are mainly concentrated within 50–80 μm, exhibiting a unimodal and positively skewed distribution. The frequency decreases rapidly for pore sizes exceeding 120 μm, indicating relatively limited pore-fracture development, a concentrated pore-size distribution, and better structural uniformity. The relatively continuous

coal matrix provides stable propagation paths for ultrasonic waves, thereby facilitating wave energy transmission and first-arrival identification. In contrast, the pore-size distributions of the cataclastic coal specimens (CC-2, CC-4, and CC-6) are substantially broader, with markedly extended right tails and appreciable frequencies for pore sizes larger than 150 μm . This indicates that tectonic deformation promotes fracture propagation and pore connectivity, resulting in the formation of more large-scale pore-fracture structures. The broadened pore-size distribution reflects increased structural heterogeneity across multiple length scales, providing favorable conditions for multi-scale wave scattering during ultrasonic propagation. Statistical analysis further shows that cataclastic coal exhibits larger mean pore sizes and significantly higher standard deviations than primary coal, indicating greater spatial variability in pore size. Although all specimens exhibit positively skewed distributions, the higher skewness of cataclastic coal suggests a greater proportion of large pores and fractures.

The increase in large pores and the broadening of the pore-size distribution enhance wave scattering and diffraction, leading to continuous wave energy redistribution and dissipation within the complex pore-fracture network. Consequently, ultrasonic propagation is characterized by reduced wave velocity, lower first-arrival amplitude, stronger attenuation of high-frequency components, and more pronounced coda waves. These observations are consistent with the ultrasonic experimental results, in which cataclastic coal exhibits lower P-wave and S-wave velocities, longer propagation delays, and stronger low-frequency coda responses than primary coal, whereas primary coal shows higher wave velocities and more stable spectral characteristics. These findings demonstrate that the pore-fracture size distribution and its spatial connectivity are key microscale structural parameters governing the

acoustic response of coal. As pore size and fracture-network complexity increase, ultrasonic propagation gradually changes from near-linear transmission in a relatively continuous medium to multiple scattering in a highly heterogeneous medium, resulting in substantial changes in wavefield characteristics. Therefore, the digital core analysis confirms that tectonically induced pore-fracture development and scale enlargement not only enhance the multi-scale heterogeneity of coal but also provide the microscale structural basis for the observed reductions in wave velocity, spectral broadening, coda-wave enhancement, and wave energy attenuation. These results further identify the pore-fracture system as the critical link between coal microstructure and ultrasonic wave propagation, as well as the key controlling factor investigated in the subsequent wavefield simulations.

3.3 Acoustic wave propagation characteristics

Wavefield snapshots of ultrasonic propagation in the four numerical models are presented in Fig. 10. As shown in Fig. 10a, when the model consists solely of a homogeneous coal matrix without mineral inclusions or pore-fracture structures, ultrasonic waves propagate in a stable and continuous manner. The mechanical excitation generates both compressional (P) and shear (S) waves, with the P-wave propagating downward along the transmission direction and the S-wave spreading laterally owing to shear deformation in the elastic medium. As propagation proceeds, the wavefront maintains a regular arc-shaped geometry with a nearly straight propagation path and a relatively uniform energy distribution. Owing to the homogeneous nature of the medium, wave attenuation is limited, and the P-wave reaches the vicinity of the receiver at approximately 50 μ s, indicating that the coal matrix imposes little resistance to wave propagation.

As shown in Fig. 10b, the introduction of mineral inclusions causes local perturbations to the wavefield while exerting only a limited influence on the overall propagation behavior. Because the acoustic impedance contrast between the coal matrix and mineral inclusions is relatively small, the incident wave is partially reflected and partially transmitted at the interface, accompanied by local mode conversion. Consequently, slight wavefront distortion and localized energy concentration can be observed near the mineral boundaries. However, transmission remains dominant over reflection, and the overall propagation path, wave velocity, and wavefield pattern remain largely unchanged. In contrast, the pore-fracture model (Fig. 10c) exhibits substantially different propagation characteristics. When the incident wave reaches a fracture filled with air, the large acoustic impedance mismatch between the fracture and the coal matrix causes most of the incident energy to be reflected, with only a small fraction transmitted across the interface. As a result, strong reflections occur around the fractures, disrupting wavefront continuity and inducing pronounced diffraction and scattering. The propagation path becomes increasingly tortuous, wave energy attenuates rapidly, and the arrival of the transmitted wave is delayed relative to the homogeneous model. The wavefield becomes even more complex in the combined mineral-fracture model (Fig. 10d), where local scattering induced by mineral inclusions and strong reflections generated at fracture interfaces act simultaneously. Mineral inclusions mainly cause local wavefront perturbations and energy redistribution, whereas the pore-fracture system dominates wave reflection and energy attenuation. Consequently, the composite model exhibits more pronounced wavefront distortion, more tortuous propagation paths, and stronger wave attenuation than the mineral-only model. These results indicate that the pore-fracture system is the primary heterogeneous factor

controlling ultrasonic wave propagation in coal, whereas mineral inclusions mainly modify the local wavefield without significantly altering the overall propagation characteristics.

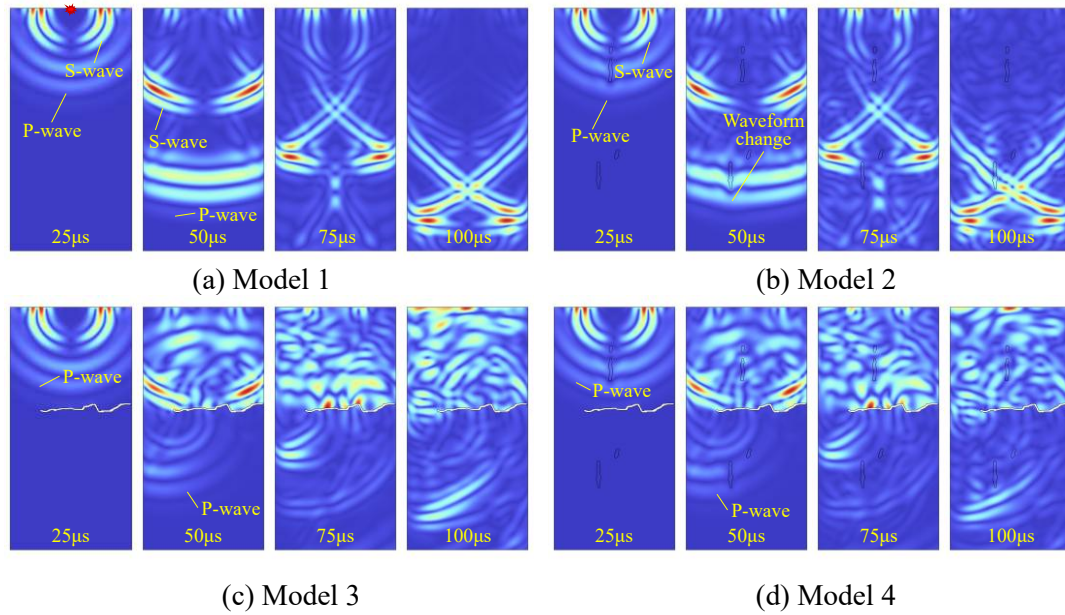


Fig. 10. Wavefield snapshot

The time-frequency characteristics of the received ultrasonic signals for the four numerical models are presented in Fig. 11. As shown in Fig. 11a, for the homogeneous coal matrix model, the signal energy is mainly concentrated within the 50–150 kHz frequency band. The first arrival reaches the receiver at approximately 55 μs, and the dominant energy is distributed between 60 and 80 μs. Owing to the homogeneous and continuous nature of the medium, ultrasonic waves propagate along nearly straight paths with limited energy loss. Consequently, the time-frequency energy is highly concentrated and continuous, forming a single, well-defined energy peak with rapid attenuation of high-frequency components, indicating weak waveform distortion and a high signal-to-noise ratio. Figure 11b shows the time-frequency spectrum of the model containing mineral inclusions. Compared with the homogeneous model, the dominant frequency range remains nearly unchanged, and the first arrival still occurs at approximately 55 μs. The principal energy remains concentrated within the 50–150 kHz range,

exhibiting only slight energy attenuation and spectral broadening. Because the acoustic impedance contrast between the mineral inclusions and the coal matrix is relatively small, only limited reflection and transmission occur at the interfaces, with the transmitted wave remaining dominant. Consequently, mineral inclusions mainly introduce localized wavefield perturbations without significantly altering the overall propagation path or the first-arrival time. Only a few weak energy patches generated by interface scattering appear at later times, and the overall time-frequency pattern remains highly similar to that of Model 1.

In contrast, the time-frequency characteristics change markedly in the pore-fracture model (Fig. 11c). Owing to the large acoustic impedance mismatch between the air-filled fractures and the surrounding coal matrix, most of the incident wave energy is reflected at the fracture interfaces, while only a small fraction is transmitted. As a result, ultrasonic waves can no longer propagate along the original direct path but instead bypass the fractures or reach the receiver after multiple reflections and diffractions. Consequently, the first arrival is delayed to approximately 58 μs , accompanied by a pronounced reduction in the amplitude of the dominant energy. Moreover, fracture-induced multipath propagation substantially increases the complexity of the later wavefield, producing multiple discrete energy clusters between 80 and 200 μs . The coda-wave duration is significantly prolonged, and the energy distribution evolves from a concentrated pattern to a broader frequency band, indicating that fractures not only increase the effective propagation path but also enhance scattering and mode conversion, thereby substantially increasing wavefield complexity. Figure 11d presents the time-frequency spectrum of the combined mineral-fracture model. Although its overall evolution is similar to that of Model 3, the wavefield becomes even more complex. The combined effects of interface

scattering from mineral inclusions and strong reflections from fractures further deflect the propagation paths, causing ultrasonic waves to experience additional interface reflections and scattering during propagation. The first arrival remains approximately 58 μ s, whereas the subsequent coda becomes more pronounced, with a greater number of discrete energy peaks appearing between 100 and 200 μ s. Consequently, the time-frequency energy distribution becomes more dispersed and persists for a longer duration. These results indicate that mineral inclusions alone exert only a limited influence on the first-arrival characteristics; however, when coupled with fractures, they further increase local propagation-path complexity and reinforce fracture-induced multipath propagation and coda-wave superposition, resulting in a more complicated time-frequency response.

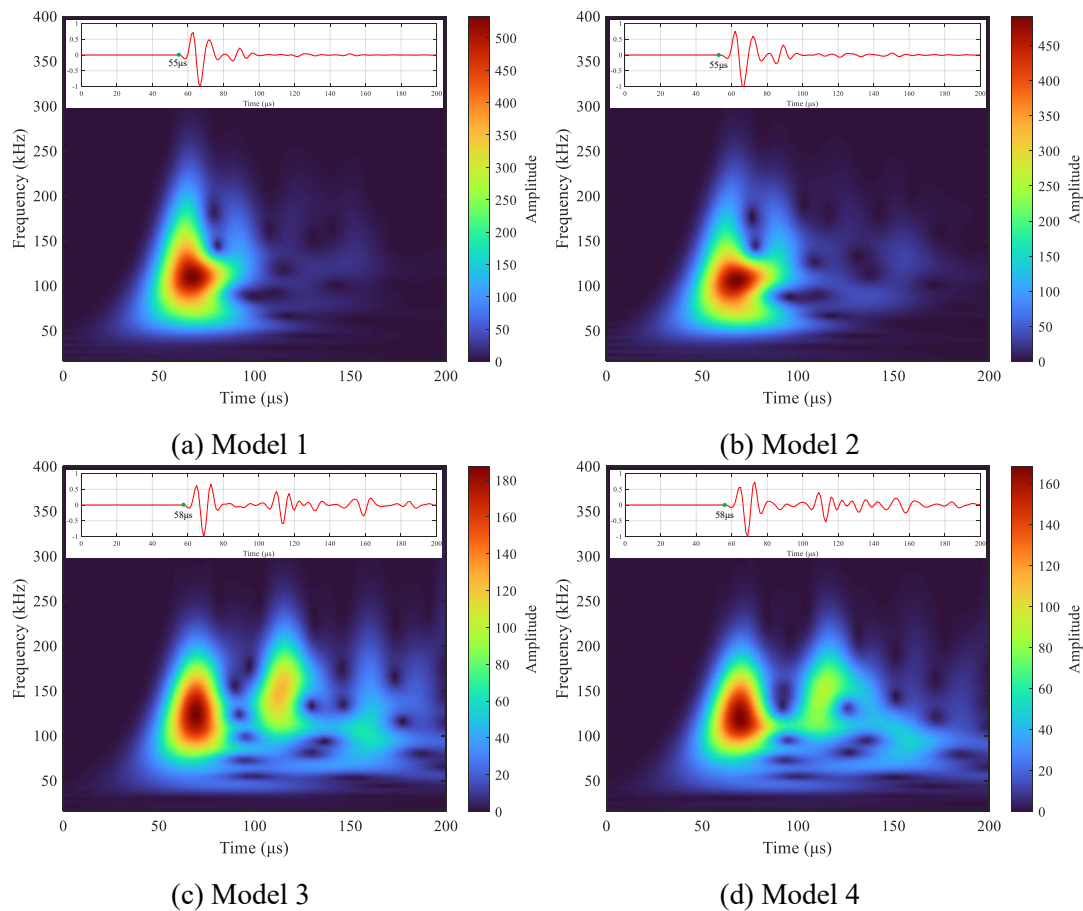


Fig. 11. Time-frequency spectrum characteristics of received waves

Overall, comparison of the four models demonstrates that mineral inclusions primarily produce localized wavefield perturbations with little influence on first-arrival propagation. In contrast, the pore-fracture system, owing to its pronounced acoustic impedance mismatch with the coal matrix, fundamentally alters the propagation path, causing the propagation mode to transition from direct transmission to diffraction- and multiple reflection-dominated propagation. This leads to delayed first arrivals, reduced dominant energy, prolonged coda waves, and increasingly complex time-frequency characteristics. Therefore, the pore-fracture system is the dominant structural factor governing ultrasonic wave propagation paths and the evolution of time-frequency responses in coal, whereas the influence of mineral inclusions is comparatively limited.

4. Conclusion

(1) Significant differences in ultrasonic wave propagation were observed between primary coal and cataclastic coal due to their distinct multiscale heterogeneous structures. The average P-wave and S-wave velocities of primary coal were 2038.33 m/s and 1123.50 m/s, respectively, whereas those of cataclastic coal were 1571.67 m/s and 879.33 m/s, representing reductions of 22.89% and 21.73%, respectively. These results indicate that tectonic deformation weakens coal continuity and enhances wave attenuation.

(2) CT-based digital core reconstruction showed that both coal types contained similar mineral contents (6–8%), whereas the porosity of cataclastic coal (2–3%) was higher than that of primary coal (1–2%). In addition, cataclastic coal exhibited a broader pore-size distribution, with more pores and fractures larger than 150 μm , indicating that pore-fracture development is

the primary structural factor controlling the acoustic differences between the two coal types.

(3) Primary coal exhibited relatively continuous waveforms with dominant frequencies concentrated at 75–85 kHz, whereas cataclastic coal showed greater waveform complexity, enhanced low-frequency components, stronger attenuation of high-frequency components, and broader multi-peaked spectra. The dominant time-frequency energy shifted from 100–250 μ s in primary coal to 150–350 μ s in cataclastic coal, reflecting the longer propagation paths and stronger multiple scattering induced by the pore-fracture network.

(4) Wavefield simulations demonstrated that mineral inclusions caused only localized wavefield perturbations, with little influence on the first-arrival time or overall propagation behavior. In contrast, fractures delayed the first arrival from 55 μ s to 58 μ s (approximately 5.45%) and generated multiple discrete energy clusters between 80 and 200 μ s, indicating that fractures dominate ultrasonic wave propagation by increasing propagation-path complexity and enhancing scattering and energy attenuation.

CRedit authorship contribution statement

Hongyang Xu: Project administration, Writing – original draft, Formal analysis, Writing – review & editing. Cheng Zhai: Supervision, Funding acquisition, Resources, Writing - review & editing. Yong Sun: Conceptualization, Methodology, Software, Writing – review & editing. Jizhao Xu: Investigation, Writing – review & editing. Xu Yu: Supervision, Writing – review & editing. Hexiang Xu: Investigation, Writing – review & editing. Hongda Wen: Visualization, Writing – review & editing. Yuhang Cheng: Supervision, Writing – review & editing. Hao Qiu : Investigation, Writing – review & editing.

Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available from the corresponding author upon reasonable request.

Acknowledgments

Funding for this work were provided by the Joint Funds of the National Natural Science Foundation of China for Enterprise Innovation Development (No. U25B20138).

References:

- Cao, Y., Davis, A., Liu, R., Liu, X., & Zhang, Y. (2003). The influence of tectonic deformation on some geochemical properties of coals—a possible indicator of outburst potential. *International journal of coal geology*, 53(2), 69-79.
- Di Martino, M.D.P., De Siena, L., & Tisato, N. (2022). Pore space topology controls ultrasonic waveforms in dry volcanic rocks. *Geophysical Research Letters*, 49(18), e2022GL100310.
- Dong, Q., Li, X., Jia, Y., & Sun, J. (2021). A numerical simulation of blasting stress wave propagation in a jointed rock mass under initial stresses. *Applied Sciences*, 11(17), 7873.
- Du, L., Jia, C., Wang, H., Sun, P., Chen, Y., Su, H., Cheng, C., Huang, X., Wang, Z., Lai, P., Wang, B., & Hu, Z. (2024). Response Patterns of Acoustic Wave Characteristics to Reservoir Petrophysical Parameters in Different Bedding Directions : A Case Study of Low - and Middle-Rank Coals in Xinjiang , China. *ACS OMEGA*, 9(39), 40723-40737.
- Fan, C., Jiang, X., Fan, N., Xiao, B., Yang, L., & Yang, Z. (2024). Scale effect of coal porosity and permeability characteristics based on CT 3D reconstruction from a microperspective. *Energy & Fuels*, 38(3), 1813-1821.
- Fan, N., Wang, J., Deng, C., Fan, Y., Wang, T., & Guo, X. (2020). Quantitative characterization of coal microstructure and visualization seepage of macropores using CT-based 3D reconstruction. *Journal of Natural Gas Science and Engineering*, 81, 103384.
- Gregor, D., & Moczo, P. (2020). The finite-difference modelling of seismic wave propagation in the poroelastic medium-the 2D P-SV case, *The finite-difference modelling of seismic wave propagation in the poroelastic medium-the 2D P-SV case*: Comenius University, Faculty of Mathematics, Physics and Informatics, 84218
- Hou, Q., Li, H., Fan, J., Ju, Y., Wang, T., Li, X., & Wu, Y. (2012). Structure and coalbed methane

- occurrence in tectonically deformed coals. *Science China Earth Sciences*, 55(11), 1755-1763.
- Huang, T., Zhai, C., Liu, T., Sun, Y., Xu, H., Wang, Y., & Huang, J. (2025). Microstructural evolution and hydraulic response of shale self-propped fracture using X-ray computed tomography and digital volume correlation. *International Journal of Mining Science and Technology*, 35(3), 345-362.
- Ju, Y., Yan, Z., Li, X., Hou, Q., Zhang, W., Fang, L., Yu, L., & Wei, M. (2012). Structural characteristics and physical properties of tectonically deformed coals. *Journal of Geological Research*, 2012(1), 852945.
- Landinez, G., Rueda, S., & Lora-Clavijo, F.D. (2021). First steps on modelling wave propagation in isotropic-heterogeneous media: numerical simulation of P–SV waves. *European Journal of Physics*, 42(6), 065001.
- Li, S., Tang, D., Xu, H., & Yang, Z. (2012). Advanced characterization of physical properties of coals with different coal structures by nuclear magnetic resonance and X-ray computed tomography. *Computers & geosciences*, 48, 220-227.
- Li, Y., Cui, H., Zhang, P., Wang, D., & Wei, J. (2020). Three-dimensional visualization and quantitative characterization of coal fracture dynamic evolution under uniaxial and triaxial compression based on μ CT scanning. *Fuel*, 262, 116568.
- Li, Y., Zhai, C., Sun, Y., Xu, J., Yu, X., & Huang, T. (2023). Characterizing water vapor adsorption on coal by nuclear magnetic resonance: Influence of coal pore structure and surface properties. *Energy*, 282, 128420.
- Ling, F., Li, Q., Qian, Y., Jiang, Z., Liu, R., & Li, W. (2021). *Research on attenuation law and application of elastic wave propagation in multi-coal seam fracture*, ISRM-ARMS11-2021-239.
- Martínez-Martínez, J., Benavente, D., & García-del-Cura, M.A. (2012). Comparison of the static and dynamic elastic modulus in carbonate rocks. *Bulletin of engineering geology and the environment*, 71(2), 263-268.
- Masson, Y., & Virieux, J. (2023). P-SV-wave propagation in heterogeneous media: Velocity-stress distributional finite-difference method. *Geophysics*, 88(3), T165-T183.
- Nakagawa, S., & Schoenberg, M.A. (2007). Poroelastic modeling of seismic boundary conditions across a fracture. *The Journal of the Acoustical Society of America*, 122(2), 831-847.
- Pan, Z., & Connell, L.D. (2012). Modelling permeability for coal reservoirs: a review of analytical models and testing data. *International Journal of Coal Geology*, 92, 1-44.
- Sakellariou, A., Sawkins, T.J., Senden, T.J., & Limaye, A. (2004). X-ray tomography for mesoscale physics applications. *Physica A: Statistical mechanics and its applications*, 339(1-2), 152-158.
- Seriani, G., & Oliveira, S.P. (2008). Dispersion analysis of spectral element methods for elastic wave propagation. *Wave motion*, 45(6), 729-744.
- She, J., Zou, G., Peng, S., Gong, F., Zhao, T., Liu, Y., Li, B., & Yin, C. (2025). The elastic wave dispersion mechanism of different coal structures under room-dry conditions. *JOURNAL OF GEOPHYSICS AND ENGINEERING*, 22(2), 449-464.
- Song, X., Chen, T., & Zhang, D. (2023). The Acoustic Characteristics of Tectonically Deformed Coal in Huaibei Coalfield. *ENERGIES*, 16(13), 15.
- Srivastava, M.K., Kishor, K., Singh, A.K., Mukherjee, S., & Bharti, S.K. (2025). Tectonically deformed coal: Focus on microstructures & implications for basin evolution. *Marine and Petroleum Geology*, 172, 107223.
- Van Pamel, A., Sha, G., Rokhlin, S.I., & Lowe, M.J. (2017). Finite-element modelling of elastic wave propagation and scattering within heterogeneous media. *Proceedings. Mathematical, Physical, and*

- Engineering Sciences*, 473(2197), 20160738.
- Wang, C., Li, Q., Ren, F., Wang, J., Wang, J., Song, X., Lin, Y., Liu, H., Wu, Y., Tu, J., & Li, B. (2025). Coupled simulation study of CO₂ adsorption in coal matrix based on CT-derived representative elementary volume (REV). *SCIENTIFIC REPORTS*, 15(1), 16.
- Wang, G., Qin, X., Shen, J., Zhang, Z., Han, D., & Jiang, C. (2019). Quantitative analysis of microscopic structure and gas seepage characteristics of low-rank coal based on CT three-dimensional reconstruction of CT images and fractal theory. *Fuel*, 256, 115900.
- Wen, H., Zhai, C., Xu, J., Sun, Y., Wu, F., Xu, H., & Wang, Y. (2026). Pore characterization of coal cuttings based on low-field nuclear magnetic resonance: A new method. *Fuel*, 406, 137066.
- Wu, M., Li, H., Wang, L., Yang, X., Dai, C., Yang, N., Li, J., Wang, Y., & Yu, M. (2023). μ CT quantitative assessment of the pore-fracture structures and permeability behaviors of long-flame coal treated by infrared rapid heating. *Energy*, 274, 127308.
- Xu, H., Zhai, C., Ranjith, P.G., Xu, J., Wen, H., Liu, T., Li, S., Jiang, B., & Li, B. (2026). Pore-fracture evolution and fractal characteristics of coal under triaxial compression : Insights from in-situ nuclear magnetic resonance. *INTERNATIONAL JOURNAL OF ROCK MECHANICS AND MINING SCIENCES*, 204, 19.
- Xu, H., Zhai, C., Sun, Y., Xia, J., Lai, Y., Dong, X., Xu, H., Huang, T., & Cai, Y. (2024). Imaging small geological structure in coal mines based on reflected acoustic logging of underground cross-seam boreholes. *Geoenergy Science and Engineering*, 234, 212675.
- Xu, H., Zhai, C., Sun, Y., Zhu, X., Xu, J., Zheng, Y., Tang, W., Wang, Y., & Chen, A. (2026). Transparent exploration method for hidden small geological structure based on acoustic reflection imaging of horizontal boreholes. *International Journal of Coal Science & Technology*, 13(1), 46.
- Yao, Y.L.D. (2016). Petrophysics and fluid properties characterizations of coalbed methane reservoir by using NMR relaxation time analysis. *Coal Science and Technology*(6).
- Yu, S., Bo, J., Ming, L., Chenliang, H., & Shaochun, X. (2020). A review on pore-fractures in tectonically deformed coals. *Fuel*, 278, 118248.
- Yu, X., Xu, H., Zhai, C., Regenauer-Lieb, K., Sang, S., Sun, Y., & Jing, Y. (2024). Characterization of water migration behavior during spontaneous imbibition in coal: From the perspective of fractal theory and NMR. *Fuel*, 355, 129499.
- Yu, Z., Zhai, C., Huang, J., Xu, H., Wang, Y., Chen, A., Huang, T., Xu, H., Qiu, H., & Yang, Q. (2026). Study on the effect of CO₂ foam fracturing fluid on coal microstructure modification and gas adsorption-diffusion characteristics under different pressures. *Chemical Engineering Journal*, 176137.
- Zhang, K., Wang, S., Wang, L., Cheng, Y., Li, W., Han, X., Liu, C., & Su, H. (2022). 3D visualization of tectonic coal microstructure and quantitative characterization on topological connectivity of pore-fracture networks by Micro-CT. *Journal of Petroleum Science and Engineering*, 208, 109675.
- Zhang, N., Yao, S., & Wang, Y. (2022). Nanopore structure and mechanical properties in brittle tectonically deformed coals explored by atomic force microscopy. *Frontiers in Earth Science*, 10, 844120.
- Zhao, J., & Cai, J.G. (2001). Transmission of elastic P-waves across single fractures with a nonlinear normal deformational behavior. *Rock Mechanics and Rock Engineering*, 34(1), 3-22.
- Zheqiang, J., Heping, X., Zhang, R., Cunbao, L., Wang, M., Mingzhong, G., Zhaopeng, Z., & Zetian, Z. (2020). Acoustic emission characteristics and damage evolution of coal at different depths under triaxial compression. *Rock Mechanics and Rock Engineering*, 53(5), 2063-2076.